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REPORT 80-19

Environmental engineering and ecological baseline investigations along the Yukon River–Prudhoe Bay Haul Road

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Jerry Brown and Richard L. Berg, Editors

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During the period 1975-1978 the Federal Highway Administration sponsored a series of environmental engineering investigations along the Yukon River to Prudhoe Bay Haul Road. In 1976 the Department of Energy joined these investigations with a series of ecological projects which continue to the present. Both agencies' research efforts were conducted on a cooperative basis with CRREL's in-house research program. The objectives of the research focused on 1) an evaluation of the performance of the road, 2) an assessment of changes in the environment associated with the road, 3) documentation of flora and vegetation along the 577-km-long transect, 4) methodologies for revegetation and restoration, and 5) an assessment of biological parameters as indicators of environmental integrity. In support of these objectives, specific studies were undertaken that investigated the climate along the road, thaw and subsidence,

20. Abstract (cont'd)

beneath and adjacent to the road, drainage and side slope performance, distribution and properties of road dust, vegetation distribution, vegetation disturbance and recovery, occurrence of weeds and weedy species, erosion and its control, revegetation and restoration, and construction of the fuel gas line. This report presents background information on the region, detailed results of the road thaw subsidence and dust investigations, and summaries of revegetation, fuel gas line, vegetation distribution, soil, and weed studies.

PREFACE

This report was prepared by Dr. Jerry Brown, Chief, Earth Sciences Branch, Research Division; Dr. Richard L. Berg, Research Civil Engineer, Geotechnical Research Branch, Experimental Engineering Division; Lawrence A. Johnson, Biologist, Alaskan Projects Office; and Richard K. Haugen, Geographer, Dr. Daniel E. Lawson, Research Physical Scientist, and Deborah Roach, Biologist, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Additional contributors to this report were Dr. K.R. Everett, Ohio State University, Dr. Gary Guymon, University of California-Irvine; Dr. Albert Johnson and Susan Kubanis, San Diego State University; Dr. Patrick Webber, Dr. Vera Komárková, and Donald Walker, Institute of Arctic and Alpine Research, University of Colorado; Barbara Murray and Dr. David Murray, Institute of Arctic Biology, University of Alaska.

Funding for this research was primarily provided by the U.S. Federal Highway Administration (FHWA) and by the Department of Energy (DOE). Additional funding was provided by DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground*, Scientific Area A2, *Cold Regions Environmental Interactions*, Work Unit 002, *Cold Regions Environmental Factors*, and DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions*, Technical Area D, *Cold Regions Design and Construction*, Work Unit 004, *Volume Changes Induced by Freezing and Thawing of Pavement Systems*.

The Alaska Department of Transportation and Public Facilities (DOTPF) participated in the joint program through in-kind field and office support. In addition, the Army Research Office funded two 3-year university grants for soils and revegetation studies at sites along the road. A list of the jointly sponsored university projects is found in Appendix B.

The projects and investigators involved in these joint FHWA-DOE-CRREL-sponsored investigations are participating in the US-USSR Agreement on Cooperation in the Field of Environmental Protection under Project 02.05-21, *Protection of Northern Ecosystems*.

This report was technically reviewed in various sections by Drs. Dwight Hovland and Julius Rockwell, Bureau of Land Management (formerly Alaska Pipeline Office, Anchorage), and Frederick Crory, William Quinn and Paul Sellmann of CRREL. A number of others from agencies within Alaska provided helpful suggestions as did many of the university contributors.

The participants appreciate the cooperation of the Alyeska Pipeline Service Company, which allowed access to the road and study sites and permitted procurement of its aerial photographs, and of the Bureau of Land Management. They would also like to thank Glenn Johns, FHWA, Juneau, and Walter Parker, former Commissioner, DOTPF, for their early and sustained encouragement to undertake these investigations. Douglas L. Smith, FHWA, Washington, D.C., has been the Contract Manager for the project. Robert Eaton and Charles Collins of CRREL participated in many aspects of the field investigations and separate reports including their contributions are in preparation. Susan Rindge assisted in preparation of the several geologic sections of the report. Catalino Espiritu, Kenneth Bobetsky, David Osborn and Ernest Parizeau assisted in reduction of road survey and temperature data. James Morse and Kenneth Straney assisted in fabrication of temperature sensors. For the

climatic section, Peter Keleman and Richard Mead assisted in data processing and Gary DeCoff in programming for the climatic data bank. Stephen Quarry and Fred Page of CRREL assisted in preparation and analyses of some of the dust samples under the supervision of Dr. I.K. Iskandar.

Harold Larsen prepared and compiled the numerous engineering drawings and Eleanor Huke prepared many of the maps. Numerous university-based personnel participated and assisted in the field investigations.

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This constitutes the final report to the Federal Highway Administration.

PHOTO CREDITS

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SUMMARY

Introduction

Construction of the 1.2-m-diam trans-Alaska pipeline necessitated construction of an adjacent road over more than one-half of its length because no permanent road existed in the area. The road, built in two sections by the Alyeska Pipeline Service Company, was constructed to the State of Alaska's secondary highway standards. The first section, or "TAPS Road," approximately 90 km in length, was constructed between August 1969 and July 1970 and extended from near Livengood to the Yukon River. The second section, the 577-km-long "Haul Road" between the Yukon River and Prudhoe Bay, was built in seven segments in five months, from 29 April to 29 September 1974 (see Fig. 1 in text). The road was officially turned over to the State of Alaska in October 1978.

Construction of the Yukon River-Prudhoe Bay Haul Road allowed, for the first time in Alaska, the opportunity to observe the performance of a road system which crosses both the discontinuous and the continuous permafrost zones. In addition to crossing highly variable permafrost conditions, the road also traverses diverse climatic, biotic and geologic conditions. Our comprehensive engineering and environmental investigations of the road and its immediate environment provide the data base required to improve road design and maintenance practices and further develop methods to minimize and restore impacts of road construction and operations in arctic and subarctic regions.

Included in the Haul Road are 20 permanent bridges, over 1000 culverts and 135 material sites. There are 15 oil pipeline crossings of the road of which nine are across buried sections of the oil pipeline and six are across aboveground portions of the oil pipeline. The road right-of-way (67 m wide) incorporates the buried oil pipeline for about 19 km and the aboveground pipeline for about 25 km. A 0.2- to 0.25-m-diam fuel gas line crosses the road seven times and is buried within 5 m of the toe of the road for about 180 km of its 230-km length.

A three-year research program to evaluate the performance of the road and to assess changes in the adjacent environment associated with the road was initiated in the summer of 1976. Four major objectives were initially identified:

1. Determination of the rate and magnitude of thaw penetration and subsidence under and adjacent to the Haul Road.

2. Documentation of existing flora, vegetation and soil types and determination of the rate of change in plant communities, soil fauna, and soils due to natural and man-made surface disturbances.

3. Acquisition of knowledge to enhance restoration by native plant species.

4. Characterization of the annual air temperature and precipitation regimes for representative areas along the Haul Road in order to provide the data base required to substantiate environmental and engineering road designs.

This report presents approaches, results, conclusions, and recommendations based on the investigations conducted under portions of the four objectives. We consider these results to be an initial characterization of road performance and environmental stresses resulting from the road and related pipeline activities. Ongoing ecological projects funded by other agencies are currently resulting in refinements to these initial investigations.

Climate

Local thermal and moisture regimes have had a major influence on the road design, construction and performance and their effect on the surrounding environment. To provide a more adequate data base for these important parameters, we have conducted climatic observations at 22 sites along the Yukon River–Prudhoe Bay Haul

Road. Temperature and precipitation characteristics suggest differentiation of the region encompassed by the Haul Road into the following four major climatic regions.

Interior

The Interior region extends from the Yukon River north to the timberline site 40 to 45 km north of the oil pipeline's construction camp at Dietrich. The length of the thaw season is the longest (123 to 168 days) and thawing degree-day totals are the highest (1182° to 1904°C-days) in this region. The warmest mean annual temperatures (−3.7° to −6.9°C) occur here, especially in the southern part. Precipitation during the summer is primarily due to convectional activity, and the maximum amounts are about equal to those found in the Brooks Range. Total annual precipitation is 168-455 mm.

Brooks Range

Sites from Chandalar Shelf to Atigun Camp in the Brooks Range are included in this region. Thawing degree-day totals are low (453° to 1189°C-days), as with the Arctic Coastal Plain, but the thaw season is slightly longer (87-131 days). The extremely cold winter temperatures typical of the continental climate of the Interior and Arctic Foothills regions do not usually occur at the higher elevations in the Brooks Range because they are above the usual winter temperature inversion. Mean annual temperatures in this region range from −5.9° to −6.9°C. The highest annual precipitation amounts (295–450 mm) occur in this region and the most intense, single-day rainfall during the study period occurred on the Chandalar Shelf.

Arctic Foothills

The Arctic Foothills region includes the stations from Galbraith Lake to the Sagwon bluffs. Differentiation of this region from the Coastal region to the north is based on its higher elevation and greater distance from the sea. The Arctic Foothills have a more continental climate than the Arctic Coastal Plain. The thawing index ranges from 760° to 1125°C-days. The thaw season is shorter (104-139 days) and cooler than that of the Interior region, resulting in colder mean annual temperatures (−9.0° to −11.1°C). The amount of precipitation is smaller than for the two southerly regions (140 to 267 mm annually), and convectional precipitation during the summer is rare.

Arctic Coastal Plain

This region includes stations from Franklin Bluffs north to Prudhoe Bay. Cold winters, cool summers (the thawing index ranges from 318° to 877°C-days) and short thaw season (91 to 128 days) result in the coldest mean annual temperatures (−10.6° to −12.8°C) and the greatest freezing degree-day accumulations. Wind is a significant environmental factor due to wind chill effect on humans and the blowing and drifting of snow. Precipitation amounts are relatively low (170 to 266 mm), about the same as those in the Arctic Foothills, but a greater proportion occurs as snow rather than rain (95-165 mm frozen vs 56-101 mm unfrozen).

Biota

The Haul Road passes through approximately 280 km of forest and 320 km of tundra vegetation before it reaches Prudhoe Bay. From the Yukon River to the southern foothills of the Brooks Range the vegetation consists of mixed deciduous-coniferous forests. By far the largest forest type in terms of area covered is a low forest dominated by black spruce which occurs on most level and gently rolling surfaces below an elevation of 700 m. White spruce tends to occupy steeper slopes and well-drained ridges. Depending on fire history, aspen and paper birch are mixed with spruce in various proportions up to pure or mixed stands of both of these deciduous successional species. Balsam poplar is found extensively on river terraces.

Above an elevation of about 700 m, forest vegetation gives way to shrubby tundra, consisting primarily of alder and dwarf birch, which is in turn replaced by a mixed herbaceous-dwarf shrub tundra vegetation at higher elevations. Tundra vegetation of the Arctic Slope consists largely of a sedge-tussock type on the Foothills and a sedge-meadow type on the Coastal Plain. Riparian habitats, late-lying snowbeds, rock outcrops and lakes and ponds add diversity to what otherwise appears to be a monotonous vegetation on the Arctic Slope.

Some plant species have been recorded for the first time in Alaska, and other documented species are rare in this region. Numerous range extensions for vascular plants, lichens, hepatics and mosses have been found along the Haul Road.

Soils and vegetation maps are an essential component of terrain surveys and are important for a wide variety of environmental investigations. In this study 21 vegetation and seven soil maps (scale 1:6,000) of representative locations were prepared. The large-scale mapping program produced three types of maps: 1) a master map, 2) a soil map, and 3) a vegetation map. The master maps contain information on vegetation, landform, microrelief, and slope. The vegetation maps are derived from the vegetation portion of the master map code. In forested areas the vegetation codes include dominant tree taxa, size and density of trees, and the understory communities.

Large grazing animals present within the transportation corridor include caribou, sheep and moose. Black bears and grizzly bears were common along the road during construction. North of the Brooks Range there is a relatively high density of arctic fox. Grayling and slimy sculpins, the two predominant fish species, are present in many streams and lakes along the entire length of the Haul Road. Round whitefish, the next most common species, is found in most streams 3 m or more in width. In rivers north of the Brooks Range, arctic grayling, ninespine stickleback and arctic char are in high abundance.

Roadbed, drainage and side slopes associated with permafrost

Principal objectives of the roadbed investigations were to determine the magnitude of thaw under and adjacent to representative portions of the road and to determine the amount of roadway settlement at these same locations. Secondary objectives included a survey of drainage problems associated with the Haul Road and performance of side slopes.

The road traverses major portions of both the discontinuous and continuous permafrost zones. The spatial distribution of ground temperatures is highly variable; however, permafrost temperatures at depths below the zone of seasonal variation generally range from 4° to 5°C warmer than the mean annual air temperature at the same location. In lowland areas of the southern discontinuous permafrost zone, soil temperatures generally range from −0.5° to −5°C and in the continuous permafrost zone north of the Brooks Range, they range between −5°C to −11°C.

Ground ice is associated with permafrost, and its abundance and distribution are significant considerations in route selection, road design, construction practices, and maintenance requirements. Ground ice occurs as pore ice, as ice films, lenses, layers and other small segregated masses up to 15 cm or so in thickness, and as large sheets and wedges. Vertically oriented ice wedges, which have formed over many centuries in permafrost zones, commonly exceed 1 m in width at their tops. The majority of ground ice occurs in fine-grained, unconsolidated sediments. Buried icings, pond ice, sheets of injected ice and possibly buried glacial ice can also be found in the near-surface permafrost. If these are melted, costly maintenance is generally required to repair the road and/or drainage structures involved.

Buried portions of the oil pipeline are in locations relatively free of excess ground ice (thaw–stable soils) or in nonpermafrost terrain. Therefore, in areas where the pipeline and road parallel one another on similar terrain, it is possible to infer conditions of the permafrost and ground ice beneath the road. North of the Yukon River, 51% of the oil pipeline is aboveground and about 64% of the length of the Haul Road was designed for thaw-unstable soils.

Based on results from three years of field measurements at 27 sites, and from additional observations the following conclusions have been made:

1. Seasonal thaw penetration probably exceeds the roadway embankment thickness in most locations. However, it probably does not penetrate the 1.7- or 1.8-m-thick embankment on the extreme northern end of the road and at other locations where the fill is in excess of 5 to 7 m thick. Seasonal thaw penetration into the subgrade soils beneath the roadway embankment probably also exceeds the thickness of the active layer in adjacent undisturbed areas. This was the situation at all of our sites where subsurface temperatures were measured.

2. The roadway has subsided to some degree over nearly all of its length. Some of the "apparent subsidence" may be due to regrading of the road during maintenance operations, but at 11 of our 27 observation sites, the subsidence has been in excess of 10 cm and at five of these sites subsidence exceeded 20 cm. No strong relationship between subsidence, embankment thickness and cone index (soil strength) was apparent.

3. Ice-rich side slopes tend to stabilize from erosion after a few years but thaw degradation and resulting subsidence continue beneath the ditches and roadway embankment. This was also the case along the TAPS Road, and data from the

Haul Road substantiate previously recommended guidelines on ice-rich cuts.

4. The most frequent problem related to cross drainage was observed to be "maintenance clogging" of culverts. The problem is caused when short culverts are partially or entirely blocked by gravel pushed downslope from frequent grading, thereby preventing water movement through one or both ends of the culvert.

5. The most striking problems associated with cross-drainage were combined thermal and hydraulic erosion downslope from the roadway. Most occurrences of this problem were located south of Dietrich Camp on the alluvial slopes along the Koyukuk River where gully erosion was apparently induced by concentrating flow through culverts and onto ice-rich soils where nonconcentrated flow previously occurred. Based on this experience, detailed terrain interpretation should result in better placement of culverts in order to avoid such downslope ice conditions.

6. To date only a few drainage problems have been caused by water flowing parallel to the road. The most common problem of this type was ponding of various sizes and depths caused by the interception of lateral drainage by access roads which did not initially have culverts or low water crossings. The most visible problems were caused by thermal erosion due to concentrated flow over the backfilled trench of the fuel gas line.

7. The major roadway surface drainage problem is the creation of small longitudinal dikes on one or both sides of the road due to regrading. These dikes inhibit lateral runoff except at locations where the dikes are breached. Severe sideslope erosion sometimes results where the breaches occur. Dikes can generally be eliminated by skillful equipment operators during regrading.

Road dust

The potential for increased use of well-surfaced, high-speed gravel roads in tundra areas is increasing. Thus a thorough understanding of dust effects, some of which are quite subtle, is essential to proper road design, use of dust suppressants, speed control and limitation of axle weight.

Two dust collection sites were selected on the Arctic Coastal Plain and two sites on the rolling Arctic Foothills. Transects were set at right angles to the road, extending out to 1000 m on each side. Sampling stations along the transects were established at 8, 30, 125, 312, 500 and 1000 m on each side of the road and collections were made during the summers of 1977 and 1978.

Dust load decreased logarithmically away from the road at all sites and was closely related to prevailing wind direction. The southernmost site at Toolik produced the lowest total dust load, especially in the first 125 m. The largest dust loads occurred at Franklin Bluffs and Sagwon.

Silt and finer materials constituted between 8 and 15% of the road surface materials available for wind transport. Retransported particles larger than 2 mm in diameter were confined to within 8 m of the road. Beyond 20 m most of the dust materials were smaller than 50 μm. Within this finer fraction there was a significant shift to finer sizes with distance from the road.

Significant peaks in the concentration of available soil cations occurred with respect to distance from dust source and most commonly were found at the sampling sites 312 m from the road. Other peaks occurred at 30 and 125 m. These were probably related to particle size and/or particle composition and were not simply the result of microsite differences. The quantity of available cations was generally largest in the 0 to 2.5-cm depth as compared to the 2.5- to 5-cm depth. There appeared to be a significant increase in the total amount of available soil cations on the west side of the Haul Road. There did not appear to be any trend in the abundance of the available soil cations measured as the ocean was approached. The dust loads, even close to the road, contained insufficient soluble calcium and magnesium to directly affect either the pH or nutrient status of the soil. However, the direct effects of both dust and its nutrients were observed on some species of vegetation.

Concentration of some elements in road dust (Si, Al, Ba, Co) appeared to be greater in winter than summer. Most chemical elements for which data were evaluated in the road dust tended to increase in abundance away from the road with the exception of calcium. The concentrations of most elements were within their natural abundance in soil and rock (except for cobalt which is lower). The relative abundance of elements in road dust was quite constant from site to site along the portion of the road studied.

Early snow melt (2 to 3 weeks) brought about by dust accumulating on the winter snow may extend between 30 to 100 m on either side of the road.

Revegetation and restoration investigations

The construction of the Haul Road, the oil pipeline and the fuel gas line along the northern portion of the road resulted in a variety of terrain disturbances. Government stipulations required that erosion be controlled and impacted areas be revegetated or restored.

The road itself required numerous cuts and fills. Material sites were opened on the uplands and in river terraces and floodplains. These were connected to the Haul Road by access roads. Some material sites and some undisturbed sites were later used as disposal sites for organic debris and excavated materials before being revegetated and returned to government control. A few were used to stockpile gravels for road maintenance. Upon completion of the pipeline, access roads to the Haul Road were blocked by gates or gravel berms and were then revegetated. The fuel gas line created a linear disturbance immediately adjacent to the road.

Based on observations during summers 1975 through 1978, the following conclusions on revegetation are:

1. Revegetation along the Haul Road was based primarily upon currently accepted practices of mulching, fertilizing, and seeding with adapted agronomic grass species.

2. Attempts to use native grass species in the seed mix were limited. Seed increase programs for native species did not produce enough seed in the short time allowed. However, research sponsored by the Alyeska Pipeline Service Company and others has increased the likelihood of native seed production in the future.

3. Revegetation activities generally improved from 1975 through 1978 in terms of seedbed preparation, scheduling, and availability of supplies and equipment. This was probably due to a decrease of pipeline construction activity so that revegetation could receive higher priority.

4. Temporary erosion control was a recurring problem along the pipeline and road.

5. Native species have been slowly reinvading revegetated areas. Exotic weed species have been observed at a number of revegetated sites, although it is not known how long they will persist. Many revegetated areas have 80-90% grass cover derived from the initial seed mix. The long-term persistence of the exotic species and their effect upon reestablishment of native vegetation cannot yet be evaluated.

6. The visual impact engineering (VIE) program along the road using transplants of native trees and shrubs has been very successful to date.

7. The willow cutting program to replace lost wildlife browse was not successful in 1977; however, the revised 1978 program using unrooted cuttings provided promising results.

8. Preliminary results from CRREL restoration studies demonstrate that willow cuttings and tussock sodding could be feasible means of reestablishing arctic upland vegetation.

Observations of the use of snowpads during construction of the fuel gas line, the excavation of the gas line trench, the backfilling of the trench and subsequent erosion control and revegetation procedures provided opportunities for examining the response of permafrost to trenching and burial of a utility line in close proximity to the road. The fuel gas line was constructed during the winter months through a snow work pad. Observations on methods to control erosion, on associated revegetation problems and on effects of snowpad construction upon vegetation and the underlying tundra are summarized as follows:

1. Beneath the snowpad, microtopography was generally reduced due to such factors as debris filling the depressions and abrasion of tussock or hummock tops. Areas under thinner snowpads or with more pronounced microrelief were more severely affected.

2. Debris cover was much more extensive where gravel for the backfill was placed on the snowpad prior to being placed in the trench. Consequently, the cover of vascular plants was reduced.

3. Depth of thaw was generally greater where the snowpad had been located than in undisturbed tundra. The increase in depth of thaw ranged up to 30 cm but averaged about 10 cm approximately 18 months after construction was completed.

4. Plant species varied in susceptibility to damage from snowpad construction and debris. Upright willow and birch shrubs were frequently sheared off. Mosses, possibly due to their low stature, were more susceptible to damage from debris. Cover of vascular plants was very similar under the snowpad and on undisturbed tundra by 1978.

5. Although snowpad construction, trenching, and backfilling operations did cause some impact to the tundra, the degree of vegetation damage and permafrost degradation due to construction activities was relatively minor when

the operation was carefully conducted and blasting was not used.

Environmental guidelines

This report presents a summary of existing and proposed environmental guidelines which are particularly applicable to road construction in arctic and subarctic regions. The guidelines are presented under the following categories: 1) minimization of impact during construction, 2) consideration of fish and wildlife, 3) criteria for drainage and erosion control, 4) the effect of road cuts in ice-rich soils, 5) stabilization of roadway embankments and 6) criteria for revegetation and restoration.

General recommendations

1. Comprehensive environmental and engineering investigations commenced on this road within a year after its completion. In order to take advantage of this continuity of observations, it is recommended that these investigations continue for purposes of documenting and assessing long-term road performance and environmental responses.

2. Our investigations did not have the resources to document, from the project files, a complete construction history of the road. A detailed environmental engineering documentation of the preconstruction and construction phases of this project should be prepared.

3. As the road becomes older and more maintenance is required, the effectiveness of the design, construction techniques, and remedial methods should be reassessed. If cost data for maintenance are available, appropriate cost analyses should be conducted.

4. Although our investigations did not involve the design of drainage for fish passage, improved criteria now exist from knowledge gained in this construction project. Efforts should be made to include these recent criteria into design and placement practices for culverts and bridges in arctic and subarctic areas.

5. Knowledge gained from revegetation and restoration along the road and pipelines should be consolidated into new erosion control and rehabilitation guidelines and put into practice.

6. Experience on the performance of ice-rich and thaw unstable slopes along the Haul Road should be incorporated into recommendations on terrain evaluation and road design.

ENVIRONMENTAL ENGINEERING AND ECOLOGICAL BASELINE INVESTIGATIONS ALONG THE YUKON RIVER-PRUDHOE BAY HAUL ROAD

Jerry Brown and Richard L. Berg, Editors

INTRODUCTION

The construction of the Yukon River–Prudhoe Bay Haul Road allowed, for the first time in Alaska, the opportunity to observe the performance of a road system which crosses both the discontinuous and the continuous permafrost zones. In addition to crossing highly variable permafrost conditions, the road also traverses diverse climatic, biotic and geologic conditions. CRREL suggested that comprehensive engineering and environmental investigations of the road and its immediate environment would provide a data base for improving road design and further developing methods to minimize and restore impacts of road construction and operations in arctic and subarctic regions. Recommendations for these types of research efforts were contained in a report of the National Academy of Sciences (National Academy of Sciences 1975).

Our investigations should be particularly significant in light of the continuing deliberations concerning future use of the road and the utility corridor (Laycock 1979, Finkler 1979, North Slope Borough 1979, Division of Policy Development 1977, U.S. Department of the Interior 1978, Bureau of Land Management 1980). Should the road be opened for unrestricted use by the public, or limited to "industrial" use? Potential uses of the highway suggest enhanced resource development opportunities but also raise questions concerning additional disturbances to the streams, flora and fauna, and disruption of traditional lifestyles. A thorough understanding of the environmental impacts associated with the road is a desirable component of this decision process.

The road crosses several major climatic, physiographic and vegetation regions and the discontinuous and continuous permafrost zones, which in many areas contain massive ground ice. These unique, cold-dominated environmental conditions provide the opportunity to evaluate the performance of this road and to begin the assessment of environmental changes associated with the road. Melting of massive ice adjacent to or under the road and subsequent subsidence or erosion are of major concern because these will affect performance and maintenance of the road, erosion control and restoration of landscapes adjacent to it, and sediment transport into streams. The ability to stabilize and restore stripped or impacted forested taiga and tundra surfaces is important to road maintenance, ecology and aesthetics, and will reduce the potential negative impacts to fishery resources that could result from abnormal siltation. Similarly, the assessment of continued dust loading on the surrounding ecosystem is required.

In 1976, CRREL proposed and initiated a three-year research program to evaluate the performance of the road and to assess changes in the surrounding environment associated with the road. Four tasks were initially identified and mutually agreed upon between FHWA and CRREL.

1. Influence of surface modification on the permafrost table. *Objective*—To determine the rate and magnitude of thaw penetration and subsidence under and adjacent to the Haul Road.

2. Influence of surface modification on vegetation and soils. *Objective*—To document existing flora, vegetation and soil types and establish the rate of change in plant communities, soil fauna, and soils due to natural and manmade surface disturbances.

3. Restoration of terrain affected by road construction activities. *Objective*—To conduct experiments and observations to enhance restoration by native plant species and maintain current knowledge of the rapidly evolving arctic and subarctic restoration technology.

4. Analysis of climatic gradients. *Objective*—To characterize the annual air and ground temperature and precipitation regimes for representative areas along the Haul Road in order to provide the data base required to substantiate

environmental and engineering road designs.

A series of sites were established beginning in summer 1976. Recurrent observations were made and new sites established in 1977 and 1978. A set of maps containing locations of all CRREL research sites, cooperative projects, and other relevant studies is contained in Appendix C. This report presents approaches, results, conclusions, and recommendations based on the investigations established under portions of the four tasks. The results reported are considered the initial characterization of road performance and environmental stresses resulting from the road and related pipeline activities. Projects initiated under the FHWA sponsorship are continuing under DOE, ARO and CRREL funding and will be subjects of future reports and recommendations. Therefore this report should be viewed as a compilation of the initial three years of research (1976-1978) along the road.

CHAPTER 1. THE ROAD AND ITS ENVIRONMENT

by J. Brown

Introduction

Construction of the trans-Alaska oil pipeline necessitated construction of an adjacent road over more than one-half of its length for access to workpads and for logistics. The road, built by the Alyeska Pipeline Service Company, was constructed to the State of Alaska Department of Transportation and Public Facilities (DOTPF) secondary highway standards in two sections. The first section, constructed between August 1969 and July 1970 and extending approximately 90 km from Livengood to the Yukon River (Fig. 1), was referred to as the "TAPS Road." (The Alaska DOTPF has since designated it the Yukon Highway.) The second section, the 577-km-long "Haul Road" between the Yukon River and Prudhoe Bay, was built in seven segments in five months, 29 April to 29 September 1974 (McPhail et al. 1976).

Included in the Haul Road are 20 permanent bridges, over 1000 culverts and 135 material sites. The road is unique in that it is closely associated with the 1.2-m-diam hot oil pipeline and in the northern portion with a 0.2- to 0.25-m-diam buried fuel gas line (see cover). There are 15 oil pipeline crossings of the road of which 9 are across buried sections of the oil pipeline and 6 are across aboveground portions of the oil pipeline. The road right-of-way (67 m wide) incorporates the buried oil pipeline for about 19 km and the aboveground pipeline for about 25 km. In the buried mode, the heated oil pipeline is expected to eventually thaw the permafrost within the roadbed (Lachenbruch 1970). The fuel gas line, which carries gas at below-freezing temperatures from Prudhoe Bay to Pump Stations 2, 3 and 4 north of the Brooks Range, crosses the road seven times and is buried within 5 m of the toe of the road for about 180 km of its 230-km length. The road was officially turned over to the State of Alaska in October 1978.

Many years of road construction experience under subarctic discontinuous permafrost conditions have been gained within Alaska; however, most road design methods still cause the degradation of underlying near-surface permafrost with resulting high maintenance costs where the permafrost is ice-rich. Experience in arctic road construction under conditions of continuous permafrost has been more limited and has been concentrated around military facilities, town sites, and recently, the Prudhoe Bay road net. McPhail et al. (1975, 1976) briefly summarized design and construction considerations for the Haul Road and Berg et al. (1978) reported 1976-1977 thaw penetration results from along the road. A Canadian report described observations on highway cuts through permafrost, including the Livengood-Yukon River portion of the Haul Road (Pufahl et al. 1974). Also, Huculak et al. (1978) reported on the design considerations for the Dempster Highway in Canada. Lotspeich (1971, 1974) proposed comprehensive environmental guidelines for Alaskan road construction. Morehouse et al. (1978) analyzed the environmental surveillance activities associated with the construction of the trans-Alaska pipeline and specifically discussed aspects of Haul Road construction. The Army and Air Force have a series of design manuals for road and other construction in the Arctic and Subarctic (U.S. Army and Air Force 1966).

Prior to construction of the Haul Road, the only recent experience north of Livengood with permanent roads in Alaska was the TAPS Road and the Prudhoe Bay road net. The TAPS Road provided many examples of road performance in the discontinuous zone of permafrost; Smith and Berg (1973), Berg and Smith (1976), and Jackman (1974) have reported on the behavior of portions of this road. The Prudhoe Bay spine road, constructed largely during the winter 1969, is situated in the continuous permafrost zone. Knight and Condo (1971) reported on road and test section performance in the Prudhoe Bay area.

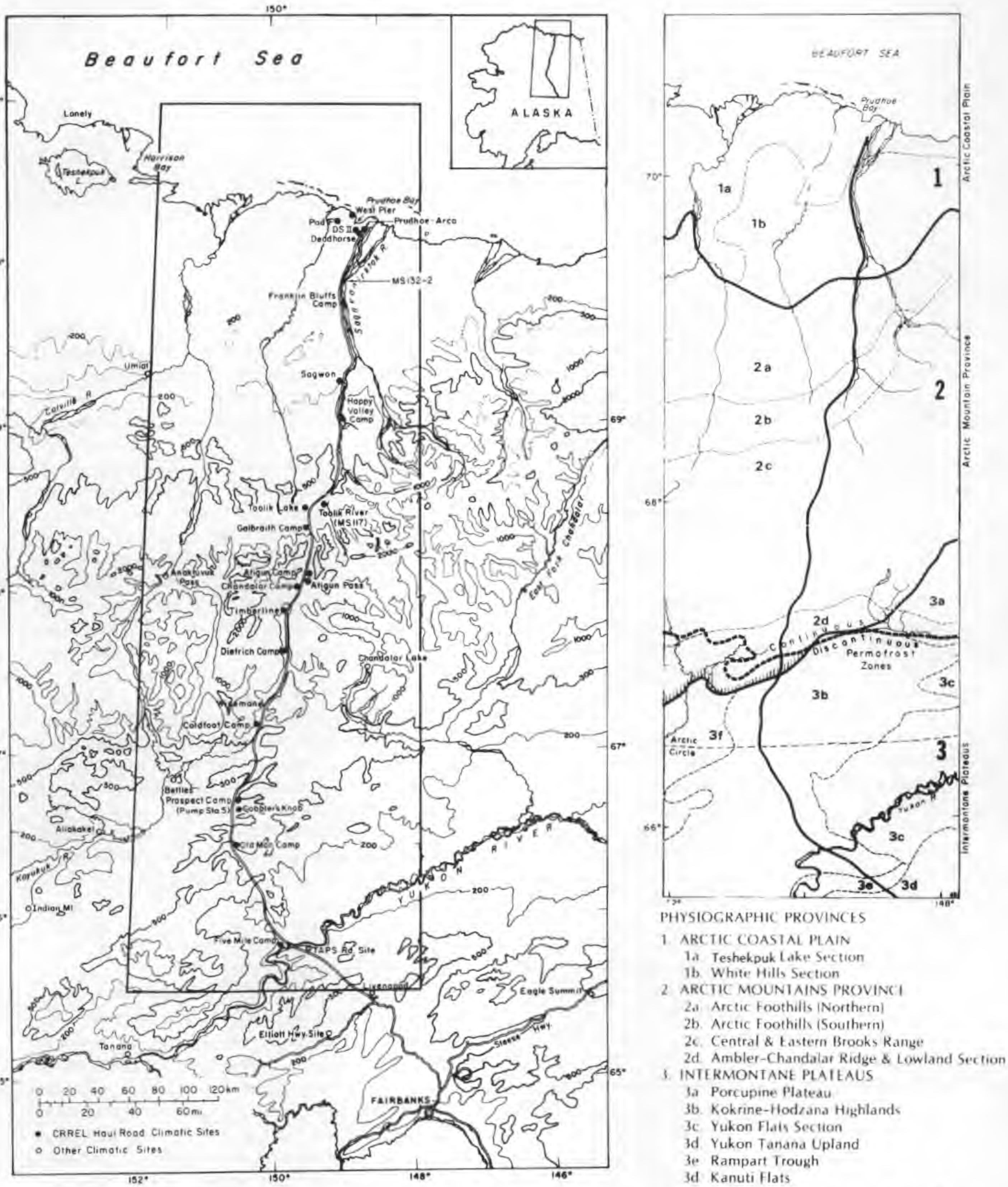


Figure 1. Location map of Haul Road and its physiographic setting. CRREL Haul Road climatic sites and pipeline camps are indicated by solid dots. Other National Weather Service stations used for regional analysis are indicated by open dots. Physiographic provinces and permafrost delineations are based on Wahrhaftig (1965) and Ferrians (1965), respectively.

Figure 2. Beginning of the Haul Road on north bank of the Yukon River, 11 August 1976.

General physiography*

The Yukon River to Prudhoe Bay transportation corridor crosses three main physiographic provinces (Fig. 1). They are, from south to north, the Intermontane Plateaus, the Arctic Mountain System, and the Arctic Coastal Plain (Wahrhaftig 1965). Figures 2-9 are aerial oblique photographs of the road and pipeline from the Yukon River to the northern Coastal Plain. The following descriptions have been modified to emphasize the terrain conditions along the Haul Road route.

North of the Yukon River, the road passes through even-topped, rounded ridges with elevations of 600 to 1200 m that are replaced to the north by more rugged mountains. These are the Kokrine–Hodzana Highlands in the Intermontane Plateaus Province.

Next, the road progresses into the Arctic Mountains Province, which is divided into four sections from south to north: a ridge and lowland section, a rugged mountainous area, and two regions with foothills-type topography.

*Prepared by D.E. Lawson

The Ambler–Chandalar Ridge and Lowland begins at the South Fork of the Koyukuk River. The southern part of this section is a discontinuous line of rolling to rugged ridges with elevations of 900 to 1400 m. Further north and extending to Coldfoot is a region of lowlands and low passes (60 to 600 m in elevation) that contains several east-trending ridges.

East-trending topography continues in the Brooks Range which begins abruptly at Coldfoot. Ridges rise to rugged, glaciated summits of about 1300 to 2000 m in the south and 2300 to 2700 m in the north. Differences in weathering of belts of sedimentary and metamorphic rock produced the easterly grain of the topography. Cliff- and bench-slopes characteristic of glacially eroded, bedded rocks are also present. Major rivers flow north and south in flat-floored, glaciated valleys.

North of the Brooks Range, the road drops abruptly to the hills and lowlands of the Arctic Foothills just north of Galbraith Lake. The southern Foothills vary in height from 350 to 1050 m and include irregular buttes, knobs,

Figure 3. Oil pipeline and Haul Road bridge crossings at the Middle Fork of the Koyukuk River, 11 August 1976.

Figure 4. Haul Road and elevated oil pipeline crossing an ice-rich treeless slope along Middle Fork, Koyukuk River, 11 August 1976. In background, road and buried oil pipeline cross a tree-covered low-ice content slope.

Figure 5. Haul Road and buried oil pipeline 19 km north of Dietrich Camp on terrace of the Dietrich River, 11 August 1976. Bedrock material site in foreground.

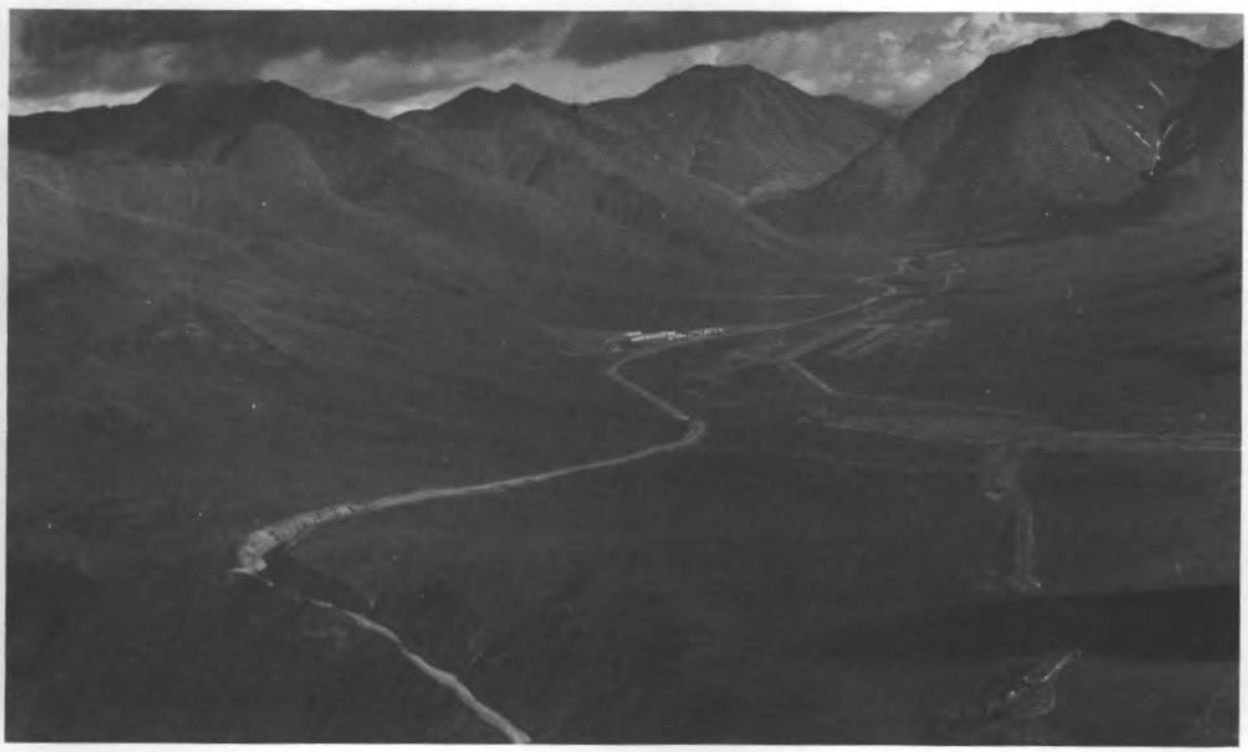


Figure 6. Looking north onto Chandalar Shelf showing road ascending through steep cut, 11 August 1976. Atigun Pass is in background and Chandalar Camp in center of photograph.

Figure 7. Looking north down Atigun Valley with road crossing colluvial-alluvial slopes. Atigun Camp is in center of photograph, 11 August 1976.

Figure 8. Road crossing foothills between Happy Valley Camps, 11 August 1976. Sagavanirktok River is to the east. The gravel-filled fuel gas line trench is seen adjacent to the road on the right side of this ice-rich permafrost setting. The oil pipeline is across the river.

Figure 9. View looking north across the Arctic Coastal Plain, 11 August 1976. The road and buried oil pipeline parallel each other and the Sagavanirktok River. Ice-wedge polygons are seen in the foreground.

mesas, east-trending ridges and intervening, gently undulating tundra uplands. Elevation in the northern Foothills changes from about 350 m in the south to 180 m in the north. The northern Foothills are characterized by broad east-trending ridges and local mesa-like mountains.

Finally, the road passes onto the Arctic Coastal Plain near the confluence of the Sagavanirktok and Iviskak Rivers where it slopes gently to the Arctic Ocean. The topography is flat, with low relief except where pingos (ice-centered mounds) and occasional bluffs and river terraces break the horizon. The Coastal Plain is poorly drained and marshy. Elongated and oriented thaw lakes cover a large proportion of it.

Regional climate*

The Haul Road traverses two general climatic regions, the continental Interior and the Arctic. Several distinct climatic zones can be identified within these regions based on topographic and/or vegetation boundaries as well as their climatological elements. The Interior is predominantly a forested region with alpine tundra occurring at elevations over 700 m. The alpine tundra area increases northward, until it is transitional with the arctic tundra in the Brooks Range. The northern Arctic Foothills and the Arctic Coastal Plain are distinguishable climatically from the region to the south due to elevational differences and distance from the Arctic Ocean.

The Interior is a zone of temperature extremes and relatively high precipitation as compared to the Arctic regions. During the summer, storm tracks enter this area from the south or southwest, but most of the precipitation is of the convectional type, and is widely scattered and variable in amount (Watson 1959). The greatest amounts of precipitation occur during the summer. During the winter, the Interior is dominated by relatively dry Continental Polar air masses,

*Prepared by R.K. Haugen

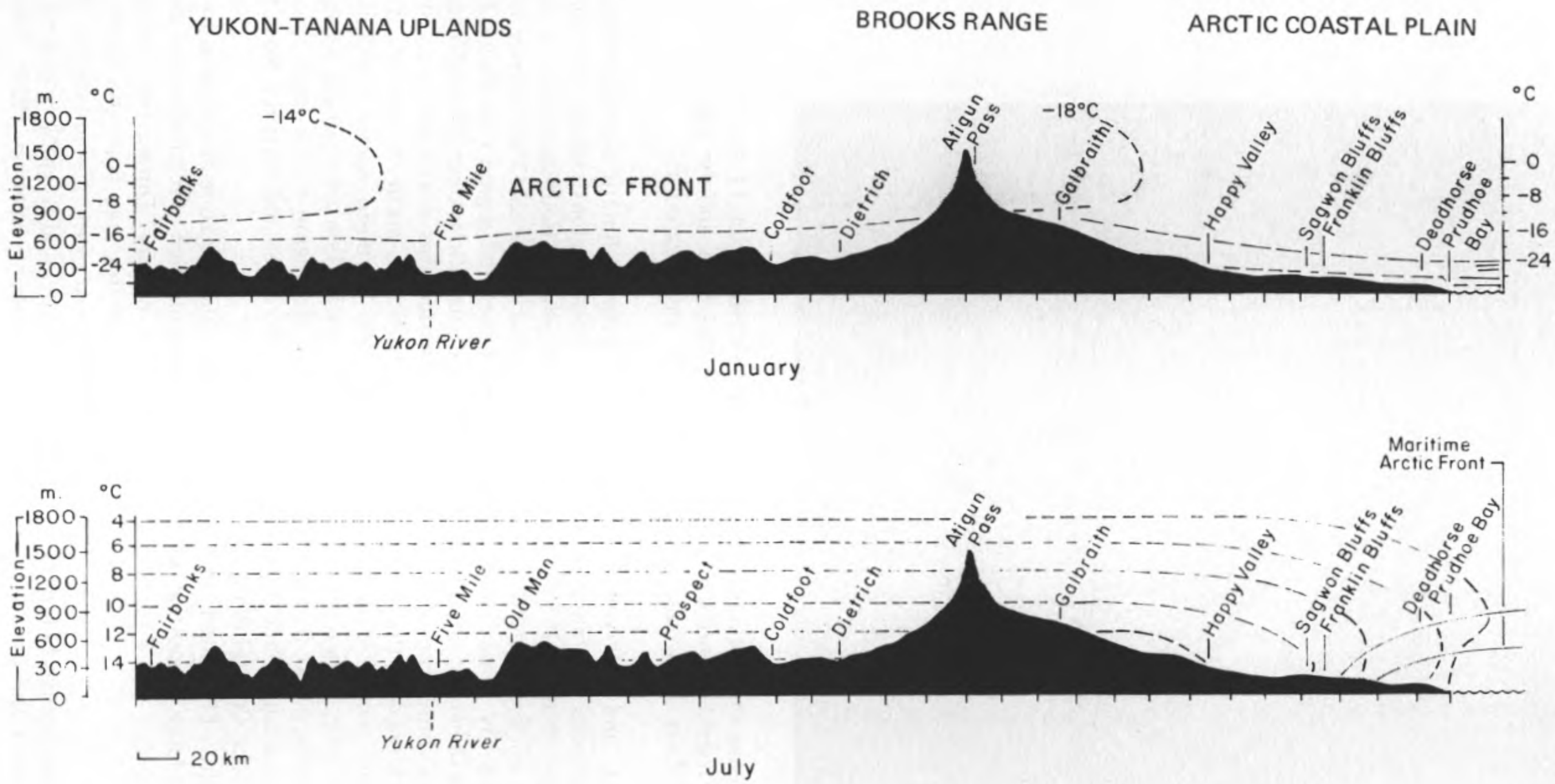


Figure 10. Cross sections of the vertical temperature distribution for the Haul Road transect. Climatic regions as discussed in this report are shown. [Adapted from Conover (1960), using current data; distances on scale in 20-km intervals.] The Continental Divide coincides with Atigun Pass.

and sinking cold air creates high atmospheric pressure during the winter. Occasionally, maritime air intrudes into the area from the west or southwest, causing major snowstorms (Bilello 1974). The alpine areas within the Interior typically have less extreme temperatures but higher precipitation than the forested areas at lower elevations.

North of the Continental Divide is a region of extreme winter temperatures, cool summer temperatures, and relatively low precipitation. Unlike the Continental Interior, wind is a major environmental factor throughout much of the year. Although winds rarely exceed 17 m/s (32 knots), they are seldom calm on the Arctic Coastal Plain (Conover 1960). The winds result in considerable blowing and drifting of snow, together with poor visibility and severe wind chill factors during the coldest months (Searby and Hunter 1971). During the winter, the entire Haul Road is under the influence of cold arctic air to an elevation of 800 to 1000 m.

During July and August, a sea breeze from the open water of the Arctic Ocean dominates the coastal climate (Moritz 1977, Kozo 1979). Radiational heating of the inland tundra surfaces creates a local pressure deficit, causing colder air from the ice-free Arctic Ocean to move inland, and resulting in a prevailing northeasterly wind. This often creates cloudy and foggy conditions near the coast which extend in and persist until the air is warmed sufficiently by radiation. The inland extent of the sea breeze phenomenon is at least 17 km (Kozo 1979), although prevailing northeasterly wind is observed considerably further inland (see discussion of wind direction and velocities in Chapter 3). General relationships of air temperature to elevation and latitude during January and July are shown in Figure 10.

Climatic data base

Prior to 1970, few climatic data were available for the region now traversed by the Haul Road. Barrow and Barter Island had the only representative records for the northern Arctic Coastal Plain, and for the Arctic Foothills, a seven-year record (1948-53) at Umiat was the only data base. The Brooks Range was represented by a discontinuous record for Anaktuvuk Pass, 90 km west of the road. Chandalar Lake and Bettles were the nearest stations representing the forested Interior.

Beginning in 1971, cooperative National Weather Service (NWS) observations were undertaken by the Alyeska Pipeline Service Company at most construction camps. These records were discontinuous until May 1975. When construction of the pipeline began, the Alyeska–NWS observations were essentially continuous until the closing of camps in 1977 and 1978. Observations were hourly, generally for 18 hours per day, in support of aircraft operations at camp airfields. Air temperature, total sky cover, cloud type, wind speed and wind direction were the major parameters observed. Daily precipitation totals were also recorded at most stations.

In 1976, CRREL established air temperature and some precipitation measurement sites at the camps and at remote sites along the road, similar to our program at remote sites in the Yukon–Tanana Uplands of interior Alaska (Haugen and Brown 1978). Twenty-two temperature recording sites were in operation by CRREL as of July 1978. These sites were operated primarily during the thawing season, but some winter data are available (Fig. 11).

The CRREL climatic program, begun in 1976, had two major objectives: 1) to continue temperature and precipitation data at the construction camps after the Alyeska–NWS observations terminated, and 2) to provide climatic observations at higher elevations and other locations to complement the camp data base.

Initially, the intention was to operate CRREL instrumentation only during the summer season for purposes of estimating thawing degree-days. However, some winter data have been obtained even though the operation of unattended instrumentation during the arctic winter is very difficult. The relatively mild winter of 1977-78 permitted the operation of several battery-powered thermographs. During 1977 and 1978, four Wyoming snow gages were constructed and installed in cooperation with the Soil Conservation Service and the Bureau of Land Management. These gages, designed to measure winter precipitation in areas where blowing snow often renders the standard precipitation gage inaccurate, are now providing data at several remote and high-elevation locations along the Haul Road.

Temperature

Haul Road temperature regimes include some of the most extreme ranges encountered on the North American Continent. The all-time low temperature for the United States, −62°C (−80°F),

1975–78 HAUL ROAD STATIONS—NORTH TO SOUTH

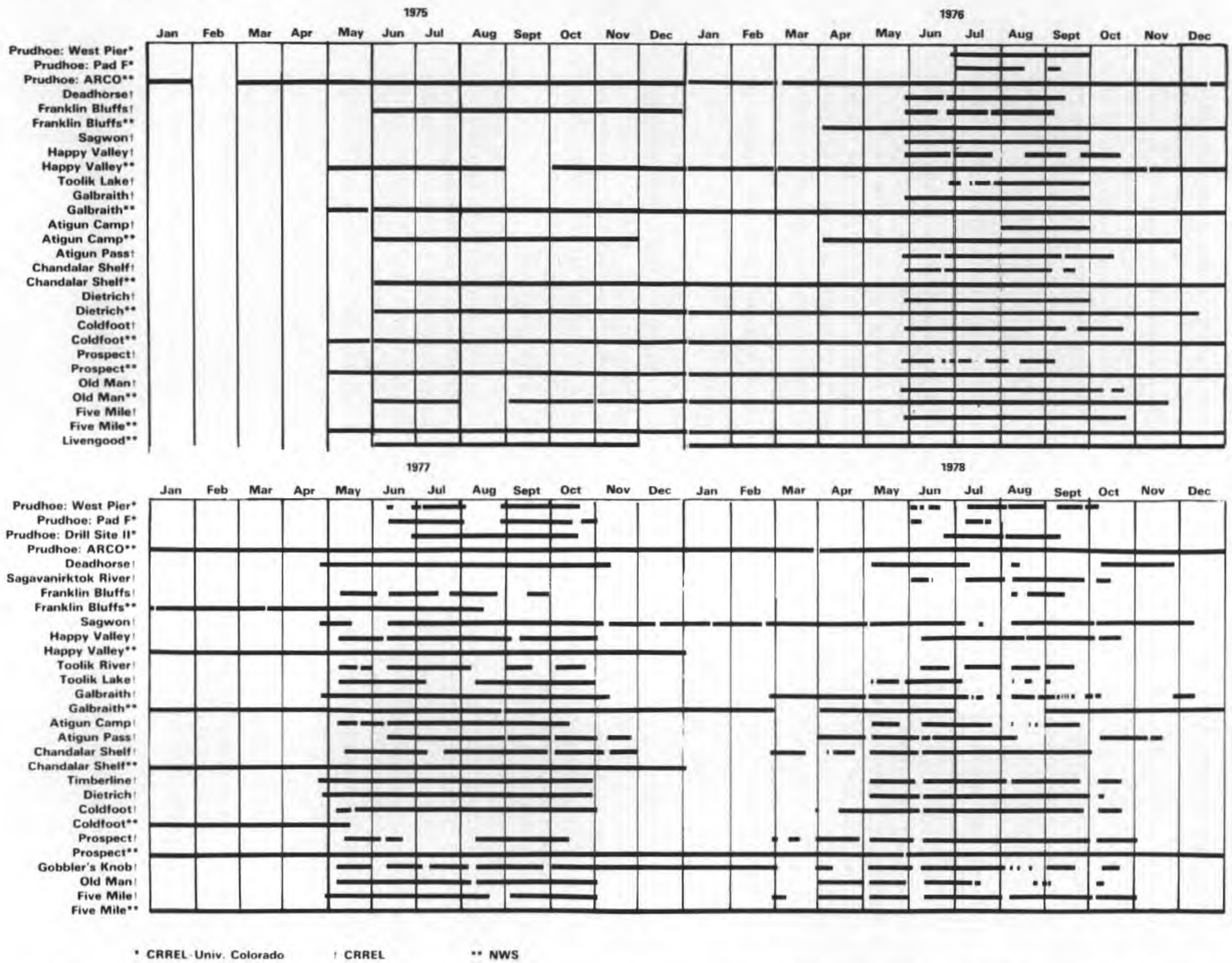


Figure 11. A graphic display of Haul Road climatic station records. CRREL, CRREL-University of Colorado and National Weather Service records are distinguished by symbols (see legend). Small breaks in the thaw season records were filled by regression analysis to permit the compilation of degree-days and monthly means. Regression was done on maximum and minimum temperatures separately. In the few cases where significant (P>0.05) relationships were not found, simple differences between the means were used.

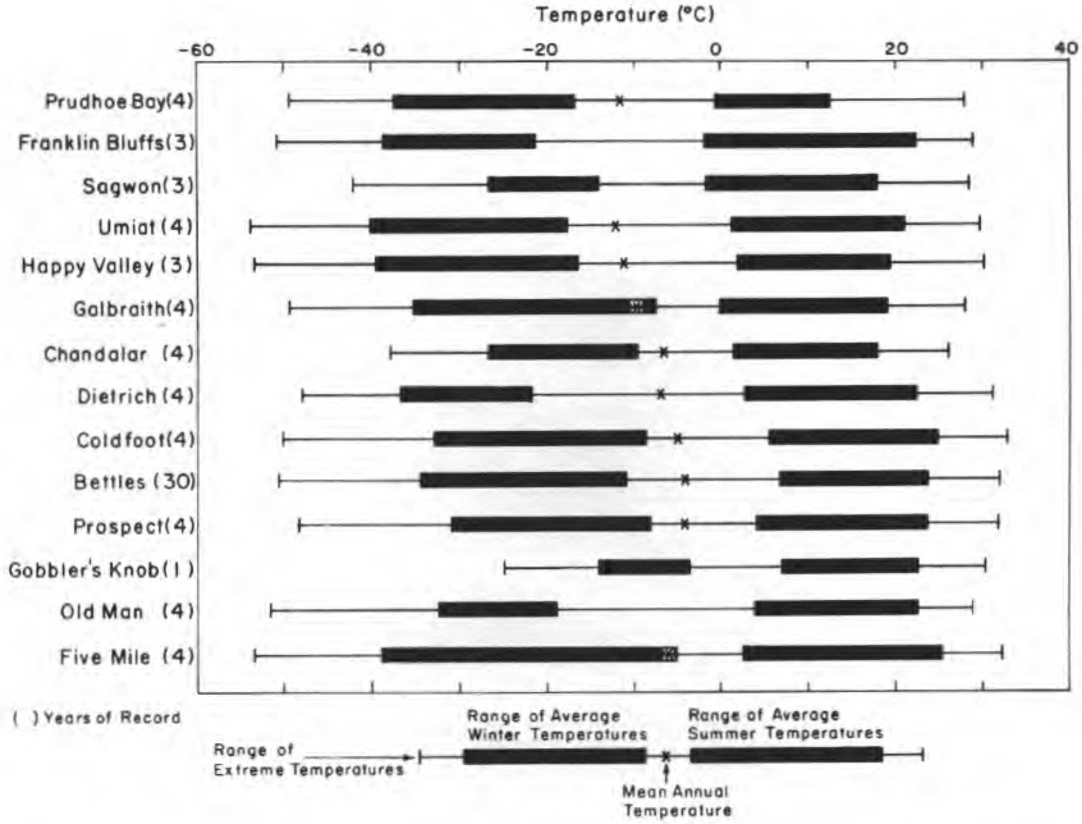


Figure 12. Annual temperature regimes for Haul Road stations. Mean annual temperatures are indicated by "X" on the extreme range line for stations with at least three years' continuous record. Umiat and Bettles are included for comparison. The range of the coldest and warmest monthly minimum and maximum temperatures are indicated by solid bars for winter (Dec–Feb) and summer (June–Aug) for each station.

was recorded at Prospect Creek Camp airport, 24 January 1971. During the period of our study, 1975-78, most Haul Road stations experienced extreme minimum temperatures below -50°C, and at least half the stations had summer maximum temperatures over 30°C, an extreme range of over 80°C (144°F).

Average annual air temperatures (1975-78) along the Haul Road range from -11.5°C at Prudhoe Bay to a high of -4°C for some of the stations south of Dietrich (Fig. 12). These values, however, are based on only three or four years of record and so are not directly comparable to a standard NWS 30-year normal. Comparison of Umiat temperatures with the previous seven-year record for Umiat (1948-53) and the 1975-78 Bettles record with the 30-year normal at Bettles suggests, however, that the mean annual temperatures resulting from our 1975-78 data are within one or two degrees of a long-term average annual temperature (Fig. 12).

The higher elevations along the Haul Road, represented by the Gobbler's Knob and Chandalar sites, tend to be above the average height of the winter temperature inversion, and have warmer average winter temperatures (Fig. 12). The extremely cold temperatures recorded at the valley stations (e.g. Prospect, Coldfoot, Dietrich) are the result of inversions of the vertical temperature profile, caused by cold air downslope drainage. The cooler summer temperatures at the high elevation sites reflect a normal decrease of temperature with elevation.

Mean monthly and annual temperatures were tabulated for all Haul Road stations during 1975-78 (Table 1). All the 1975 data and most of the subsequent winter data are from NWS records. Most of the thaw season record is a combination of NWS-CRREL data. The 1978 data are primarily from CRREL instrumentation.

Temperature patterns for the entire Haul Road typify a Continental climate for the entire year

Table 1. Monthly, annual and seasonal air temperature summary for Haul Road stations (1975-1978).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	THAW DD	SEASONAL FREEZE DD
1975															
Prudhoe Arco					-6.4	3.5	6.8	4.4	-2.5	-13.7	-26.3	-31.7		464	
Franklin Bluffs						5.5	10.1	7.4	-2.4	-13.7	-32.7	-32.7		752	
Happy Valley					-6.1	7.2	10.6	8.3		-13.1	-23.2	-30.0		806	
Galbraith						7.5	10.6	7.2	-2.7	-12.3	-22.8	-27.8		833	
Atigun Camp						8.3	9.2	7.2	-2.7	-11.8	-20.7			795	
Chandalar Shelf						9.3	12.2	7.8	-2.0	-10.9	-20.2	-22.7		924	
Dietrich Camp						12.0	15.3	10.9	3.6	- 7.0	-23.1	-29.9		1307	
Coldfoot Camp					5.9	12.8	15.8	11.2	3.2	- 6.1	-22.0	-26.8		1532	
Prospect Camp					6.7	12.3	15.6	11.3	3.2	- 7.7	-22.0	-27.0		1543	
Old Man Camp						12.1	14.3		2.9	- 8.1	-22.1	-27.5		1250	
Five Mile Camp					8.0	13.5	14.5	11.3	3.5	- 7.8	-26.3	-33.1		1582	
1976															1975-76
Prudhoe W. Pier						1.7	4.1	4.2	0.3						
Prudhoe Pad F							5.4	4.1	1.1						
Prudhoe Arco	-30.8	-31.9	-29.0	-16.5	-5.9	3.2	6.8	6.6	1.7	-11.4	-16.5	-30.4	-12.8	571	5642
Deadhorse					-1.9	4.3	7.3	5.8	1.4						
Franklin Bluffs				-18.4	-7.5	5.8	10.5	10.7	2.7	-12.6	-19.2	-35.1		847	
Sagwon					-2.2	5.0	10.8	10.5	2.7						
Happy Valley	-28.4	-29.3	-23.7	-13.9	-5.2	7.4	11.8	11.6	4.0	-13.0	-19.5	-35.6	-11.1	1093	5096
Toolik Lake						8.2	13.7	9.0	1.5						
Galbraith	-26.8	-30.3	-22.2	- 9.3	-1.4	8.1	10.6	10.0	2.3	-14.6	-14.9	-30.5	- 9.9	1006	4841
Atigun Camp				- 6.5	-0.3	8.3	10.3	10.0	2.7	-13.2	-11.9			1021	
Atigun Pass					-5.9	2.3	5.3	5.9	-0.3	- 8.5					
Chandalar Shelf	-21.1	-22.2	-18.5	- 8.3	0.0	7.7	10.2	9.7	2.7	-11.8	-11.8	-19.7	- 6.9	974	3888
Dietrich	-27.9	-29.5	-16.7	- 4.7	4.9	10.7	13.4	12.4	5.6	- 9.0	-12.4	-26.7	- 6.9	1460	4263
Coldfoot	-24.6	-27.2	-14.8	- 3.3	5.7	12.1	13.7	13.1	6.0	- 7.4	-10.3	-20.8	- 4.8	1563	3843
Prospect	-23.0	-26.1	-13.7	- 2.3	5.9	13.7	14.3	13.1	5.6	- 6.4	- 9.9	-20.1	- 4.1	1675	3761
Oldman	-22.8	-27.8	-16.6	- 4.4	4.5	11.5	12.8	12.1	5.6	- 7.0	-10.2			1445	3958
Five Mile	-30.2	-31.4	-15.2	- 2.5	6.1	12.8	13.7	12.1	4.5	- 8.8	-15.0	-27.0	- 6.8	1545	4513
1977															1976-77
Prudhoe W. Pier						-1.5	2.6	4.2	1.6	- 3.1				318	
Prudhoe Pad F						4.0	4.2	6.2	1.7	- 4.0				491	
Prudhoe DS II						0.1	4.2	7.1	2.2						
Prudhoe Arco	-23.1	-28.0	-31.9	-19.1	-5.5	3.7	5.5	8.2	2.5	- 4.7	-21.4	-23.4	-11.4	654	5026
Deadhorse					-1.2	5.7	7.6	9.8	3.8	- 6.0				879	
Franklin Bluffs	-25.1	-29.6	-33.7	-20.0	-3.4	5.7	7.5	12.1	3.2					884	5471
Sagwon					-3.5	6.7	10.0	12.9	3.3	- 9.2				1040	
Happy Valley	-24.5	-31.2	-32.5	-18.0	-4.5	8.0	12.1	12.4	2.5	- 9.8	-24.9	-21.6	-11.0	1125	5412
Toolik River					-0.9	6.3	10.0	10.8	1.3	- 7.0				932	
Toolik Lake					-0.7	5.4	9.8	12.0	-0.2	-10.0				914	
Galbraith	-16.8	-20.6	-27.0	-17.3	-1.3	7.6	10.2	11.3	0.3	-11.3	-26.4	-22.7	- 9.5	982	4382
Atigun Camp					0.2	6.3	11.7	12.8	1.2	- 4.2				1071	
Atigun Pass						2.5	8.5	9.4	-4.9	-13.5				625	
Chandalar Shelf	-14.4	-13.7	-20.4	-11.8	1.5	9.3	11.7	12.6	2.0	-10.2	-18.1	-19.6	- 5.9	1189	3173
Timberline				- 7.5	4.1	11.5	14.5	12.4	2.3	- 7.7				1428	
Dietrich				- 7.7	5.1	13.0	15.4	13.7	5.1	- 6.6				1626	
Coldfoot					5.4	13.2	18.8	18.1	7.1	- 4.6				1904	
Prospect	-12.9	-13.1	-18.8	- 9.0	5.4	12.6	14.8	13.8	4.1	- 6.9	-31.9	-25.8	- 4.8	1582	2767
Gobbler's Knob					6.1	15.0	18.1	17.0	5.4	- 3.7				1871	
Oldman					5.9	13.1	14.2	13.4	4.2	- 5.6				1540	
Five Mile	-20.9	-17.5	-20.8	- 9.0	7.3	14.2	16.2	14.1	4.9	- 7.1	-26.2	-32.3	- 6.4	1756	3629

*Thawing and freezing degree-days represent the accumulative departure of mean daily temperatures above or below, respectively, $0^\circ C$.

Table 1 (cont'd).

1978

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	THAW DD	SEASONAL FREEZE DD 1977-78
Prudhoe W. Pier						2.5	8.2	5.1	2.4	-4.9				573	
Prudhoe Pad F							6.7							215	(Incomplete)
Prudhoe DS II						3.7	7.4	5.9	2.9						
Prudhoe ARCO		-26.0	-24.5	-16.5	-7.6	2.8	8.4	5.2	2.6	-12.9	-14.8	-23.3	-10.6	606	4409
Deadhorse Tower					-9.0	1.3	5.4			-14.7	-15.3				
Deadhorse Runway					-4.5	2.8	7.8								
Sag River						4.3	10.3	6.7	1.9	-5.0				747	
Franklin Bluffs							7.3	3.2							
Sagwon	-17.9	-24.1	-24.3	-15.9	-9.9	3.0	11.4	6.8	1.7	-10.8	-12.1	-17.6*	-9.6	760	4225
Happy Valley						8.1	13.2	8.0	4.2	-7.8				974	
Toolik River						9.6	13.8	9.3	2.4	-8.5				1102	
Galbraith	-15.5	-20.3	-24.4	-11.3	-1.8	5.8	12.7	7.2	2.0	-19.1	-14.0	-22.1	-9.0	781	3365 (less Mar '78)
Atigun Camp					-1.4	6.2	11.9		3.0					722	
Atigun Pass			-26.0	-14.2	-3.3	1.5	8.1							610	
Chandalar Shelf		-14.5	-18.0	-8.3	0.5	7.6	13.2	10.7	1.7	-10.9				1107	
Timberline					2.8	7.8	17.3	10.9	4.7					1223	
Dietrich					3.7	9.4	15.8	12.8	5.2	-8.9				1443	
Coldfoot				-2.6	5.1	10.1	15.1	12.8	6.5					1562	
Prospect	-14.5	-17.0	-13.7	-4.1	5.5	10.5	14.6	11.8	5.5	-5.7	-14.3	-17.1	-3.7	1511	
Gobbler's Knob	-6.7	-9.4	-13.1	-7.0	0.3	10.1	15.9	12.9	6.8					1447	
Old Man				-4.7	4.5	9.1	15.0	11.8	7.0					1403	
Five Mile	-20.8	-22.7	-15.7	-4.2	5.3	10.1	16.1	12.4	6.8	-6.0	-17.6	-23.4	-4.7	1526	3912

with the exception of the maritime influence on summer temperatures in the region north of Happy Valley. The mean annual diurnal range of temperatures (amplitude × 2) serves as an index of continentality. This value averages less than 8°C north of Happy Valley Camp and greater than 10°C south of it. The highest mean annual diurnal temperature range is at Five Mile, 13.7°C. Values of 12° to 13°C, however, are common between the Brooks Range and Happy Valley and in the Interior at the lower elevation stations.

The variation of thawing degree-day (°C) accumulations ranges from approximately 1850 degree days at the Yukon River to less than 500 in the Prudhoe Bay area (Fig. 13). The length of the thaw season* ranges from approximately 160 days at the Yukon River to 105 at Prudhoe Bay. At higher elevations along the Haul Road (Chandalar, Atigun Pass and Atigun Camp) thawing degree-day accumulations are similar to values north of Sagwon. In terms of relative warmth, the 1978 thaw season was slightly above average for the entire road compared to the 1975-78 observational record. The 1977 thaw season was by far the warmest south of the Brooks Range.

Freezing degree-days (°C) range on the average from slightly less than 3500 degree days in the southern portion to about 5000 in the north. Since fewer winter data are available, the transect lines appear smoother than for thawing degree-days. With the exception of two winters' data for Chandalar and one winter for Gobbler's Knob, the higher elevations are not well-represented with freezing degree-day data. South of the Brooks Range, the winters of 1976–77 and 1977–78 were considerably warmer than prior winters, whereas north of the Brooks Range, only the 1977-78 winter was warmer. The year-to-year variation of thawing degree-days at any given site is considerably less than that for freezing degree-days. The variability of winter temperatures from year to year is illustrated in Figure 13.

Summer temperature gradients with latitude and elevation can be compared to vegetation distribution and growth characteristics. The altitudinal and latitudinal timberline of the white spruce forest occurs within the road transect at approximately 720 m elevation near Finger Mountain, Gobbler's Knob, and at the northern

*Defined as the period between the first and last day when the average temperature is above or below 0°C for five successive days.

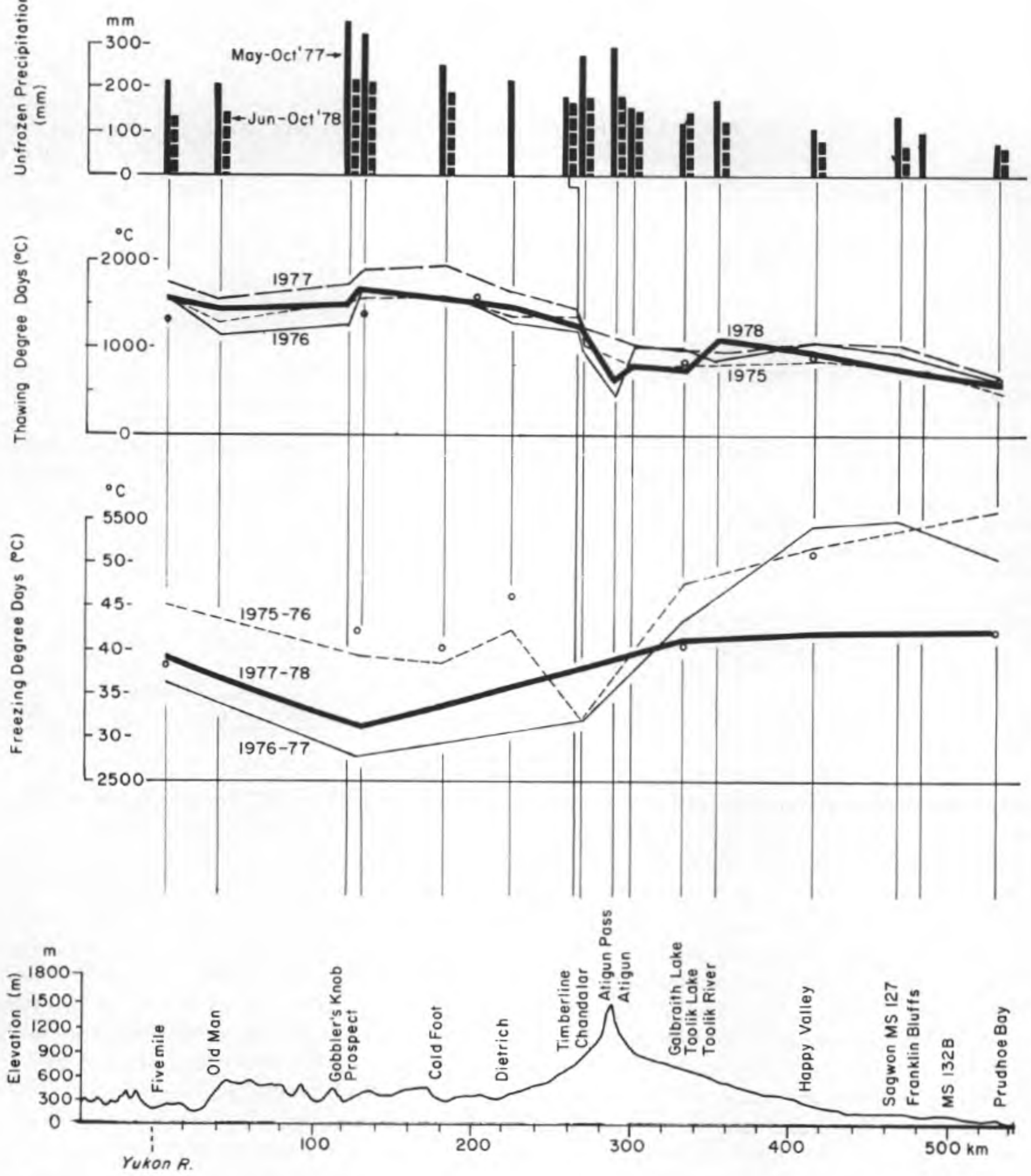


Figure 13. Climatic transects for the Haul Road, illustrating the variation of precipitation, thawing, and freezing degree-days (°C) over the transect. Small circles on the thawing and freezing degree-day cross sections indicate values obtained by averaging available data prior to 1975.

limit of tree growth 40 km north of Dietrich. Application of the so-called Nordenskjöld formula for determination of the temperature equivalency of the timberline (Haugen and Brown 1978) gives an approximate July mean temperature value of 12°C. This formula is $V = 9°C - 0.1°K$, where V is the temperature of the warmest month at the timberline, and K is the temperature of the coldest month. The calculated 12°C July temperature at the elevation of the Haul Road timberline is in essential agreement with our observational data.

Temperature-vegetation gradients were also investigated on the Arctic Coastal Plain. Thawing degree-day accumulations are linearly related to the distance due south of the coast (Fig.

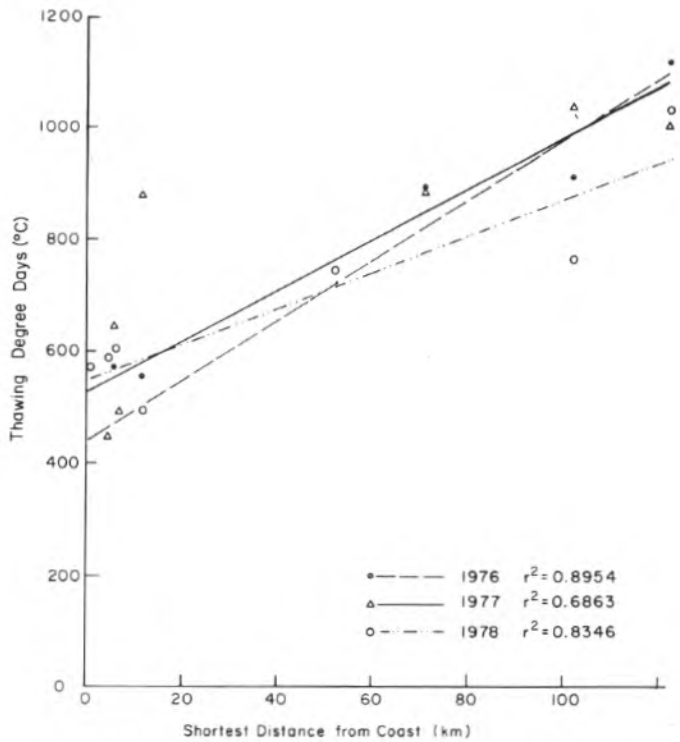


Figure 14. Gradients of thawing degree-days (°C) from the Arctic Ocean inland to Happy Valley, 1976-78.

Table 2. Monthly and seasonal surface transfer coefficients, summers of 1976–1978.

Location	*Year*	*June*	*July*	*August*	*September*	*Seasonal*
Galbraith	1976	1.68*	1.46	1.35	1.33*	—
(gravel)	1977	0.48	1.52	1.19	2.7	1.72
	1978	1.6	1.23	1.45	2.21	1.62
Sagwon	1976	—	0.70	0.67	0.43	—
(tundra)	1977	0.42	0.81	0.69	0.58	0.63
	1978	0.73	0.79	0.60	0.74	0.72
Deadhorse**	1976	1.08	1.30	1.36	1.63*	1.34
(gravel)	1977	1.12	1.33	1.05	0.82	1.08

* Incomplete data.
** Deadhorse 1978 data insufficient.

14). Regression and correlation analysis of three summers' data, 1976-78, provides coefficients of determination (r^2) of 0.69 to 0.90 for this relationship. University of Colorado personnel found similar correlations with the height and biomass of *Salix lanata*, the arctic willow, by using the same July temperature data and thawing degree-day values.

Ground temperature measurements were obtained at graveled surfaces at Galbraith and Deadhorse airports and from tussock vegetation at Sagwon. Surface transfer coefficients were calculated from air and ground temperature data, and values obtained during the three summers are presented in Table 2.

Precipitation

Although distinct differences exist in precipitation amounts and characteristics along the Haul Road, variations with latitude and elevation are not as readily defined as for temperature. The 1976-78 record indicates annual totals ranging from 140 mm (Sagwon) to over 400 mm in the Atigun Pass–Chandalar Shelf area (Table

Table 3. Total annual precipitation (mm).

Name	*1975*	*1976*	*1977*	*1978*
Prudhoe Bay W.G.			223	183
Sagwon W.G.			238	140
Happy Valley		202	183	
Toolik River			267	194
Galbraith	188	254	204	195*
Atigun Pass W.G.				295
Chandalar Shelf W.G. (1978)		450	409	394
Coldfoot	406	400	408	
Bettles	235	383	356	241
Prospect	286	374	440	334
Old Man	291	393**		
Five Mile	168	250	309	282

* Galbraith—March and August estimated from Toolik.
W.G.—modified Wyoming gage.
**Old Man—December 1976 missing.

Table 4. Thaw season precipitation totals (mm), 1975-78.

Location	*1975*	*1976*	*1977*	*1978*	*1978 (incl. May)*
Prudhoe Bay W.G.			81	58	
Franklin Bluffs	ND	56	101		
Sagwon W.G.		74	145	61	66
Happy Valley	ND	110	118		
Toolik River W.G.			177	135	
Toolik Lake		95	123		
Galbraith	132	141	121		
Atigun River			285	150	
Atigun Camp	189	117	164	180	
Atigun Pass W.G.		226	292	217	248
Chandalar Shelf W.G.	200		268	182	209
Timberline		167	181	170	
Dietrich	84	130	220		
Coldfoot	302	282	256	194	
Prospect	201	253	326	205	213
Gobbler's Knob		203	367	214	
Old Man	197 (est. Aug)	219	214	146	
Five Mile	116	128	217	137	159

W.G.—Wyoming snow gage.

3). From the timberline south to Old Man, the 30-year normal precipitation at Bettles is probably representative of all but the higher elevations along the Haul Road. South of Old Man to the Yukon River, total precipitation is distinctly less, exceeding 300 mm at Five Mile (Table 3) only once since 1975.

During the 1975-78 study period, 1977 was the wettest year. May-October (thaw season) precipitation during 1977 was greater than in 1978 at all sites except Toolik River (Fig. 13). Based on comparisons with Bettles and Umiat, 1976 was a near-normal year for precipitation. The 1978 data for May are not presented because these were available for only a few stations (Table 4) and their inclusion would render the rest of the comparison less valid. The available data (Table 4) indicate that the 1978 values would be 4 to 16% greater if the month of May were included in the graphic comparison (Fig. 13).

The greatest total annual precipitation during the study period was 440 mm recorded at Prospect for 1977 (Table 3). A consistent increase of precipitation with elevation has been documented for two summers (Table 4) between Prospect and Gobbler's Knob, which is only 8 km to

Table 5. Unfrozen vs frozen precipitation, Wyoming snow gage.

Location	Duration of thaw season	Unfrozen	Frozen	Total	Percent unfrozen
Prudhoe Bay	1977 31 May-6 October	81	142	223	36
	1978 5 June-29 Sept	58*	125	183	32
Sagwon	1977 30 May-5 October	144	94	238	61
	1978 3 June-15 Sept	52	88	140	37
Toolik River	1977 25 May-19 Sept	157	110	267	59
	1978 1 June-18 Sept	107	87	194	55
Atigun Pass	1978 30 May-8 October	217	57*	295	74
Chandalar	1978 18 May-18 Sept	213	181	394	54

*Gage bridged over by snow.

Table 6. Greatest one-day precipitation (mm), unfrozen.

Location	Date	Amount
Franklin Bluffs	26 June 1975	25
Happy Valley	30 Nov 1976	15
Galbraith	8 June 1976	24
Atigun Camp	30 July 1976	36
Chandalar Shelf	26 July 1975	89
	30 July 1976	32
Dietrich	30 July 1976	20
Coldfoot	18 June 1975	46
Prospect	24 July 1977	52
Old Man	8 Aug 1976	27
Five Mile	31 May 1977	34

the south. No winter precipitation data are available for Gobbler's Knob, however. Measured 1977 thaw-season precipitation at Gobbler's Knob was the greatest for all Haul Road sites (367 mm) during the period 1975-1978.

Over the entire Haul Road transect during most years, the majority of the precipitation received annually is unfrozen. The distribution of unfrozen vs frozen precipitation at the four Haul Road Wyoming gage sites (plus an additional Wyoming gage site at Prudhoe Bay), indicates that about one-half the annual precipitation is unfrozen at Sagwon and Prudhoe Bay, the northernmost Wyoming gage sites (Table 5). Toward the south, the thaw season becomes longer, and the unfrozen precipitation percentage becomes larger. South of Chandalar, NWS records indicate that approximately two-thirds of the annual precipitation is unfrozen.

Precipitation intensity in terms of the greatest one-day total during the thaw season was also tabulated (Table 6). The most intense precipitation occurs during thunderstorms south of the Continental Divide. The greatest single-day totals are 89 mm at Chandalar (27 July 1975) and 52 mm at Prospect (24 July 1977). Although precipitation is not observed on an hourly basis at Haul Road NWS stations, the hourly records of cloud cover and type indicate the 89 mm of precipitation at Chandalar occurred during a nine-hour period, and the 52 mm at Prospect was recorded during approximately two hours.

North of the Continental Divide, thunderstorm activity is rare. Weak low pressure centers passing from west to east, often along the boundary of the summer Maritime Polar Front, are responsible for perhaps half the Arctic summer precipitation. The immediate coastal area, however, is usually under the influence of the maritime air, resulting in cloudy skies, on-shore winds or sea breezes, and precipitation that is more frequent but in smaller amounts than in the tundra areas to the south. The ranges of temperature and precipitation values along the Haul Road are summarized in Table 7.

Table 7. Range of climatic values; summary of 1975–78 stations.

	Interior	*Brooks Range*	*Arctic Foothills*	*Arctic Coastal Plain*
Degree-day totals (°C)				
Thawing	1182–1904	453–1189	760–1125	318–897
Freezing	2767–4513	3173–3888	4225–5412	4409–5642
Thaw season				
Length of thaw (days)	123–168	87–131	104–139	91–128
Starting date	18 Apr–1 Jun	3 May–10 Jun	18 May–27 Jun	25 May–9 Jul
Precipitation (mm)				
Frozen	NA	57–181	87–110	125–142
Unfrozen	84-367	117–292	52–157	58–81
Total annual	168-445	295–450	140–267	183–223
Temperature (°C)				
Mean annual	–6.9 to –3.7	–6.9 to –5.9	–11.1 to –9.0	–12.8 to –10.6
Mean annual diurnal range	12.8 to 14.6	10.8 to 12.6	7.6 to 11.6	7.2 to 9.6
Annual temp range (extreme low-high)	–53.3 to +33.0	–37.8 to +26.1	–53.3 to +30.0	–50.6 to +28.9

Surficial and bedrock geology*

The following general description of the surficial geology along the Haul Road corridor north of the Yukon River is based mainly upon the engineering geology maps prepared by the United States Geological Survey (USGS) (Ferrians 1971a, 1971b; Kachadoorian 1971a, 1971b, 1971c; Ferrians and Kachadoorian 1971), the recently published surficial geology maps of the Philip Smith Mountains and Chandalar Quadrangles (Hamilton 1978a, 1978b, 1979), and the terrain unit maps prepared by R&M Consultants (1974) for the Alyeska Pipeline Service Company. These maps should be consulted for more detailed descriptions of the geology. The bedrock geology is only briefly described. Table 8 and Figure 15 describe it in more detail. Locations discussed below are shown in the maps in Appendix C.

Kokrine–Hodzana Highlands (Intermontane Plateaus)

Along the Haul Road, the surficial materials of the Kokrine–Hodzana Highlands (see Fig. 1) consist mainly of diverse unconsolidated deposits with minor outcrops of igneous and metamorphic rocks. Colluvial silt, sand and rock fragments, glaciofluvial sand and gravel, windblown silt (loess) in upland and lowland positions, lacustrine and swamp deposits, and alluvial sand and gravel compose the unconsolidated materials. The exposed and underlying bedrock is mainly Paleozoic and probably Precambrian schist and gneiss along with other Paleozoic metamorphics, volcanics, and sedimentary rocks; Mesozoic granitic intrusives, volcanics, and sedimentary rocks; and Tertiary volcanic rocks. Granite, volcanics, schist and phyllite outcrop in roadcuts.

North of the Yukon River, the road traverses the lower, eastern slope of the Ray River valley. The sediments underlying this section of the road are mainly windblown, sometimes organic-rich silts. Solifluction has reworked some areas of these deposits. Thaw lakes, those formed by the melting of ground ice, occur in these deposits near the Yukon River. Thaw lake deposits are generally fine-grained and organic-rich (Williams 1962).

Colluvial deposits, derived from solifluction, slope wash and other mass wasting processes, become more prevalent about 20 km north of the Yukon River in the Fort Hamlin Hills. Colluvium consists of a heterogeneous mixture of silt, sand and subangular to angular rock fragments. Coarse-grained deposits generally occur on the upper parts of slopes, whereas fine-grained deposits generally occur on the lower parts of slopes and in low-lying areas. Polygonal ground patterns may be associated with ice wedges that are common in the loess and in some fine-grained colluvium.

Locally, gravel, sand and silt deposited by the Ray River and its tributaries underlie the road. Silt deposits are generally limited to the channels and floodplains of slow moving, low gradient streams. They may be associated with silty

*Prepared by D.E. Lawson.

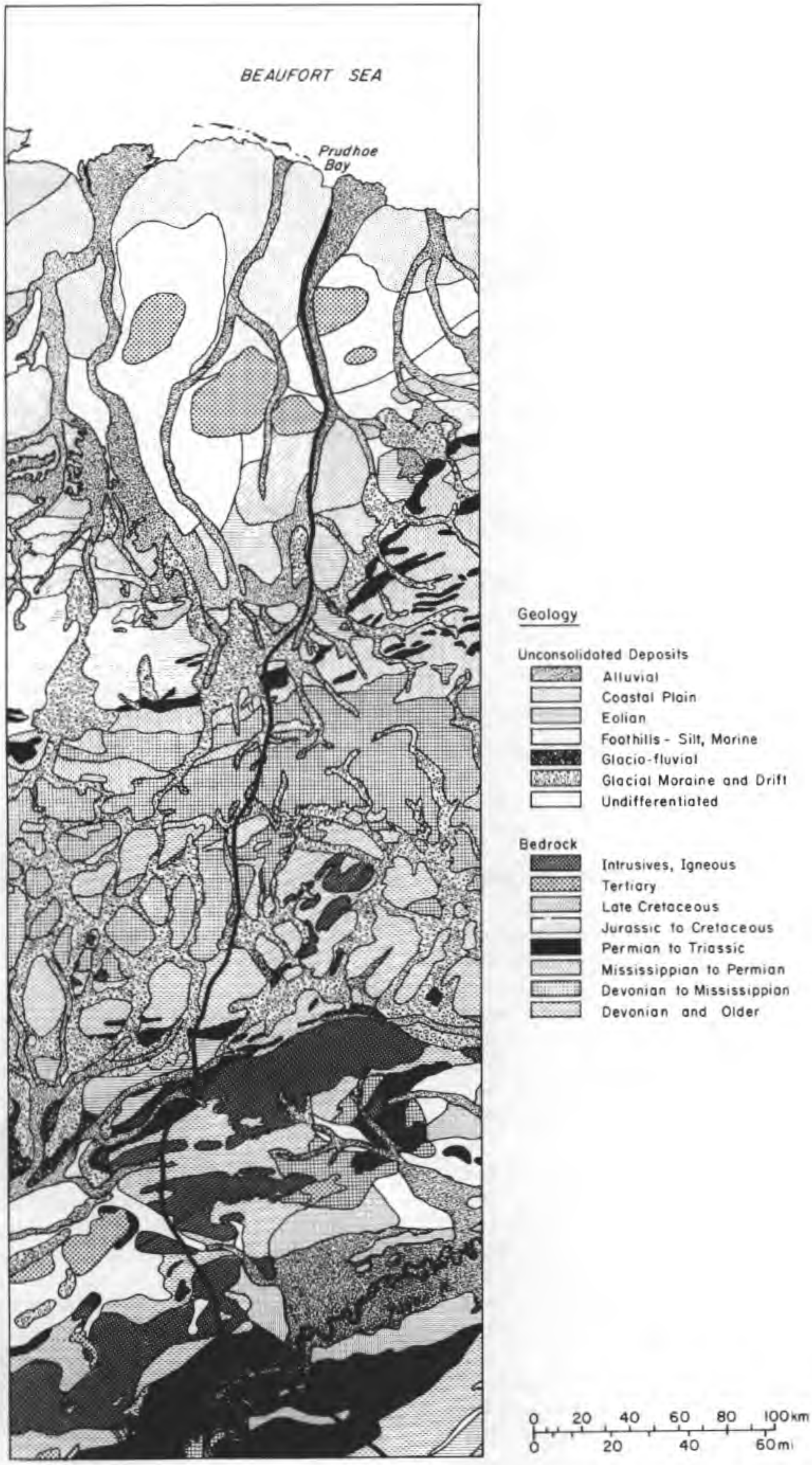


Figure 15. Bedrock and surficial geology of the Haul Road (map modified from University of Alaska 1975).

Table 8. Generalized bedrock types encountered along the Haul Road.

	Bedrock	*Kokrine–Hodzana Highlands*	*Ambler–Chandalar Ridge, Lowland section & Central & Eastern Brooks Range*	*Arctic Coastal Plain and Arctic Foothills*
I	Intrusives, igneous	Cretaceous granitic rocks—quartz monzonite, granodiorite, syenite, monzonite	Intrusive rocks Devonian to Cretaceous	
T	Tertiary	Light-colored volcanic rocks—basalts and tuffs		Siltstone, sandstone, conglomerate
Kc	Late Cretaceous	Sandstone, conglomeratic sandstone, conglomerate, coal	Sandstone, conglomeratic sandstone, conglomerate, coal	Well-indurated sandstone and conglomerate
KJ	Jurassic to Cretaceous	Early Cretaceous graywacke, shale, siltstone, conglomerate	Early Cretaceous graywacke, conglomerate, shale, argillite	Soft and fissile shale, well-indurated sandstone and conglomerate
T_rP	Permian to Triassic	Complex of volcanics and intrusives; locally includes Permian chert, shale, argillite	Shale, limestone, sandstone, siltstone, chert	Soft shale and siltstone, well-indurated limestone and sandstone
PM	Mississippian to Permian	Argillite, chert, shale, limestone	Limestone, dolomite	Hard, well-indurated limestone, dolomite, chert, soft shale
MD	Devonian to Mississippian	Graywacke, shale, conglomerate	Conglomerate, slate, limestone, shale	
Dm	Devonian and older	Paleozoic and Precambrian schist, quartzite, gneiss, argillite, grit	Quartz schist, slate phyllite marble, siltstone, limestone	Hard, well-indurated conglomerate and sandstone, fissile shale

colluvium. Clean sands and gravels, perhaps remnants of streams terraces, are also present in the Ray River valley.

The Haul Road traverses colluvial deposits for almost the entire distance from the Ray River to the Jim River Valley. Bedrock outcrops occur adjacent to the road and in the surrounding hills. Linear to arcuate patterns in the vegetation (and possibly soils) that are visible on regional aerial photographs show drainage patterns and the probable directions of downslope transport of the colluvial materials from these bedrock outcrops. Solifluction appears active on some lower parts of stream valley slopes.

The valleys of the Kanuti River, West Fork of the Dall River, Fish Creek and Bonanza Creek contain silt- to gravel-size alluvial deposits. Loess and solifluction deposits may be superimposed upon floodplain deposits. Organic-rich silts occupy the swampy floodplain of Bonanza Creek and the swampy lowland near Olsons Lake along the Kanuti River.

Just north of the Ray River, the road ascends to an upland region dominated by colluvial deposits over bedrock and bedrock outcrops. Bedrock outcrops southeast of Caribou Mountain along the Haul Road are mostly granitic and sometimes highly weathered into features called tors (Fig. 16).

Tors are remnants of larger hills that were eroded under periglacial conditions. The bedrock undergoes intensive frost shattering and the resulting debris is moved downslope from its source by solifluction, slope wash and other mass-wasting processes (French 1976). Gently inclined slopes and benches, referred to as cryoplanation terraces, form adjacent to the tors as part of the erosional process (Reger and Péwé 1976). Once these processes reduce slope angles to the point where movement by solifluction is restricted, the frost action on the colluvial debris leads to local sorting and patterned ground development. Sorted polygons and nets with cobble and boulder margins, evidence of these processes, occur adjacent to the road (Fig. 16).

Along the Jim River and its tributaries, Prospect, Douglas and Grayling Creeks, colluvial materials cover slopes adjacent to bedrock uplands, but the low sloping creek valleys contain alluvium. Glaciofluvial sand and gravel deposits underlie these more recent alluvial deposits along the Jim River and are commonly associated with glacial drift along Grayling Creek and the tributary valley to the north of the South Fork of the Koyukuk River. A layer of reworked windblown silt often covers older alluvial sands and gravels. Talus cones and occasionally alluvial fans occupy the base of steep bedrock slopes

Figure 16. Bedrock remnant of tors in vicinity of Finger Mountain, south of Old Man Camp, 19 August 1976. Sorted stone nets surround the tors.

and valleys. Colluvial deposits, in part resulting from solifluction, may occur on these slopes. The fine-grained colluvial and lowland deposits and glacial drift may be perennially frozen and contain large amounts of massive ice. For example, except for a thaw bulb beneath creeks, continuous permafrost probably underlies the Grayling Creek valley.

Arctic Mountains Province

The Ambler-Chandalar Ridge and Lowland begins at the south fork of the Koyukuk River and extends to Coldfoot where the Brooks Range abruptly begins. This part of the Haul Road route is underlain by frozen glacial till, silt, sand and gravel, colluvial silts, and alluvium (mainly sand and gravel in older terraces and active stream channels), with bedrock in the surrounding hills. Bedrock mainly consists of conglomeratic sandstone, graywacke, conglomerate, shale, schist, phyllite and mafic igneous rocks.

Most surficial materials here were reworked by colluvial processes with materials on valley slopes derived from the surrounding bedrock hills and from soils and loess. Between mileposts 105 and 110, however, there are complex deposits largely of glacial origin, including till in hummocky ground moraine and glaciofluvial and glaciolacustrine deposits in various landforms. Stagnant ice landforms include kames, eskers, kettles and discontinuous arcuate and linear ridges. Swampy lowlands and lakes, in which fine-grained, organic-rich sediments are deposited, commonly occur here.

In the valley of the Middle Fork of the Koyukuk River, deposits are largely alluvial sands and gravels in the active floodplain and in older stream terraces. Valley slopes consist primarily of fine-grained colluvial deposits that overlie glacial till, loess and glaciofluvial materials on gentler slopes, and of coarse- to fine-grained colluvium on steeper slopes. Largely massive to stratified deposits of silty sand and coarse gravel, which may be angular to subrounded, are found in alluvial fans at the mouths of mountain valleys. Loess covers some abandoned channel and floodplain deposits.

In the Brooks Range north of Coldfoot, the valley narrows and is bounded by mountain peaks that may stand 1300 m or more above the valley floor. Alluvial fans are common at the base of steep mountain tributary valleys along the road throughout the Brooks Range. Active fans may be subject to icings during winter, slushflows during snowmelt, and mudflows during summer.

In the Brooks Range, most rocks are Paleozoic limestones, sandstones, shales and various grades of their metamorphic equivalents. These rocks were folded and thrust to the north in east-trending belts from Mesozoic through early Tertiary time. Northward there is a decrease in structural complexity, relief, and age of exposed rocks.

Both the Middle Fork of the Koyukuk River and Dietrich River occupy narrow valleys, generally less than 3 to 4 km wide, that were glaciated during Pleistocene times. From Coldfoot to the Chandalar Shelf, where the Haul Road swings away from the Dietrich River, sediments in these valleys are mostly similar in origin and occurrence. The bedrock consists chiefly of Devonian siltstone, slate, phyllite, limestone and sandstone.

Colluvial debris generally lies at the base of steep to moderate bedrock slopes. It generally overlies bedrock, which protrudes through this cover where it is thin, and in some undifferentiated areas it overlies glacial drift, described mainly as till. Glacial till not covered by colluvium may extend up the slopes from the valley bottom. Solifluction is active on some slopes.

In the central low areas of the valley, sediments may consist of poorly sorted, unstratified glaciofluvial sand and gravel, sometimes in terraces. The floors of these valleys may contain thick stratified lacustrine deposits of clay, silt and sand. Beaches of fine sandy gravel represent former shorelines of these lakes. The lake deposits resulted from the damming of glacial meltwaters behind end moraines during Wisconsinan glaciations (Hamilton 1978a). Outwash sands and gravels, recent alluvium, solifluction deposits and alluvial fan deposits partly or completely bury these sediments. Older alluvium may be terraced.

After leaving the Dietrich River valley, the Haul Road ascends to the Chandalar Shelf and follows the upper reaches of the westernmost fork of the Chandalar River to the Continental Divide in Atigun Pass. This segment is generally underlain by glacial drift that may consist of till and other ice-contact deposits, glaciolacustrine ground deposits, and glaciofluvial sands and gravels. Most deposits occur in lateral and ground moraines and kame terraces. Colluvium covers these deposits and bedrock on the valley walls. Solifluction lobes are visible on slopes above the Haul Road adjacent to the westernmost tributary of the Chandalar River. Alluvial sands and gravels occupy the central part of the valley. Alluvial fans fill the mouths of narrow mountain valleys; avalanche deposits occur on some fans.

In Atigun Pass, the route is underlain by talus in cones or aprons and mantling bedrock with coarse rubble, some of which is glacially-derived. Rock glacier deposits are found in some tributary valleys just north and south of the Continental Divide (Hamilton 1978a, Ellis and Calkins, 1979). In this area, the mountains are composed of a well-indurated Devonian conglomerate. Conglomeratic sandstone and limestone continue north beyond Galbraith Lake.

The route follows the narrow Atigun River valley out of the Brooks Range near the north end of Galbraith Lake. Materials in the valley are mainly glacially derived, commonly occurring as glacial drift and deposits of a lake that once filled the valley and extended south from just north of Galbraith Lake. The Haul Road lies along the valley's lower eastern slopes and traverses mainly alluvial fans and colluvial debris, sometimes developed on older, inactive fan surfaces. Solifluction is active on some slopes. Atigun River alluvium and locally alluvial fan deposits, colluvium, eolian sand dunes and loess lie superimposed upon these deposits. Till and stratified ice-contact deposits become more extensive north of Galbraith Lake where the road crosses several well-defined arcuate end moraines.

The southern and northern sections of the Arctic Foothills were heavily glaciated. Glacial drift of different ages covers most of these sections along the Haul Road until just south of the Lupine River, where Cretaceous age sandstone and conglomerate dominate. These well-indurated rocks are common to approximately 18 km south of the Ivishak-Sagavanirktok River confluence where the bedrock changes to poorly consolidated Tertiary conglomerates, sandstones, siltstones, and occasionally coal. Much of the glacial drift and most of the bedrock is mantled by solifluction deposits and, especially near the Sagavanirktok River, by loess.

Glacial deposits include extensive till sheets in irregular ground moraines and well-developed arcuate end and lateral moraines. Glaciofluvial sands and gravels may dominate, or they may be interspersed as irregular lenses and pockets in the tills. Channeled outwash trains, kames, kettles and kame terraces, showing various degrees of weathering and erosion dependent upon age, are associated with the ground moraines of the more recent glaciations. Solifluction has obscured some deposits and landforms. Loess and colluvium cover some slopes and deposits. The active floodplain of the Sagavanirktok River is underlain by sand and gravel. Low terraces of this river are similar in composition but are also mantled by silt and sand.

Arctic Coastal Plain

The eastern portion of the Arctic Coastal Plain is underlain mainly by unconsolidated Quaternary alluvial and marine sediments. These sediments are organic-rich silty sand and sandy silt overlying sandy gravel and gravelly sand. The deposits of the braided Sagavanirktok River include the sand and sandy gravel of the active floodplain and similar materials mantled by organic-rich silty sand in flat-topped terraces that lie along the active flood plain. The sediment cover may be eolian in origin. Superimposed upon the Coastal Plain sediments are deposits of drained lake basins. These sediments are thin-bedded to massive organic-rich silty sand and sandy silt. Nearly flat-lying Cretaceous sandstone and conglomerate, and lower Tertiary poorly consolidated conglomerate, sandstone and siltstone with minor interbedded coal lie from 3 m to more than 50 m below the surface.

Permafrost and ground ice*

Permafrost (perennially frozen ground) underlies much of the Haul Road route. The road traverses major portions of both the discontinuous and continuous permafrost zones (Fig.1). According to the USGS permafrost map of Alaska (Ferrians 1965), temperatures of the perennially frozen ground (permafrost) at depths below the zone of seasonal temperature variation generally range between -5° to -1°C in lowland areas of the southern discontinuous zone. The spatial distribution of ground temperatures is highly variable. The mean annual air temperature probably ranges between -7° and 0°C. In the continuous zone north of the Brooks Range, permafrost temperatures are expected to range between -11° and -5°C. Permafrost temperatures in the Brooks Range are extremely variable.

Ground ice is associated with permafrost, and its abundance and distribution are significant considerations in route selection, road design, construction techniques, and maintenance practices. Ground ice occurs as pore ice, as ice films, lenses, layers and other small segregated masses up to 15 cm or so in thickness, and as large sheets and wedges. Segregated ice results from segregation of water from the saturated soils during the freezing process and can occupy up to 40-80% of the total volume of the upper 5 to 6 m of permafrost terrain (Sellmann et al. 1975). Vertically oriented ice wedges, which form over many centuries in the permafrost, commonly exceed 1 m in width at their tops and are responsible for the delineation of polygonal ground. It is not uncommon, however, for ice wedges to show virtually no polygonal surface expression. The majority of ground ice occurs in fine-grained, unconsolidated sediments; however, it is also found in coarse, unconsolidated materials and apparently competent bedrock. Buried icings, pond ice, sheets of injected ice and possibly buried glacial ice can also be found in the near-surface permafrost.

Considerable information on the moisture content (and, indirectly, the ground ice content) of the permafrost terrain over which the Haul Road passes is available from the road test borings (Kreig and Reger 1976, Tart and Ghuman 1979) and is summarized in the pipeline terrain maps (R&M Consultants 1974). In addition, the location and mode of construction of the pipeline offer indirect evidence of ground ice conditions. The design of the pipeline required thaw-stable conditions for the buried mode, and thus the pipeline is elevated where ground ice is abundant. The buried portions of the pipeline are in locations relatively free of excess ground ice or in nonpermafrost terrain. Fifty-seven percent of the oil pipeline is above ground north of the Yukon River. In areas where the pipeline and road parallel one another on similar terrain, it is possible to partially evaluate the permafrost and ground conditions. Furthermore, the drill logs for the vertical support members (VSM) on which the pipeline is elevated provide considerably more data on ground ice distribution. In addition, north of Pump Station 4 to Prudhoe Bay, the small diameter fuel gas line was buried in a trench within 5 m of the toe of the road. Figure 17 contains idealized cross sections of these different modes of construction for the pipelines as they occur adjacent to the road.

Three major permafrost zones are crossed by the road:

1. The uplands and valleys between the Yukon River and the southern boundary of the Brooks Range (Kokrine-Hodzana Highlands and

*Prepared by J. Brown and D.E. Lawson.

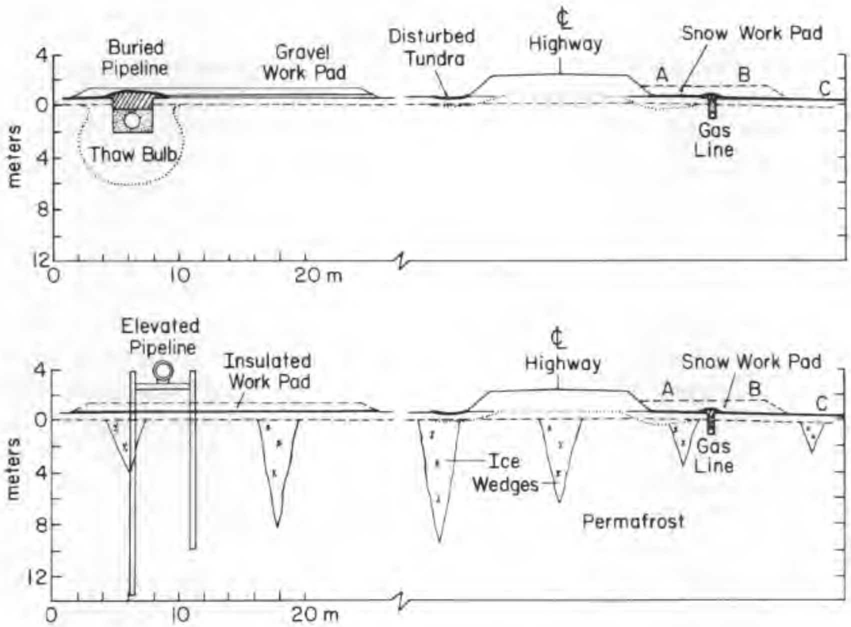


Figure 17. Idealized cross sections of the road and buried fuel gas line and the above- and belowground modes of the oil pipeline construction as they occur adjacent to the road. A, B, and C indicate position of thaw measurements.

Ambler–Chandalar Ridge and Lowlands).

2. The Brooks Range.

3. Northern Alaska (Arctic Foothills and Arctic Coastal Plain).

Kokrine–Hodzana Highlands and Ambler–Chandalar Ridge and Lowlands

South of the Brooks Range, the presence or absence of permafrost and the thickness of the seasonal thaw zone or active layer are closely related to slope angle and aspect, vegetation, thermal properties of the parent materials and drainage. Well-drained, south-facing slopes and sediments beneath the active channels of large streams are generally free of permafrost. Valley bottoms, north-facing slopes, and wet lower slopes are usually underlain by permafrost with an active layer thickness of 0.5 to 1.0 m. In the perennially frozen areas, thaw bulbs exist beneath smaller streams such as Douglas Creek. The overall extent of permafrost generally increases northward.

The distribution of ground ice is highly variable and may be extremely abundant. Windblown silts (loess) commonly contain massive ice (e.g. near the Yukon River), and fine-grained colluvial, glacial and alluvial deposits may also be ice-rich. For example, the drill logs of VSM holes located in colluvium near the Jim River contain large amounts of massive ice.

Examples of ice-rich permafrost occur at several locations on this portion of the road. At No-Name Creek (milepost 23), sediments beneath and adjacent to the road are mainly poorly drained, fine-grained deposits of eolian, colluvial and alluvial origins. The depth of thaw between the large tussocks that cover the valley bottom is less than 0.2 m (Fig. 18). The presence of massive ice in the form of wedges is indicated by the polygonal pattern visible on aerial photographs and by thermokarst ponds.

A tundra meadow containing ice wedge polygons lies immediately east of the Haul Road just south of Old Man Camp. Sediments beneath this meadow are generally fine-grained, organic-rich colluvial materials deposited by solifluction that may be underlain by alluvial materials. The access road to the airfield and the airfield itself are built on this polygonal ground. Subsidence of parts of the road and airfield indicates that the buried ice wedges have begun to melt as the result of this thin gravel overlay.

The excavation of the road cut on the south side of Rosie Creek exposed ice wedges in fine-grained solifluction deposits derived from glacial till (Fig. 19). These wedges began to melt almost immediately upon exposure and, although covered by slope materials, were still melting in August 1978. Downslope to the west of the road cut, the thermokarst pond and small

Figure 18. No Name Creek site (CRREL site 82-1), 21 August 1976. In the foreground is the tussock-covered valley which contains ice wedge polygons and thermokarst ponds. In the background is the poorly drained black spruce forest.

Figure 19. Exposure of ice wedges on the south side of Rosie Creek, 30 May 1975.

Figure 20. Siberian cemetery mounds, or baydzherakh, *downslope from the exposed ice wedge cut shown in Figure 19, 20 August 1976. Mounds are erosional remnants left after ice wedges have melted.*

Figure 21. Small thermokarst pond adjacent to moundy area shown in Figure 20, 20 August 1976. The mounds and pond indicate ice-rich permafrost.

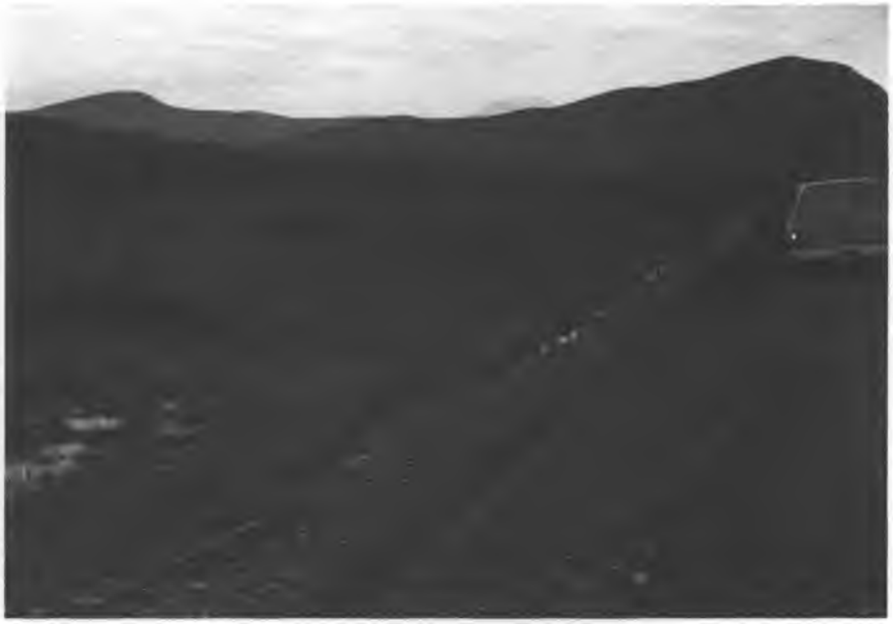


Figure 22. Ice-cored mounds on slope below Sukakpak Mountain, 17 September 1976.

hummocks, referred to as Siberian cemetery mounds or *baydzherakh*, indicate that these sediments are also ice-rich (Fig. 20 and 21).

Brooks Range

The Brooks Range lies within the continuous zone of permafrost. Both air and ground temperatures are extremely variable, as is the thickness of permafrost, but the bedrock and unconsolidated deposits of slopes are almost always perennially frozen. The coarse-textured and freely drained upper slopes have deep active layers, while the wet fine-grained lower slopes have thin active layers commonly between 0.5 and 1.0 m in thickness. Permafrost is, however, generally discontinuous beneath the floodplains and may be absent beneath the active channels of larger rivers like the Dietrich and Middle Fork of the Koyukuk River. Thaw bulbs occur beneath small drainages such as Minnie Creek.

As in most perennially frozen areas, the ice content of the fine-grained deposits usually exceeds that of coarse-grained deposits. The fine-grained deposits of the Brooks Range usually contain large amounts of massive ice, with coarse-grained materials commonly containing ice in their voids and as coatings on individual particles.

The wet lower slope which drains Sukakpak Mountain is covered by numerous mounds several meters high that often contain massive ice (Fig. 22). Black spruce trees are found on some of the mounds. Solifluction deposits developed on till compose the slopes. A thick vegetative mat covers these deposits. The small hydrostatic mounds are probably formed by freezing of groundwater that moves downslope in the thaw layer. Less likely, they may also be remnants of a buried, now degrading sheet of ice. These mounds occur on both sides of the road.

The bedrock cut on the west side of the road in Atigun Pass exposed considerable ground ice, in fractures and joints in the rock. Considerable spalling of the cut occurred during the first summer. This high ice content led to the burial of the pipeline in an insulated box on the north side of the Pass. Further north, in the Atigun River valley, VSM logs revealed the presence of much massive ice in the unconsolidated materials. Slides and slumps on the valley wall have exposed massive buried ice, probably of glacial origin.

Arctic Foothills and Arctic Coastal Plain

The Arctic Foothills and Arctic Coastal Plain are underlain by deep permafrost that reaches a

Figure 23. Collapse features in material site 119-4 presumably the result of melting of large masses of ground ice, 19 July 1977.

maximum depth of approximately 650 m at Prudhoe Bay (Gold and Lachenbruch 1973). Active layer thickness is generally less than 0.5 m in the predominantly fine-grained soils. Unfrozen zones are generally limited to deep river channels, which frequently have unfrozen gravel beneath them, and large, deep lake basins. Perennial springs indicate the presence of local zones of unfrozen bedrock. Scott (1978) has discussed the effects of permafrost on stream channel behavior in this region.

Ground ice is common in all perennially frozen materials. In the Foothills, ice wedge polygons are particularly conspicuous in poorly drained depressions and drained lake basins. A network of ice wedge polygons covers most of the Arctic Coastal Plain, its drained lake basins, and the older fine-grained alluvial deposits. Pingos have developed in the refrozen lake basin sediments. Although sometimes present in large amounts, other forms of massive ice show little surface expression. Ground ice was frequently observed and logged in the VSM borings and fuel gas line trench, and thermokarst pits indicate its presence in other areas. Some additional examples of ground ice conditions are given below.

The oil pipeline is aboveground near Slope Mountain as it crosses end and ground moraines that are presumably ice-rich. Sediments here are largely of glacial origin with till a primary component. An abandoned material site (MS119-3) on the east side of the road has begun to show collapse and meltout features (Fig. 23). The shape of the thermokarst pits suggests melting of massive ice of a type other than wedge ice. It is hypothesized that buried glacial ice could persist under this climatic regime. Ice in the form of thick and extensive lenses may also account for the collapse features.

The road crosses numerous drainages that contain well-developed ice wedge polygons such as are observed both north and south of Happy Valley Camp. In a drained lake basin immediately south of the access road to MS 124-1, the fuel gas line trench exposed a 1-km-long section of ice wedges. Figure 24 is a ground view looking into the trench, and Figure 25 is an idealized cross section showing the spacing of these wedges. The irregular distribution of the tops of these wedges indicates that they were formed and modified by several cycles of development and degradation. VSM logs in this area often show large amounts of massive ice present.

Figure 24. Closeup of trench from which ice wedge distribution was logged.

Kovacs and Morey (1978) were able to detect the top and bottom of massive ground ice along the elevated section of the pipeline using an impulse radar system.

Immediately north of Happy Valley Camp, the road cuts across several more basins and drainages that contain ice-wedge polygons. These basins are filled with organic-rich silts and sands that are locally coarse-grained (Fig. 26). A thaw lake adjacent to the road is actively eroding into an ice-rich, peaty bluff (Fig. 27).

The Happy Valley road cut encountered ice wedges and ice-rich permafrost at the top of a slope composed of colluvial debris on bedrock (McPhail et al. 1976, Hamilton 1979). Figure 28 is a photograph obtained in early 1975 and shows several exposed ice wedges. The slope has gradually receded as the ice continues to melt. As can be seen in the 1977 photographs (Fig. 29), the lower portion of the road cut also shows subsidence. Ample evidence of ice wedge polygons in the area is seen upon close inspection of aerial photographs.

The Sagwon uplands area was heavily impacted by winter and summer tractor trains in the 1960's. Disturbance of the surface vegetation triggered melting of the underlying wedges and other forms of ground ice in the fine-grained loess and colluvium. In the vicinity of CRREL site 127-2 (see App. C maps), a number of such thermokarst ponds are found (Fig. 30). Pond depths, indicating loss of volume due to ice wedge melt, ranged between 38 and 67 cm and averaged 50 cm in 13 ponds measured. Thermokarst pits due to ice wedge melt are also present in the gravelly upland material sites at MS127-2.1B.

Between Franklin Bluffs and Prudhoe Bay on the flat Coastal Plain, immediately south of the access road to material site 135-A,B,C, hydraulic erosion of ice-rich permafrost occurred and nearly undercut the road (Fig. 31). At this location, the terrain slopes gently to the north. Runoff waters apparently concentrated and flowed down a shallow depression caused by a Rolligon trail along the east side of the road. This concentrated flow during early summer 1976 initiated erosion of massive ice lying within 0.5 m of the surface. Deep gullying which moved headward towards and parallel to the road resulted. The gullies appear to follow a polygon shape which suggests melting of ice-wedges; however, inspection of the gullies during the erosion period revealed some horizontally bedded ice that may have been buried river or surface icings. The erosion was finally arrested by building a shallow gravel dam upslope from the erosion and diverting the flow through a half culvert.

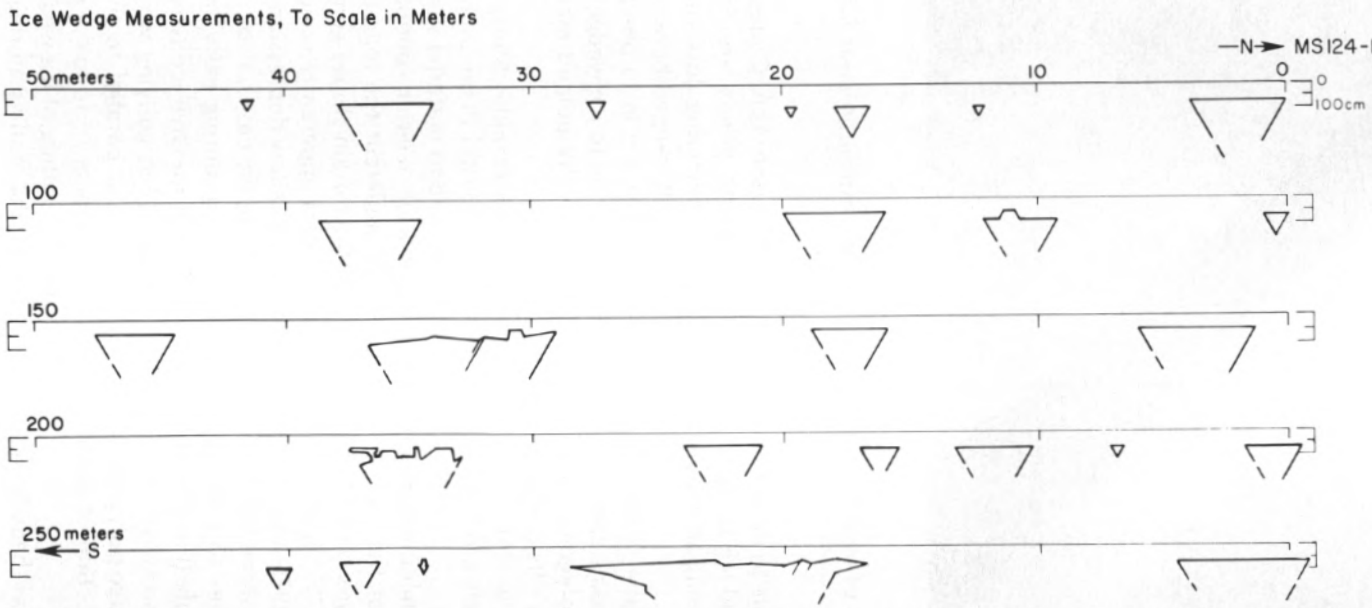


Figure 25. Idealized cross sections of fuel gas line trench immediately south of MS124-1 access road. Tops of wedges are to horizontal scale, but shapes are idealized and not to vertical scale (observed by J. Brown, 1976).

Figure 26. Polygonized drainage north of Happy Valley Camp, CRREL site 124-1, on 18 August 1976 prior to burial of fuel gas line.

Figure 27. Thaw lake actively eroding into organic- and ice-rich frozen sediments, 22 July 1977.

Figure 28. Happy Valley road cut on 15 June 1975 showing exposed ice wedges and slumping tundra mat. See Hamilton (1979) and McPhail et al. (1976) for additional 1975 photographs and discussions.

Figure 29. Happy Valley road cut on 21 July 1977 showing slumped tundra mat and the thawed areas previously occupied by ice wedges. The elevated oil pipeline is seen in the background.

Figure 30. Shallow thermokarst pond formed as ice wedges melted out following blading of tussock-covered tundra (CRREL site 127-2, 24 June 1976).

Figure 31. Erosion channels adjacent to road at MS135-A, B, C caused by melting of ice-rich permafrost, 24 June 1976. Although the pattern resembles polygonal ground, some horizontally bedded massive ice was observed in the exposed cuts.

General biota*

The Haul Road passes through approximately 280 km of forest and 320 km of tundra vegetation before it reaches Prudhoe Bay. From the Yukon River to the southern foothills of the Brooks Range the vegetation consists of mixed deciduous-coniferous forests composed of black spruce (*Picea mariana*), white spruce (*P. glauca*), paper birch (*Betula papyrifera*) and aspen (*Populus tremuloides*). Riparian vegetation in this area consists of balsam poplar (*Populus balsamifera*) and willow (*Salix* ssp.) stands. In the southern part of this area, tamarack (*Larix laricina*) can be an occasional component on wetter sites in the forest.

By far the largest forest type in terms of area covered is a low forest dominated by black spruce. This rather depauperate vegetation type occurs on most level and gently rolling surfaces below 700 m. White spruce, which begins to replace black spruce on all sites somewhat north of Wiseman, tends to occupy steeper slopes and well-drained ridges where the two species occur together, and it is the major coniferous species growing on river terraces throughout the area. Depending on fire history, aspen and paper birch are mixed with spruce in various proportions, or pure or mixed stands of both of these deciduous successional species occur alone. Balsam poplar is also found almost exclusively on river terraces.

On a moisture gradient from wet to dry, black spruce lies at the wet end, while paper birch, aspen and white spruce occur at the dry end of the gradient. The restriction of balsam poplar to terraces complicates its position on the moisture gradient, but in terms of surface soil drainage it lies on the drier end of the gradient.

Above an elevation of about 700 m, forest vegetation gives way to shrubby tundra, consisting primarily of alder (*Alnus crispa*) and dwarf birches (*Betula glandulosa* and *B. nana*), which is in turn replaced by a mixed herbaceous-dwarf shrub tundra vegetation at higher elevations. The complexity of the alpine tundra depends particularly on substrate and soil moisture, and to a lesser extent on radiation and erosion intensities. The composition of the tundra vegetation on the low interior mountains depends to a considerable extent on the substrate, with the acidic rocks along much of the road supporting an impoverished flora that lacks many species characteristic of the Brooks Range. Limestone mountains, such as Wiehl and Sukakpak Mountains, are much richer in species than most of the mountains along the Haul Road south of the Brooks Range, but still lack many typically arctic and alpine tundra species. In the Brooks Range, distinctive assemblages of species can be found in various topographic structures.

The tundra vegetation of the Arctic Slope is subdivided into a sedge-tussock type on the Foothills and a sedge-meadow type on the Coastal Plain. Riparian habitats, late-lying snowbeds, rock outcrops and lakes add diversity to what otherwise appears to be a monotonous vegetation.

Large grazing animals present within the transportation corridor include caribou, (*Rangifer tarandus*), dall sheep (*Ovis dalli*), and moose (*Alces alces*). The northern portion of the Haul Road traverses the range of a distinct subpopulation of 5000-6000 caribou, the Central Arctic Herd (Cameron et al. 1979, Cameron and Whitten 1979; in press). These aerial surveys have shown that the aggregate calf percentage in summer and fall from 1975 through 1978 along the Haul Road has been consistently lower than that of the general region.

Black bears (*Ursus americanus*), grizzly bears (*U. arctos*), and wolves (*Canis lupus*) were common along the road during pipeline construction. The highest density of the black bear population is from the Yukon River to just north of Dietrich Camp. The grizzly bears favor open slopes and mountains, while black bears range throughout forested valleys, showing a preference for open mixed forests. North of the Brooks Range there is a relatively high density of arctic fox (*Alopex lagopus*). Burrowing mammals (primarily the arctic ground squirrel, *Citellus undulatus*) are restricted to well-drained sites such as pingos, streambanks and moraines. Ptarmigan (*Lagopus lagopus*) occur sporadically along the road north of the Brooks Range (Hemming and Morehouse 1976, see also App. F for a list of fish and wildlife reports for the TAPS route).

In a survey of the pipeline route between the Yukon River and Atigun Pass, Netsch (1975) reported arctic grayling (*Thymallus arcticus*) and slimy sculpins (*Cottus cognatus*) present in all of the streams and lakes except one. Round whitefish (*Prosopium cylindraceum*) the next most common species, are found in most streams 3 m or wider. The Yukon River has the greatest

*Prepared by A.W. Johnson and D.A. Roach.

species diversity with 12 species of fish known and an additional 5 probably present. Larger streams in the area, from the Yukon River to Fish Creek, are the only places where the following are found: Arctic lamprey (*Lampetra japonica*), Bering cisco (*Coregonus laurettae*), broad whitefish (*C. nasus*), lake chub (*Conesius plumbeus*), least cisco (*Coregonus sardinella*), inconnu (*Stenodus leuichthys*), coho salmon (*Oncorhynchus kisutch*), and trout-perch (*Percopris omiscomaycus*). Other significant species which may be found in rivers along the southern section of the road include: northern pike (*Esox lucius*), lake trout (*Salvelinus manaycush*), and five species of salmon (*Oncorhynchus*). In rivers north of the Brooks Range, arctic grayling, ninespine stickleback (*Pungitius pungitius*) and arctic char (*Salvelinus alpinus*) are in high abundance. Arctic grayling and arctic char, as well as whitefish, have complex migration patterns between different areas within freshwater drainages throughout the summer months. The most interesting feature of fish distribution is the almost complete separation within major drainages of the spawning and early rearing areas of the Arctic char and grayling. The Arctic char spawn in the fall in the vicinity of cool spring and mountain stream waters. The grayling spawn in the spring in the warmer waters of tundra streams (Craig and McCart 1975).

Vegetation*

The major units of vegetation encountered along the road transect are shown in Figure 32. The following, which briefly describes the legend of this figure, is based on Viereck and Little (1972) and University of Alaska (1975).

Bottomland spruce-poplar forest is a tall, relatively dense, interior forest which occurs along the major streams. It is composed primarily of white spruce (*Picea glauca*) and balsam poplar (*Populus balsamifera*). Balsam poplar is usually an early invader of the bare floodplains that is replaced by white spruce as the forest matures. Meadows of tall grass with willows occur in periodically flooded areas. Undergrowth in this type is usually dense scrub, including alder, willow, prickly rose (*Rosa acicularis*), Labrador tea (*Ledum*), and blueberries (*Vaccinium*). Ferns, bluejoint grasses (*Calamagrostis*), fireweed (*Chamanerion*), horsetails (*Equisetum*) and other herbs, lichens, and mosses cover the ground. This forest occurs on level broad floodplains, low river terraces, and more deeply thawed south-facing slopes of major rivers in the Interior. It is found extensively along the Yukon and Koyukuk Rivers and is somewhat less extensive along their major tributaries. It occurs to elevations of more than 800 m in higher valleys.

Upland spruce-hardwood forest is composed of white spruce with scattered paper birch (*Betula papyrifera*), and aspen on moderate south-facing slopes, while black spruce grows on northern exposures and poorly drained flat areas. The understory consists of moss and low shrubs, with prickly rose, currants, Labrador tea and blueberries on the cool moist slopes, grass on dry slopes, and willows, alders, and dwarf birch or resin birch (*Betula glandulosa*) in the high open forests near treeline. White spruce trees up to 25 m high occur in mixed stands on south-facing slopes and well-drained soils and may form pure stands near streams. Paper birch and aspen stands, one early stage of succession following fire, are usually even-aged and more uniform in size than spruce stands. Paper birch and aspen stands predominate on well- to excessively drained southern slopes. This is the most extensive forest along the transect which covers most of the area south of the arctic treeline.

Lowland spruce–hardwood forest is characterized by extensive pure stands of *Picea mariana* or by stands of black spruce, paper birch, balsam poplar, and aspen. Species of willow, Labrador tea, dwarf birch, blueberries, sedges, and bog mosses compose the understory. Bogs and muskegs occur on low ground. Large areas burned since 1900 are covered by willow scrub and dense stands of small black spruce. These areas occur only in the southernmost portion of the route. This type of forest grows on peat, glacial deposits, outwash plains and on lowlands and north-facing slopes.

High brush community consists of dense thickets of willow and alder with a number of lower shrubs, herbs, grasses, ferns, and mosses in the understory. Floodplain thickets develop rapidly on alluvial deposits in floodplains that are newly exposed after flooding. Associated shrubs are buffalo berry (*Shepherdia canadensis*), roses, raspberry (*Rubus idaeus*) and thimbleberry (*Rubus parviflorus*). Islands and bars of the major rivers are usually bordered by pure willow stands, often in zones according to age. Newly exposed gravel bars are invaded by pioneer

*Prepared by V. Komárková and P. J. Webber

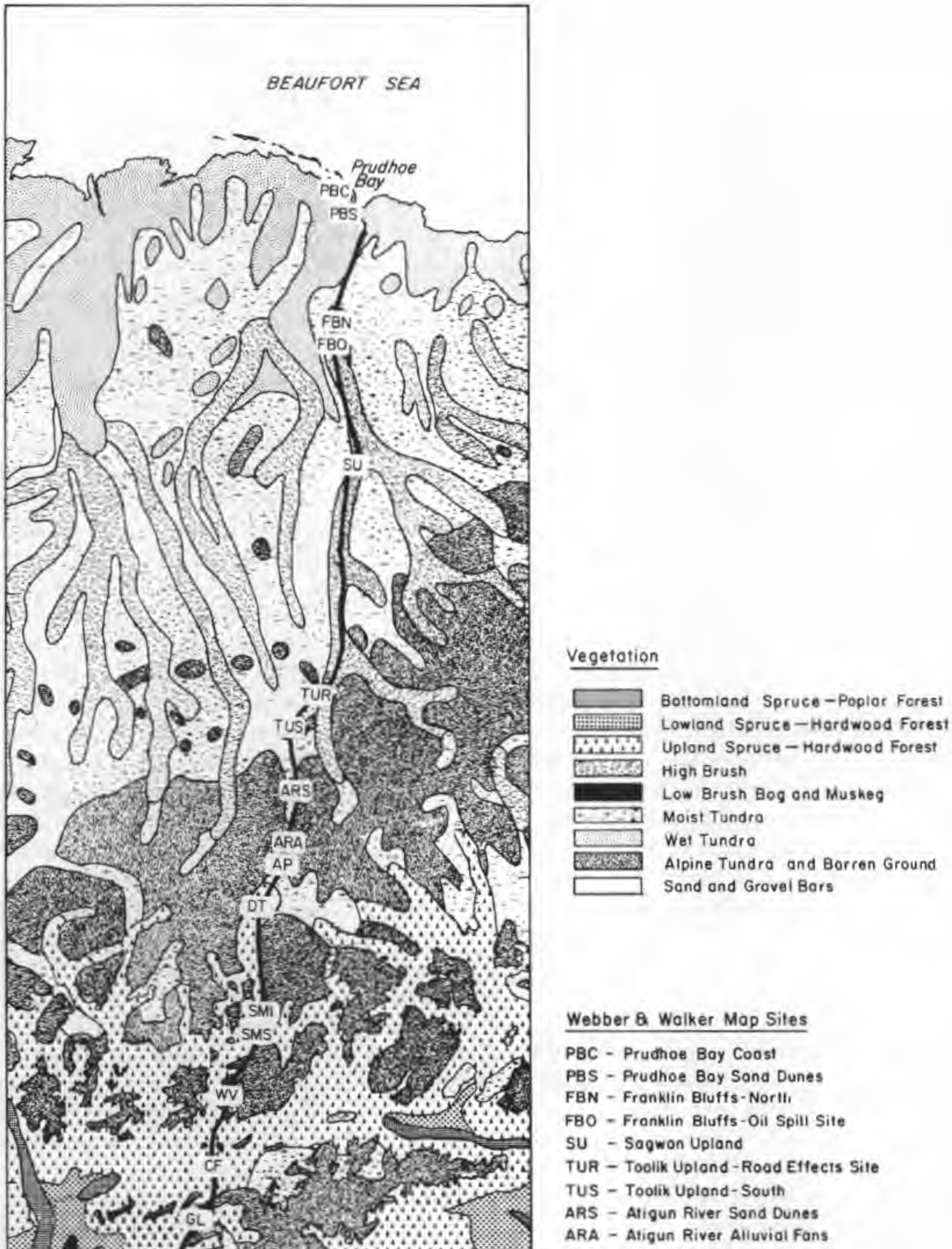


Figure 32. Major vegetation types along the Haul Road (modified from University of Alaska 1975) and locations of the 21 map sites (see Fig. 35).

plants such as horsetails, bluegrasses, and fireweed. The high brush community, found in areas that have not been disturbed for several decades, includes willows, a few herbs, many mosses and lichens, and possibly alder. A few well-developed stands of balsam poplar occur near springs in the southern foothills of the Brooks Range. High brush community occurs along the floodplains of many large rivers of the Arctic, particularly in the mountains and foothills where the active layer is deeper than in the rest of the area. Thickets of dwarf birches, alders, and willows are found near treeline and represent a transition between upland spruce-hardwood forest and alpine tundra. These thickets may be interspersed with lichens, low dwarf shrubs or alpine tundra. Crowberry (*Empetrum nigrum*), Labrador tea, Spirea (*Spiraea beauverdiana*) and blueberries occur in the understory.

Low brush bogs are patterned into ridges and depressions. Some areas contain nearly continuous stands of low brush, while others are characterized by a nearly uniform cover of sedges and moss. Bog surfaces which have elevated, meandering ridges are called strangmors. Bog vegetation consists of varying amounts of sedges, bog mosses and others, cranberry (*Vaccinium oxycoccus*), bog rosemary (*Andromeda polifolia*), dwarf birches, Labrador teas, willows, buffalo berry and blueberries. Some low-lying saturated soils support tussocks (*Eriophorum vaginatum*) and these areas are surrounded by zones of tall willows and alders. Widely spaced dwarf spruce may occur on higher ground. Muskegs and bogs occur where conditions are too wet for tree growth, primarily in unglaciated areas, old river terraces, outwash plains, filling ponds, sloughs, and occasionally on gentle north-facing slopes.

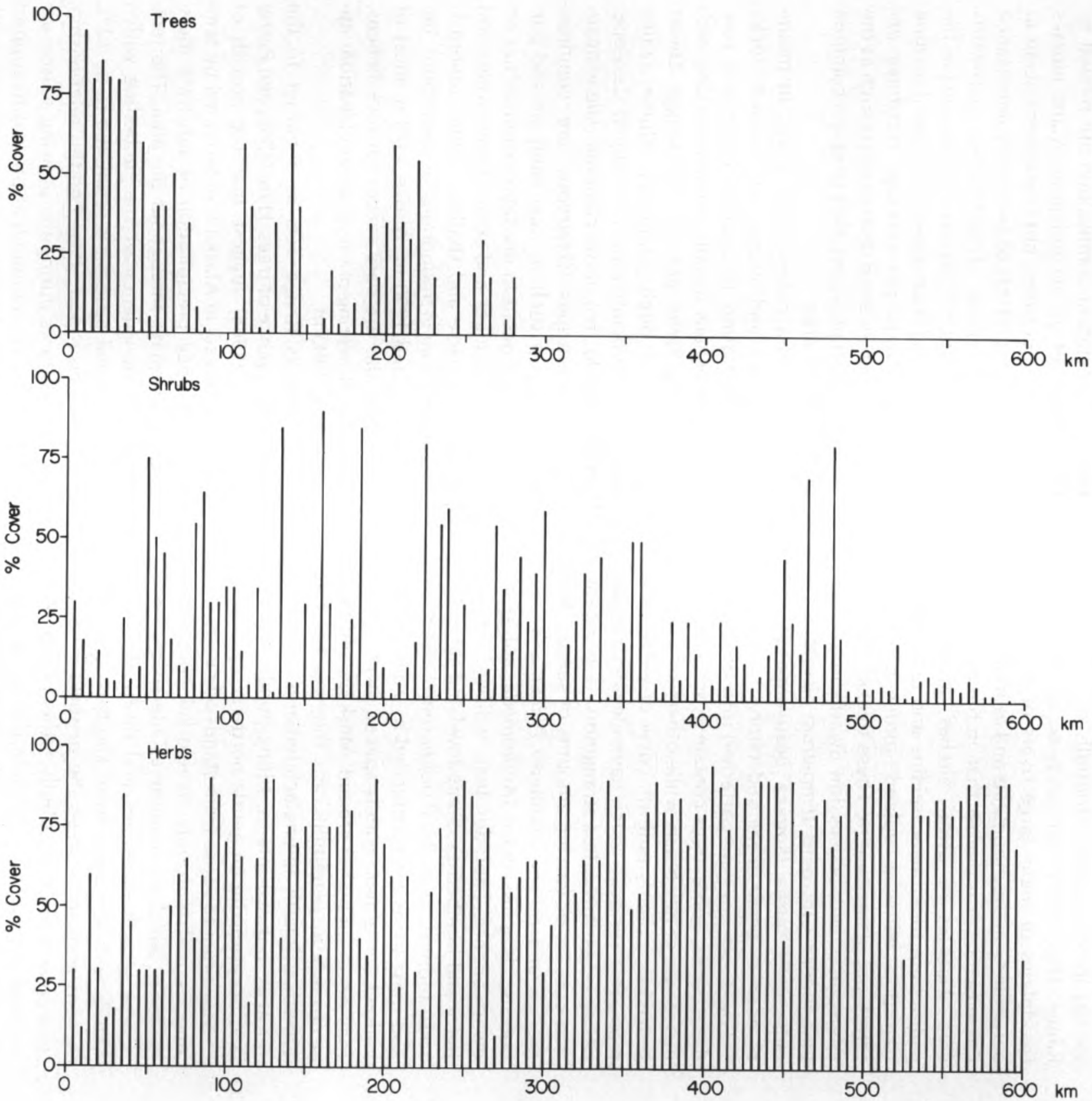
Moist tundra varies from stands on nearly continuous and uniformly developed cottongrass tussocks, which are sometimes interspersed with sparse growth of sedges and dwarf shrubs, to stands with dominant dwarf shrubs. Mosses and lichens grow in between the tussocks. Frost action creates small frost boils. Other plants in the cottongrass meadows include dwarf birch, willows, Labrador tea, bistort (*Polygonum bistorta*), blueberries, and cloudberry (*Rubus chamaemorus*). Moist tundra is the dominant plant community of the foothills. It is dissected locally by river drainages. Cottongrass tussocks, 15 to 25 cm high, cover large areas of rolling terrain on moderately drained, residual silt or peat accumulations modified by frost action.

Wet tundra consists of an almost continuous cover of grasses and sedges rooted in mosses and lichens. On slightly raised ridges dwarf shrubs may be found, while in standing water, rooted aquatic plants such as mares' tails (*Hippuris vulgaris*) occur. Sedges are common. Differences in vegetation composition are related to the microrelief of the polygons. Many mosses grow in the understory, but few lichens occur in this wet habitat. Plants of secondary importance include cottongrass (*Eriophorum*), louseworts (*Pedicularis*) and buttercups (*Ranunculus*) in the wetter sites, and four-angled Cassiope (*Cassiope tetragona*) and purple saxifrage (*Saxifraga oppositifolia*) in the raised drier habitats such as the ridges between polygons. Wet tundra is common in the coastal area.

Alpine tundra communities occur in mountainous areas and along well-drained, rocky ridges. Vegetation is usually sparse and low. *Dryas* and lichens usually dominate along with low-growing herbs, grasses, and sedges. Dwarf birches, resin birch, cranberry, alpine azalea (*Loiseleuria procumbens*), four-angled Cassiope, small Labrador tea, moss campion (*Silene acaulis*), and oxytropes (*Oxytropis*), are common. Cushion plants such as moss campion and purple saxifrage occur in dry talus communities on well-drained ridges and scree slopes, where soil is usually coarse and shallow. Alpine tundra is most common in mountains at elevations between 600 and 1250 m. Above 1370 m most of the mountains are bare except for rock lichens, but a few flowering plants grow at elevations approaching 1800 m.

The Brooks Range acts as a barrier to the northern advance of trees. Hare (1950) and Patric and Black (1968) suggest that the growth of northern forests in Alaska is determined by temperature since precipitation or substrate moisture is adequate throughout the area. The temperature equivalency of the timberline within the Haul Road transect is estimated to be 12°C (Haugen, this report). Based on this relationship, air temperatures during the growing season are presumably warm enough at present to support the growth of white spruce in some areas north of the Brooks range such as in the vicinity of Umiat and Happy Valley. Therefore in the absence of the Brooks Range, the treeline would be expected to reach farther north than it presently does.

To further characterize the composition of the Haul Road vegetation, a total of 120 sites se-


Trees
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Shrubs
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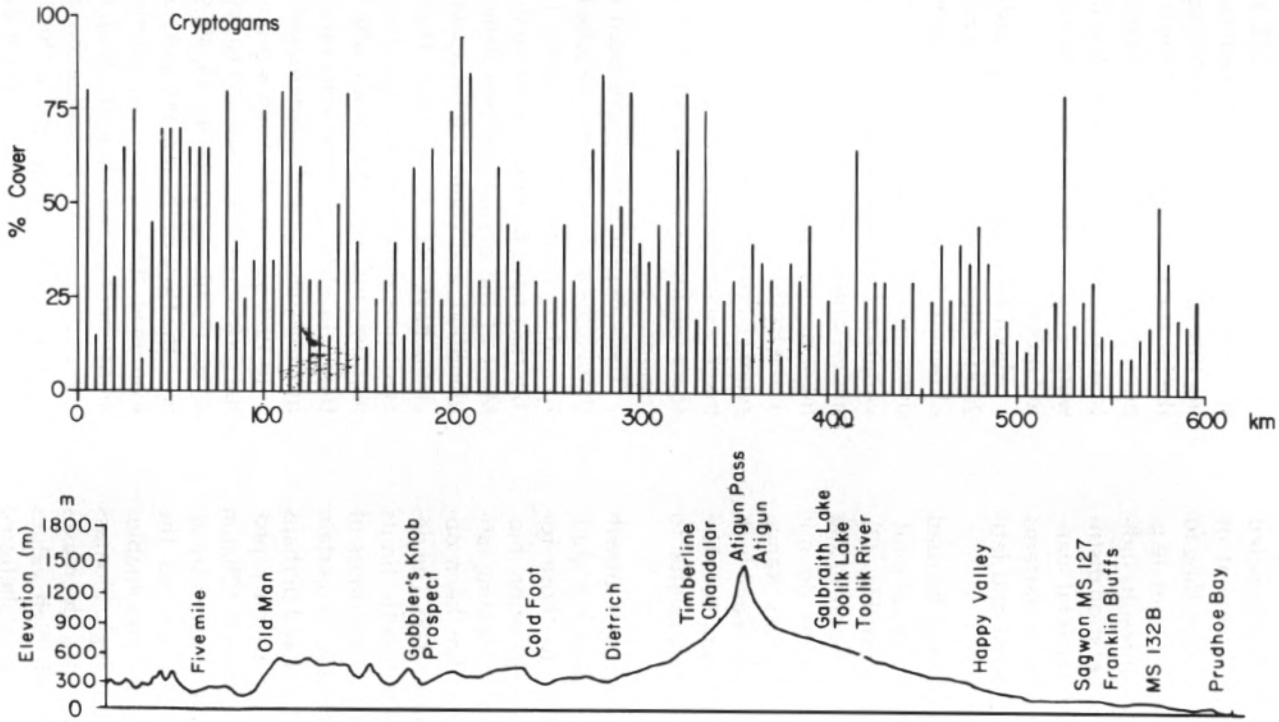


Figure 33. Distribution by percentage cover of major plant growth forms along the Haul Road transect.

lected at approximately 5-km intervals were investigated in the present study. The vegetation sampling method followed the Braun-Blanquet approach to vegetation analysis (Westhoff and van der Maarel 1973). The vegetation sample, or rélevé, consists of a cover estimate for each plant taxon present in a subjectively selected uniform vegetation stand. The environment of each sample site was characterized according to subjective environmental gradient scales (e.g. Loucks 1962). Preliminary analysis of results indicates that patterns of plant and vegetation distribution correlate with the environmental variables measured at each site, and these patterns are related to the complex altitudinal and latitudinal environmental gradients.

The main vegetational changes along the road are illustrated by the distribution of the percentage cover of the major growth forms (Fig. 33). Trees are limited to the forested region in the southern part of the transect. Shrubs do not reach high cover north of the Brooks Range while herbs do. Herbs usually do not reach high cover in the forest and shrub communities. The cover of herbs appears to be inversely related to the cover of cryptogams.

The distributions of biomass for major growth forms (estimated according to subjective gradient scales) shows trends similar to those for cover vegetation. The overall vegetation biomass decreases consistently with increasing latitude and severity of climate; this has been observed by many authors (e.g. Wein 1975). The decrease in solar radiation only indirectly limits vegetation growth. Factors such as shortness of growing season, and the availability of certain nutrients are probably as important and perhaps more important determinants of primary production than is energy input by itself (Chapin 1975). Herbs and cryptogams are favored by increasing climate severity, which removes the stronger competitors (trees, shrubs) and enables herbs and cryptogams to reach high biomass values. The biomass of shrubs also decreases with latitude, and does not reach high values north of the Brooks Range except in sheltered valley sites south of the Coastal Plain, such as at Happy Valley. Shrubs disappear in the vicinity of the ocean. Although the maximum values for herb biomass are found south of the Brooks Range in meadow stands in which trees and shrubs are absent, it reaches high values more consistently north of the Brooks Range and treeline. The biomass of bryophytes and lichens appears to be inversely related to the biomass of herbs, probably as a result of the competition from the herbs.

Floristic survey*

Following a brief reconnaissance of the arctic portion of the Haul Road in 1975, surveys of the flora along its entire length were conducted during July of 1976, 1977, and 1978. Figure 34 shows the locations of our 80 sites. Very little work had been done within the present corridor area prior to road construction, and the few data available were incomplete and from widely separated localities.

About 675 collections of vascular plants and 2000 collections of bryophytes and lichens were obtained. These specimens provide the physical documentation and the materials for analysis of variation for certain taxa which provide a better understanding of their classification. The specimens are now part of the permanent collections at the Herbarium of the University of Alaska Museum, Fairbanks, and duplicates of these have been exchanged with other institutions that share our interest in the flora of arctic and alpine regions.

The vascular plants have been identified, although there are some that require further analysis and verification by specialists. Thus far about 375 taxa have been found along the Haul Road. Most of the bryophytes and lichens have been identified, and about 280 bryophytes and 115 lichens have been determined. There was insufficient time during the surveys to completely collect the crustose lichen flora, which requires patient chiseling of rock substrates, and consequently they are underrepresented in our survey.

In 1976 special attention was paid to the original CRREL road cross-section sites (Table 9; 76-2, 4, 15, 17, 18, 21, 32, 38, 42, 45, 49, 53, 57). Otherwise the flora of the major vegetation types were examined for each of the physiographic divisions encountered along the Haul Road. Table 9 presents a general classification of these sites. Care was taken to examine the floras of very local specialized habitats, since these would be the most likely to support rare and interesting taxa.

One aspect of floristic surveys was to determine the presence of rare plants and if local populations would be extirpated by construction activities. A recent survey of the endangered and

*Prepared by D.F. Murray, B.M. Murray and A.W. Johnson

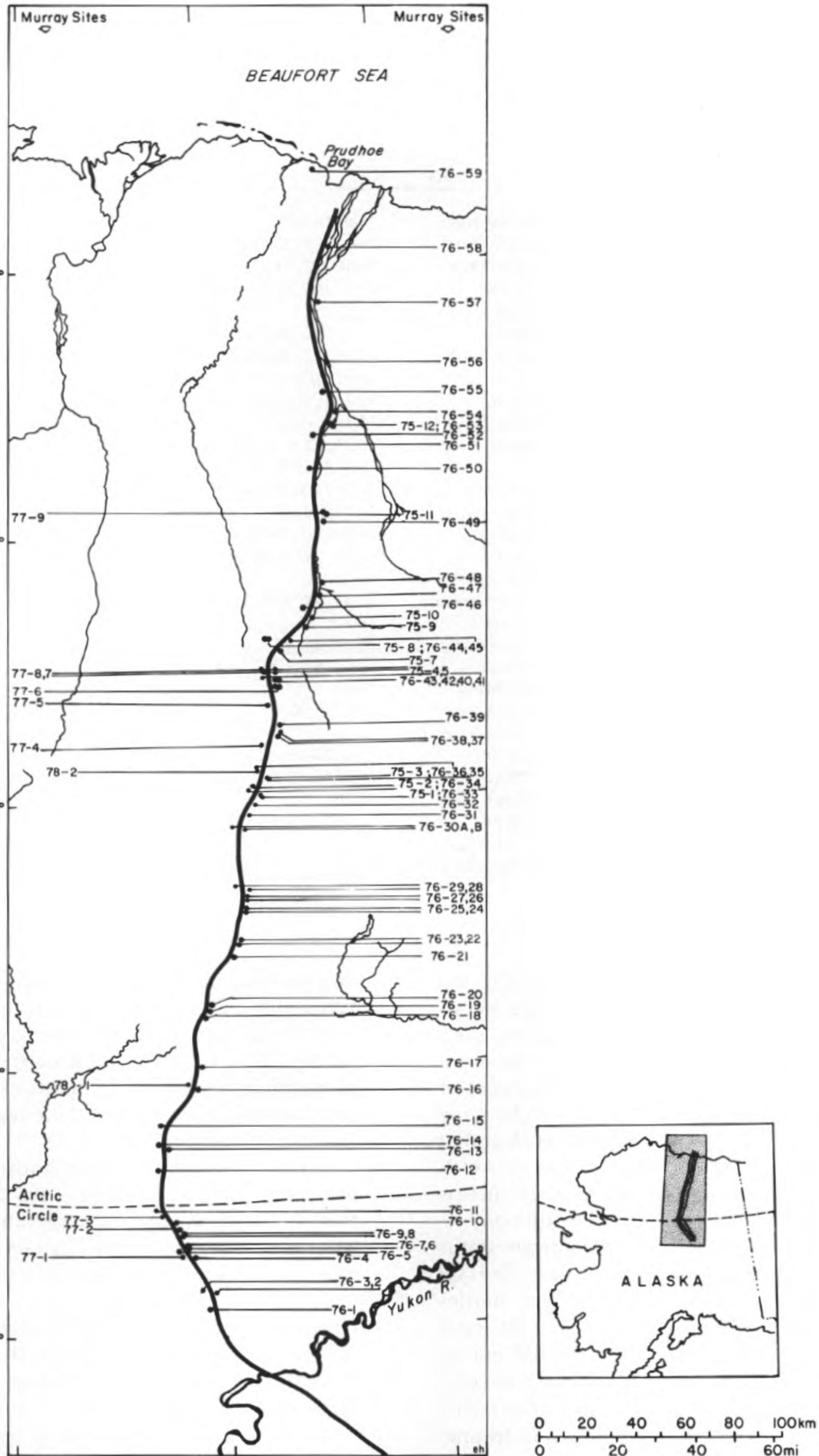


Figure 34. Location of sites investigated during the floristic survey. Number indicates year and location for that year.

Table 9. Vegetation classification of sites. (Site numbers from south to north.)

Physiographic type	*Landscape unit*	*Community*	*Site**
Upland	Forest	White spruce	76-9, 19, 27
		Black spruce	76-2, 3, 4; 78-1; 76-17, 18
		Paper birch	76-10, 12, 14; 78-1
	Thicket	Willow	78-2, 76-37, 77-9, 76-50
		Alder	76-52
	Shrubland	Alder	77-1; 76-5, 6; 77-3
	Tussock	Sedge heath	76-15, 21, 28; 75-2, 4, 5, 6, 7, 9, 10; 76-47, 49; 75-11; 76-52, 53; 75-12, 13
	Meadow	Heath	77-1, 3; 76-13, 32, 39, 44, 45; 75-8
		Sedge	76-1; 77-1, 2; 76-38; 77-5, 6; 76-45, 55, 57
		Mixed	76-36; 77-4; 76-34; 78-2; 76-36, 37, 38, 39, 40, 42, 43; 77-7, 8; 75-8; 76-44, 45, 46, 48; 77-9
		Snowbed	78-2; 75-3; 76-34, 51
		Fen	76-22, 40
	Rocky areas with sparse vegetation	Fellfield	76-7; 78-1; 75-3; 76-34, 35, 43; 77-8; 76-46, 54
		Scree	76-23, 24; 78-2; 76-40, 46
		Outcrops:	
		Conglomerate	76-39, 43; 75-4; 77-7
		Granite	76-7
		Limestone	76-23, 24, 40
Lacustrine	Lake, pond	Aquatic	76-1, 16; 75-8; 76-44, 47
Riverine	Active dune	Shrubland	76-41
	Floodplain	Alluvium with sparse vegetation	76-30A, 50
		Meadow	77-5, 76-56
		Thicket	76-30A
	Bluff	Steppe	76-20
		Meadow	76-48, 77-9, 76-54
		Thicket	77-9
Littoral	Saline meadow	Sedge-grass-forb	76-59

*See Figure 34 for locations of sites.

threatened vascular plants by one of us (D.F.M.) has shown that the majority of these taxa are associated with river terraces, flood plains, sand dunes, rock outcrop. and fellfields. These are the very landscape units that provide sources of fill for road construction used to protect the structural integrity of ice-rich soils.It is clear that compliance with the Endangered Species Act is greatly enhanced when a team of specialists is able to inspect routes prior to construction.

Of the 13 taxa proposed for threatened status in Alaska, four are found along or near the Haul Road. *Aster yukonensis* is known from Bettles and from an undetermined locality "50 miles north of Wiseman." Although we could not locate it, it may likely be found within the corridor. *Montia bostockii* is now known from Toolik Lake (site 76-44), and that population is disjunct from the main range of this species in eastern Interior Alaska and the adjacent Yukon. *Erigeron muirii* is endemic to the Arctic Slope of Alaska and has been found in the exposed gravels of the White Hills unit just north of Sagwon (site 76-54). Since *Thlaspi arcticum* is known from the gravels of the Kuparuk River at Prudhoe Bay, it is likely to be found also on the flood plains of rivers on the Coastal Plain and Foothills regions of the Haul Road corridor.

A fundamental result of the floristic inventory presented here is a baseline characterization of floristic diversity for the vegetation of both widespread and restricted habitats. This knowledge can be applied to the study of vegetation units and to the assessment of change in plant cover, particularly to the subtle changes that occur over relatively long periods of time due to chronic low intensity perturbations. Any assessment of impact by changes through development requires that the natural conditions be known. Floristics is essentially the evaluation of diversity, and from this study some interesting points have emerged.

In the Interior, uplands with only modest topographic relief support taiga in its various forms. The forest sites yielded about 24 to 50 plant taxa at each, showing that the vegetation as well as the flora can be generalized with a high degree of fidelity to the actual situation. Similarly, the extensive tussock tundra of the Arctic Foothills had a range of 13 to 60 taxa at the sites we examined, and the primary taxa are highly predictable. In the mountains where there is such a large altitudinal range and various habitats, the flora diversity is much larger. At the Brooks Range sites visited in 1976, for example, we found 246 taxa; 207 of these were found on three traverses (sites 78-2; 76-40; and 76-43, 77-7, 77-8). Two of these sites are adjacent, separated by the Atigun River and Canyon, yet they share only 58% of their vascular flora. Data on the bryophytes and lichens show similar results. What this difference in floras reflects is the effect of differing lithologies at the two sites, one predominantly of conglomerates, the other of limestones. A comparable difference exists between sites on the Coastal Plain where one is calcareous and the other of an acid soil type. Given a consideration of the total flora for each of the physiographic divisions, then within-division variability (site to site) is greater than what is seen between divisions. This diversity should argue for caution when attempting to generalize landscape units, vegetation, and floras.

The Haul Road is, of course, an outstanding latitudinal transect, along which can be traced the successive disappearance of the conspicuous trees and shrubs. These northern limits are valid only for this particular transect, but we doubt that the relative position of these limits for specific taxa will vary a great deal. Therefore, the transect is a natural laboratory for developing biogeographic generalizations on northern limits and natural zonation and for acquiring data as a basis for paleoecological reconstructions for times in the past when these zones were thought to have shifted in response to climatic changes.

Several taxa were found that significantly extend their known ranges. Species common in the taiga south of the Brooks Range that have since been found on dry bluffs and terraces formed by the Sagavanirktok River include *Carex aurea*, *C. concinna*, *Galium boreale*, and *Linnaea borealis*. Several alpine species were found disjunct from previously known populations, and these will help to refine our distribution maps for *Arenaria chamissonis*, *Carex albonigra*, *Draba cana*, *D. macounii*, *Erigeron grandiflorus*, *Koenigia islandica*, *Oxytropis scammaniana*, and *Stellaria umbellata*. On the basis of material obtained, taxonomic reevaluations of *Claytonia arctica* and *Erigeron purpuratus* are in progress, and it is planned to obtain the chromosome number for *Montia bostockii*, needed to clarify its taxonomic position and relationship to the Asian *M. vassilievii*.

The most significant floristic records of bryophytes and lichens are listed in Table 10, which includes taxa new to science (recently described and based in part on Haul Road material or still under study and undescribed), new to North America or Alaska, or additional collections of very rare plants in Alaska. Details as to these records can be found in our Herbarium collections, and many of our records are cited in Steere (1978) and Steere and Inoue (1978). Several of the most interesting cryptogams are part of an assemblage of rare mosses and lichens found on limestone, especially irrigated cliffs, in the Brooks Range at sites 76-23, 24, and 40. Since the Haul Road makes these special limestone sites so accessible, they are vulnerable. At site 76-40, which is near Galbraith Camp and Pump Station 4, there are already signs of destruction—initials carved in a large mat of the recently described rare moss, *Andreaeobryum macrosporum*.

Vegetation mapping*

Detailed vegetation maps are an essential component of an in-depth vegetation survey and are important for a wide variety of ecosystem studies. Broad classification schemes for the vegetation and habitats along the entire corridor from the Yukon River to Prudhoe Bay have been prepared by the Joint Federal/State Fish and Wildlife Advisory Team (manuscript maps), but more detailed maps are desirable to adequately portray the spectrum of vegetation communities.

In this study 21 maps (scale 1:6,000) of representative locations (Fig. 32) were prepared. This large-scale mapping program produces two types of maps: a master map and a vegetation map. The master map contains vegetation, landform, microrelief, and slope information similar to maps produced for the Prudhoe Bay region (Everett et al. 1978, Walker et al. 1980). The site illustrated is the No Name Creek test site, a

*Prepared by D.A. Walker and P.J. Webber

Table 10. New and interesting bryophytes and lichens.

Hepatics
**Cryptocolea imbricata* (76-45)
Fossombronia alaskana (76-11)
**Jungermannia pumila* (76-30B)
Mosses
**Amblyodon dealbatus* (76-22)
Andreaeobryum macrosporum (76-23, 24, 40)
**Barbula amplexifolia* (=*B. coreensis*) (76-24, 40)
****Barbula convoluta* (new variety (76-40)
**Bryoerythrophyllum ferruginascens* (76-24, 40, 46; 77-7)
Coscinodon calyptratus (77-7)
Coscinodon cribosus (76-46)
**Didymodon fallax* (=*Barbula fallax*) (76-24)
Didymodon rigidicaulis (= *Barbula reflexa*) (76-40)
**Didymodon subandreaeoides* (= *Barbula andreaeoides*) (76-23, 24)
Didymodon vinealis (=*Barbula vinealis*) (77-5)
***Encalypta brevipes* (75-4)
***Encalypta mutica* (76-30B)
****Garysmithia bifurcata* Steere (76-43)
Mielichhoferia macrocarpa (76-40)
Mielichhoferia mielichhoferi (76-46)
Oreas martiana (76-40)
**Orthothecium diminutivum* (76-40)
Paraleucobryum enerve (77-7)
Pogonatum urnigerum (76-46, 54)
Pohlia elongata (76-36)
Schistidium agassizii (76-44)
**Schistidium apocarpum* var. *pulvinatum* (76-43)
Schistidium holmenianum (76-40, 77-7)
Sphagnum orientale (=*S. perfoliatum*) (76-5)
****Tortella* new species (76-30B)
**Trichostomum crispulum* (76-23, 41)
Lichens
**Dacampia hookeri* (76-40)
Dermatocarpon rivulorum (76-35, 43)
**Glypholecia scabra* (76-40)
Parmelia multispora (76-26)
****Polyblastia* new species (76-23, 40; 77-7; 78-2)
****Staurothele* new species (78-2)
Stereocaulon apocalypticum (76-10)

* New to Alaska
** New to North America
*** New taxon, recently described or still undescribed.

ground view of which is shown in Figure 18. The vegetation map (Fig. 35) is derived from the vegetation portion of the master map code. In forested areas the vegetation codes include dominant tree taxa, size and density of trees, and the understory communities. The vegetation communities portrayed on the master maps are considered unique to a particular map, so that no two maps have the same code, even though some communities may be very similar. In the vegetation map the names of the individual communities consist of three parts: 1) a site moisture category, 2) a series of representative plant taxa in the community, and 3) physiognomic categories following as closely as possible systems already in use, i.e. those of Viereck (1975), Viereck and Dyrness (1980), Fosberg (1967), and UNESCO (1973). The vegetation maps have patterns that are based primarily on the physiognomic categories. In forested areas the pattern portrays the overstory; the understory is represented by an overprinted letter code. Master maps and vegetation maps are planned for publication as a separate CRREL report along with aerial photos, brief site descriptions, and photographs of the various vegetation units.

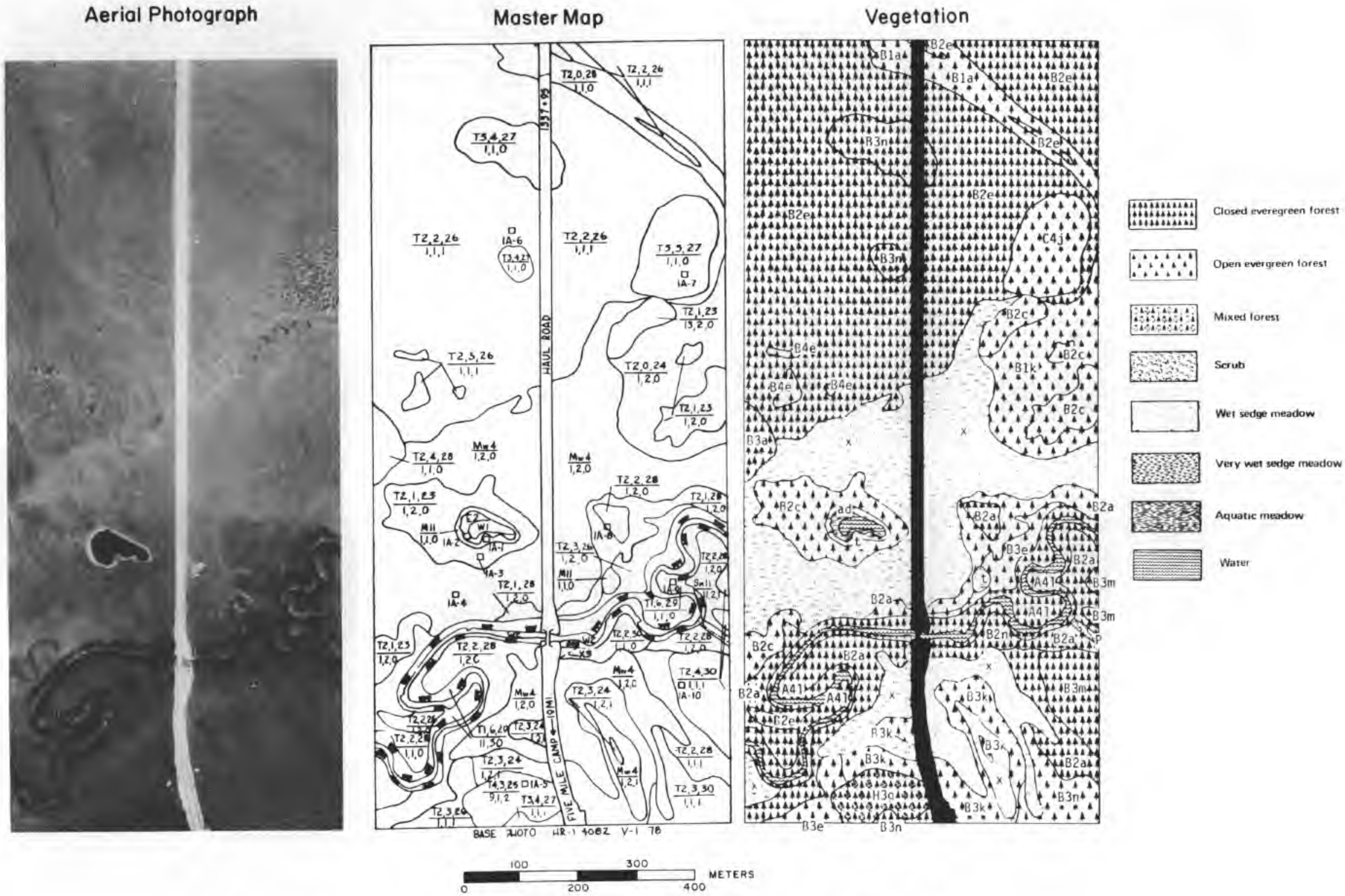


Figure 35. Aerial photograph, master map, and vegetation of site at No Name Creek.

The vegetation maps which have been constructed will be a valuable reference for future monitoring along the pipeline corridor. For example, one report has been published which used information from one of the master maps (Franklin Bluffs oil spill sites, see Fig. 32 for location) to construct an oil spill sensitivity map (Walker et al. 1978).

Soils and mapping*

The soils encountered along the road have developed under a cold temperature regime in which biological and chemical transformations are slow, and in which soil horizons, the results of these processes, are subject to physical dislocation as a result of freeze-thaw processes.

The distribution of the principal soil associations encountered along the road transect is presented in Figure 36 along with their associated landforms and textures. The seven areas mapped under the Army Research Office (ARO) sponsorship are also shown on this map. As an example, the No Name site soil map and idealized soil sections are presented in Figures 37 and 38. Figure 35 contains the vegetation maps for the same site.

South of the Continental Divide, organic horizons are thick and the active layer deeper but still generally less than 75 cm. On well-drained, gravelly sites soils occur with well-developed horizons and thick active layers. North of the Continental Divide, permafrost, at depths generally less than 50 cm, acts to retard internal drainage. Thus, as a consequence of the low temperatures and poor drainage, most soils exhibit wet, shallow, poorly differentiated profiles with a significant organic component, often little decomposed. Horizons with contorted admixtures of darker, more highly decomposed organic materials are common in the mineral horizons down to and into the permafrost.

Following the Haul Road north from the Yukon River (Fig. 36), the soils of the Kokrine-Hodzana Highlands are for the most part slightly acid to slightly alkaline silt loams. In the southern part of this area, loess is a significant component of the soils which are gray and fine textured. Moderately well-drained soils on slopes are neutral to slightly alkaline in reaction and commonly consist of fine-textured upper horizons overlying gravelly or channery subhorizons. Acid, base-poor, gravelly materials derived from granites are common in the uplands and organic soils or mineral soils with thick organic horizons occur in the tussock meadows associated with drainage (see Figs. 37 and 38).

In the northern part of the Kokrine-Hodzana Highlands, soil associations composed of poorly drained, gray mineral soils with thin organic horizons and poorly-drained soils with thick, acid, little decomposed organic horizons occur on spruce-covered lower slopes. Broad valley bottoms are commonly occupied by sedge or sedge-tussock meadows and have organic soils or very poorly drained mineral soils with thick organic horizons. Gravel terraces and gravel-covered uplands have deeply thawed, acid soils, some with fine-textured surface horizons (loess) that are leached and oxidized. Thick acid organic soils of peat plateaus are commonly associated with alkaline fen peats.

In mountainous areas below the tree line,mass movement on steep forested slopes produces complexes of poorly drained, gray mottled silt loam, gravelly textured acid soils with relatively thin organic horizons and similar poorly drained soils with thick organic horizons. Seasonal thaw is generally less than 50 cm except on crest areas and gravelly terraces where deep thawing of well-drained soils occurs along with oxidized horizons.

In the higher parts of the Brooks Range most of the area consists of steep, exposed bedrock and coarse, unstable colluvial deposits with inclusions of poorly drained or very poorly drained gravelly and stony soils, some with a significant organic component. Stable, relatively well-drained glacial and colluvial deposits have gravelly soils with dark, leached upper horizons and reddish, iron-stained subhorizons.

The majority of the soils of the Arctic Foothills are poorly drained and have developed on fine-textured materials, silt loams and silty clay loams. Poorly drained soils occur on long slopes and in broad valleys. These tundra soils are found under a tussock microtopography and most are acid. A few moderately well-drained and well-drained gravelly soils occur on ridges and on terraces marginal to the larger rivers. Organic soils are uncommon but occur in old, polygonized, drained lake basins.

On the Arctic Coastal Plain the soils are poorly drained and generally do not thaw to depths

*Prepared by K.R. Everett

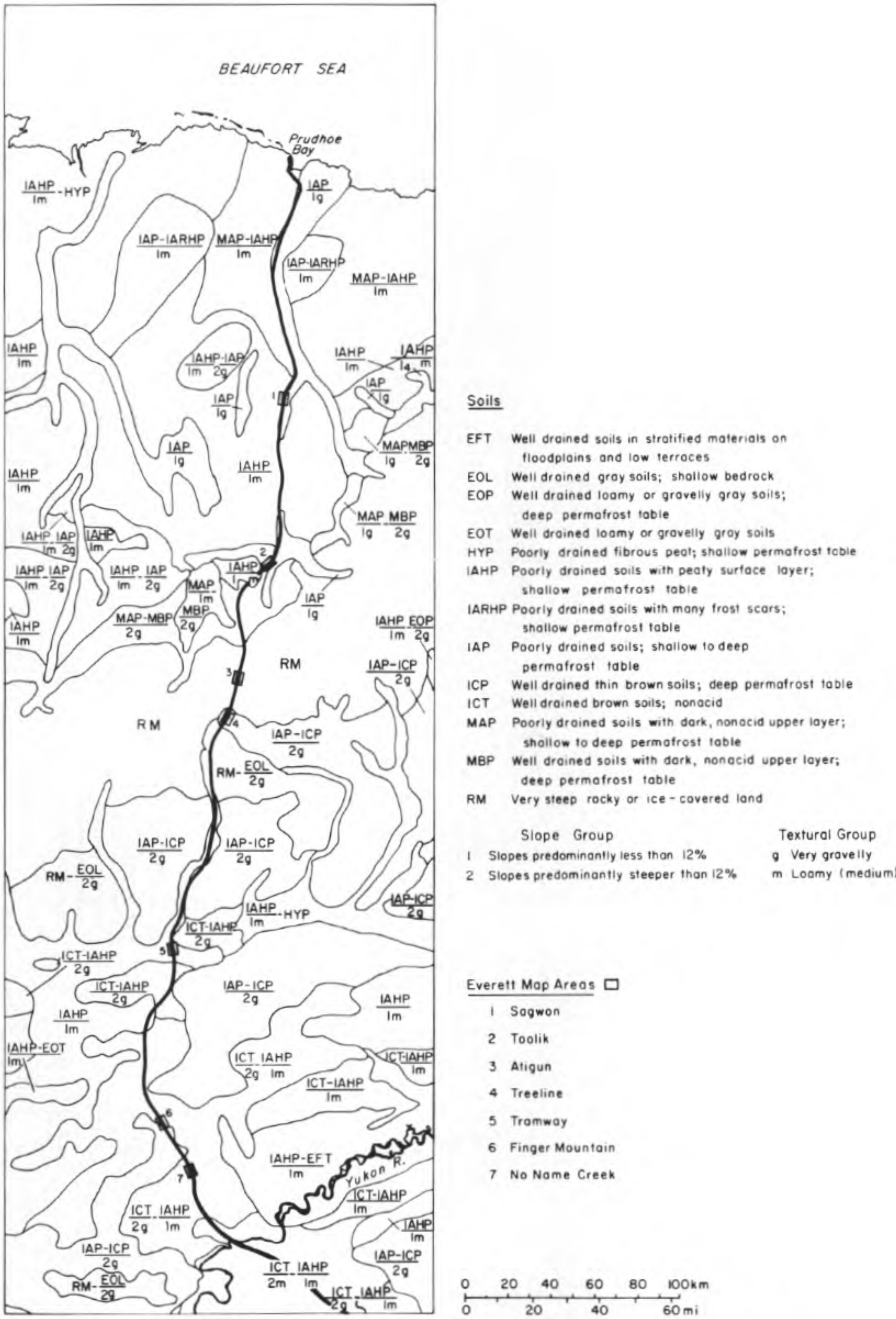
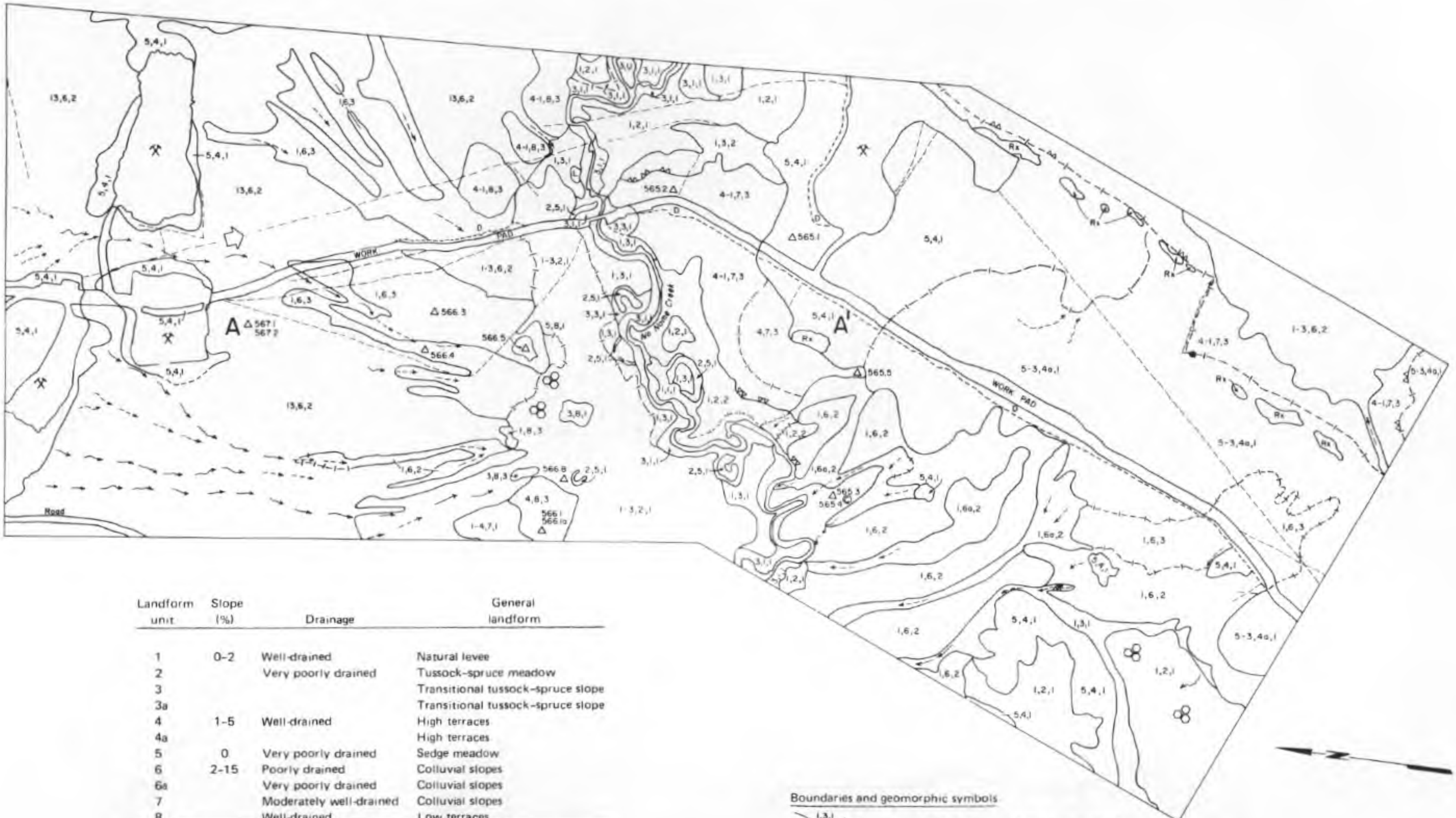


Figure 36. Soils of the Haul road region (modified from University of Alaska 1975).



Landform unit	Slope (%)	Drainage	General landform
1	0–2	Well-drained	Natural levee
2		Very poorly drained	Tussock-spruce meadow
3			Transitional tussock-spruce slope
3a			Transitional tussock-spruce slope
4	1–5	Well-drained	High terraces
4a			High terraces
5	0	Very poorly drained	Sedge meadow
6	2–15	Poorly drained	Colluvial slopes
6a		Very poorly drained	Colluvial slopes
7		Moderately well-drained	Colluvial slopes
8		Well-drained	Low terraces

Slope (°)
1. 0 to 2
2. >2 to 6
3. >6 to 12
4. >12 to 24
5. >24 to 26

Soils
1. Histic Pergelic Cryaquepts
2. Pergelic Cryofibrists
3. Pergelic Cryaquepts
4. Pergelic Cryochrepts
5. Pergelic Cryorthents

Boundaries and geomorphic symbols

1,3,1 / 2-1,6,2 Map code: soil, landform and slope, respectively; 8,4,1 dashed line indicates probable soil boundary.

Established drainage

Rx Unconsolidated gravels exposed

Area of large diameter ice wedge polygons.

Slopes in excess of 26%.

A, A' Line of profile (Fig. 38).

Cultural symbols and special spot symbols

Pipeline workpad. D indicates disturbance. Access road to material site.

Material site.

©△566.9 Soil profile location. C denotes radiocarbon date.

Winter trails.

Figure 37. Soil–landform map of the No Name Creek site, mile 21.2-23.0, Haul Road, September 1978.

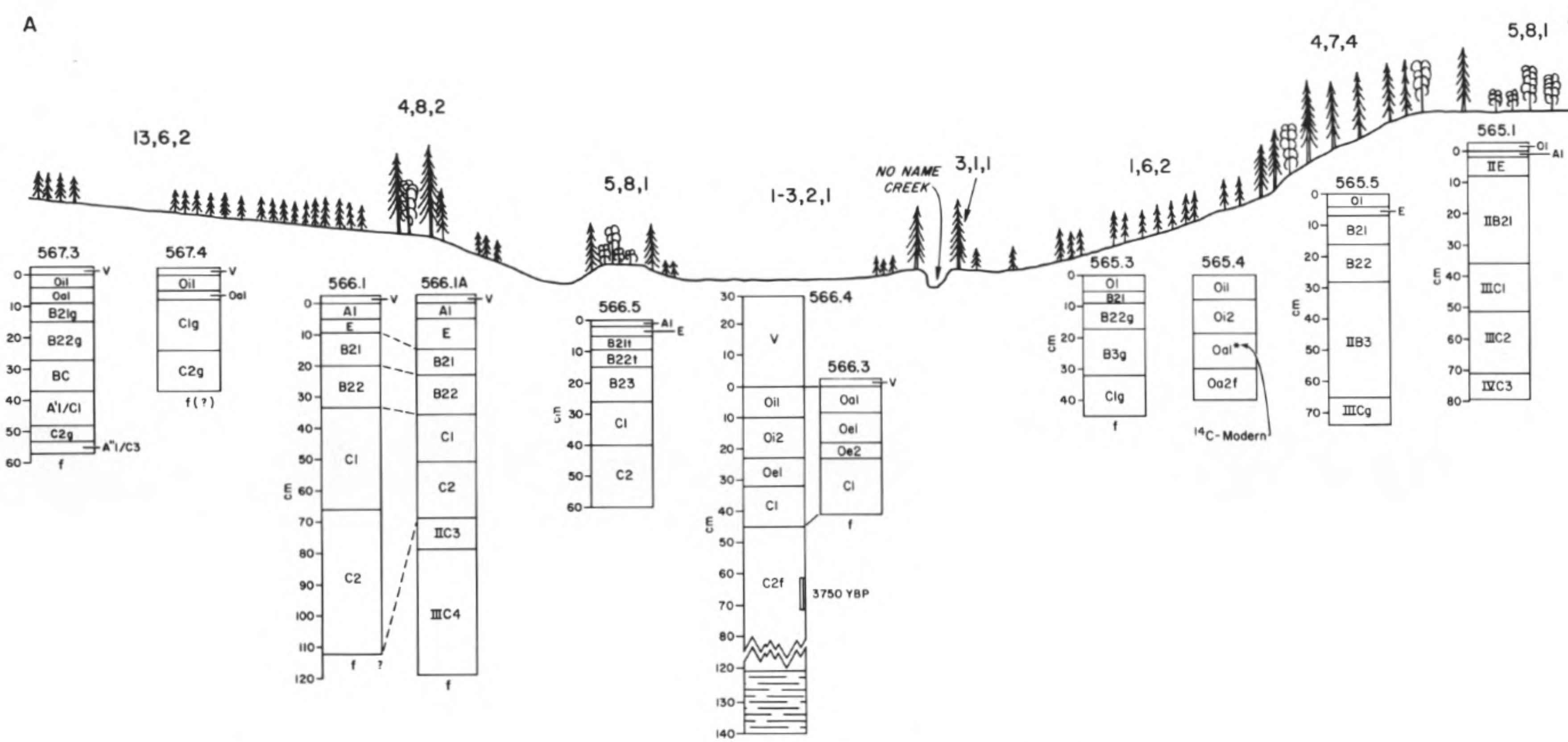


Figure 38. Idealized section projected along line A-A' in Figure 37 showing relationship among soils, vegetation and the principal landforms. Soil–landform unit designation (Fig. 37) appears above the section. Horizontal distance is approximately 2.7 km. Maximum relief is approximately 100 m.

of more than 50 cm. In most soils, organic materials of variable thickness overlie silt-loam-textured mineral horizons. A few soils, especially those in depressions, may exhibit a sufficient thickness of organic materials (peat) to be termed organic soils; other soils restricted to well-drained sites display well-developed horizons and bright oxidation colors. Most soils are alkaline and most have free calcium carbonate in their profiles.

CHAPTER 2. ROAD PERFORMANCE AND ASSOCIATED INVESTIGATIONS

by R.L. Berg

Roadbed investigations

Road design

According to Linell (1960), three basic design methods for roads and airfields on permafrost are available: 1) designing for reduced subgrade strength during the thawing season and accepting whatever roughness may occur from differential thaw settlement and seasonal frost heave, 2) limiting subgrade frost (thaw) penetration to control surface roughness caused by seasonal thawing and freezing and 3) completely protecting against thaw settlement and frost heave. Both methods 1 and 2 allow thaw penetration into the subgrade but method 2 generally requires greater embankment thicknesses and therefore is usually used only for paved high-speed airport runways. Therefore roadway embankments in permafrost areas are usually designed by methods 1 or 3 (Fig. 39).

The embankment thickness and thermal conditions resulting from reduced subgrade strength designs (method 1) cause a lowering of the permafrost table beneath the road (Fig. 39a). Since the permafrost often contains large variations in ice content in both the vertical and horizontal directions, differential settlements frequently occur. Fine-grained materials with a high ice content in the frozen state have low dry densities and high water contents when thawed resulting in low bearing capacities and low shearing strengths. These materials, which exhibit the most differential settlement, are termed thaw-unstable soils. Designs for complete protection (method 3 shown in Fig. 39b and 39c) cause the permafrost table to rise because the roadway thickness and thermal conditions do not permit seasonal thawing to penetrate the embankment. Figure 39c illustrates a recent adaptation of method 3, in which a combination of gravel fill and thermal insulation is used to control the depth of seasonal thawing (McDougall 1977).

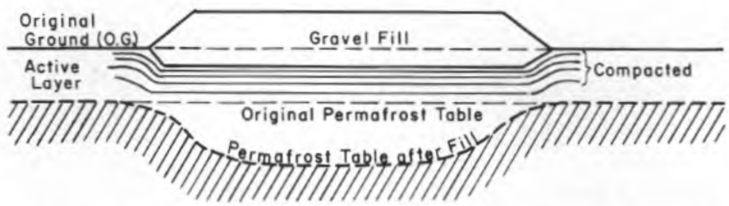
In method 1, the minimum gravel embankment thickness that will support the design traffic without excessive load-induced maintenance is determined from the strength of the thawed active layer.

In method 3, the embankment thickness, and insulation thickness if used, are determined from a thermal analysis. Since the original active layer will remain frozen, its bearing capacity will generally be sufficient to carry the imposed loads, but, when an insulating layer is used,the minimum thickness of gravel over it is determined by structural analysis. This design procedure provides a stable roadbed free from differential thaw subsidence. However, a problem which may result from the raised permafrost table is blockage of lateral drainage through the active layer.

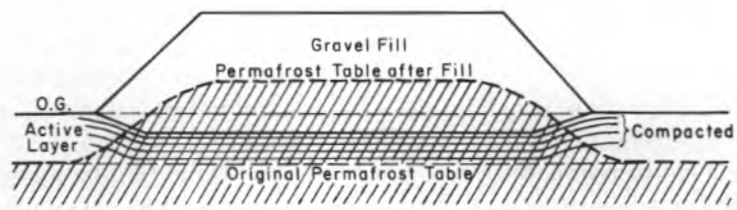
Generally uninsulated roadway embankments on warm permafrost are designed using method 1. Where permafrost temperatures are within a few degrees of the melting point of ice, gravel embankment thicknesses on the order of 5 to 7 m would frequently be necessary if method 3 is used. Esch (1973) and Esch and Rhode (1976) discuss two projects in the Subarctic where method 3 was used by incorporating insulating layers. The Research Group on Experimental Roadbed Research (1979) describes using method 3 incorporating insulating layers in a test road located in an alpine permafrost area in China.

In the Arctic, permafrost temperatures are much colder and thawing indexes are much lower than in subarctic areas and method 3 designs have been used more often (Knight and Condo 1971, Condo et al. 1971, Johnston and Penner 1974, Popov et al. 1978, and Crory et al. 1978).

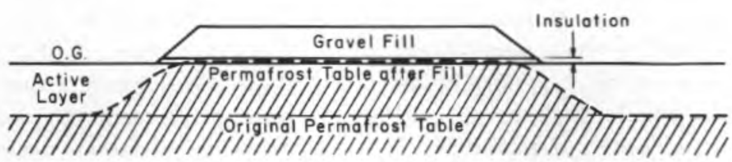
Two design procedures were used to determine the embankment thickness for the Haul Road. Over competent subgrade materials, defined by the Alyeska Pipeline Service Company as soils having a California Bearing Ratio (CBR) greater than 3 when thawed, the embank-



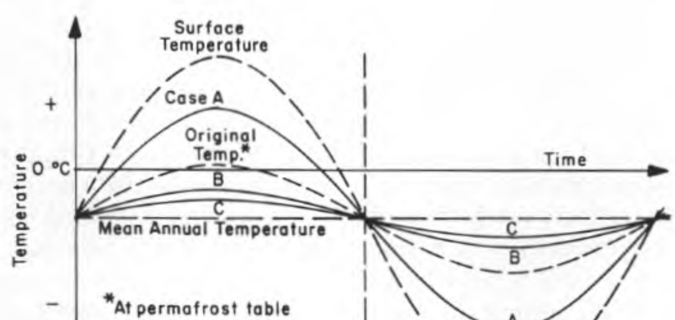
a. Effect on permafrost table if insulating effect of fill plus compacted active layer is less than the insulating effects of original active layer (from Ferrians et al. 1969), an example of design method 1.



b. Effect on permafrost table if insulating effect of fill and active layer is greater than the insulating effect of the original active layer (from Ferrians et al. 1969), an example of design method 3.



c. Effect on permafrost table if insulating effect of fill, insulation and active layer is greater than the insulating effect of the original active layer (from McDougall 1977), an example of design method 3.



d. Effects of cases a, b, and c on amplitude of seasonal temperature variation at original permafrost table (modified from Ferrians et al. 1969).

Figure 39. Effect of gravel fill and insulating layers upon thermal regime.

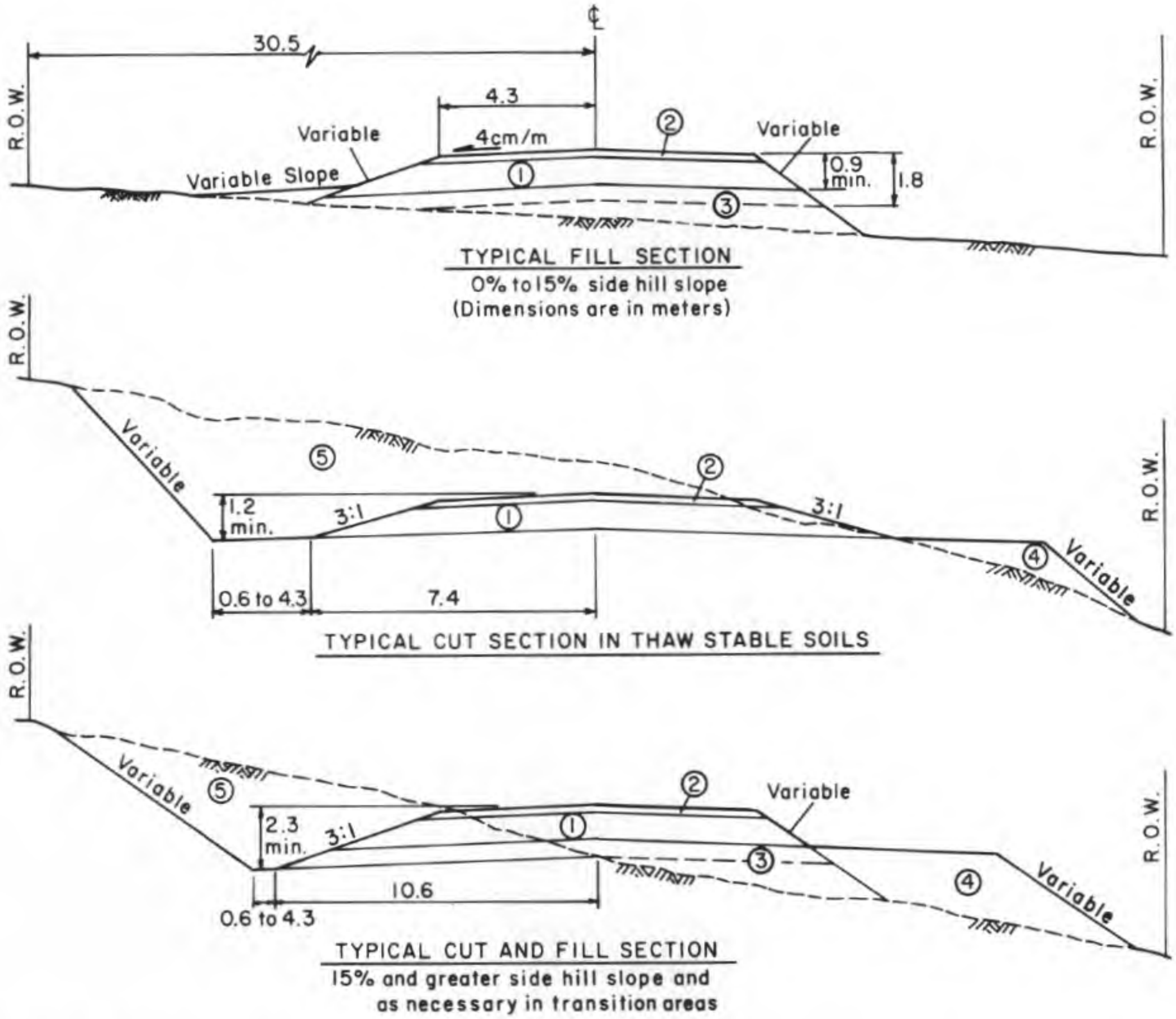


Figure 40. Typical Haul Road cross sections (Alyeska Pipeline Service Company 1971), with 1) select material (borrow excavation — common); 2) 15-cm surface course; 3) borrow excavation (common), borrow excavation (rock), suitable unclassified excavation or rock excavation; 4) available waste disposal area (maximum elevation not to exceed bottom of select material); 5) unclassified excavation and/or rock excavation.

ment was a minimum of 0.9 m thick. Over incompetent subgrade materials, i.e. soils with a CBR of less than 3 when thawed, the embankment thickness was based on the reduced subgrade strength method (U.S. Army and Air Force 1966) south of the Brooks Range and upon construction experience north of the Brooks Range. These procedures generally resulted in use of method 1 south of the Brooks Range and either method 1 or 3 north of the Brooks Range. In both designs the upper 0.9 m of the embankment typically consisted of a select fill overlain by 15 cm of surface coarse material (Fig. 40).

The Haul Road has two gravel-surfaced traffic lanes, each a minimum of 4.3 m wide, with a cross slope on each lane of 4.2 cm/m (Fig. 40). The design speed is about 70 km/hr. Longitudinal grades are generally less than 8%, but grades up to 12% were allowed in mountainous terrain. The design vehicle was a semi-trailer combination with tandem axles on the tractor and trailer and a total overall length of 16.8 m (Alyeska Pipeline Service Company 1971). Technical specifications for the select fill and surface course material are as follows (Alyeska Pipeline Service Company 1971):

Embankment construction shall consist of constructing roadway embankments, ramps for road, turnarounds, storage lanes and trail crossing, and includes preparation of areas upon which embankments are to be placed, the placing and compacting of approved material in areas where unsuitable material has been removed.

Only approved materials shall be used in the construction of embankments. The material in the top three (3) feet [1 m] of the embankment shall be select material and shall have a plasticity index not greater than 6 as determined by AASHO Method T 90 and a liquid limit not greater than 25 as determined by AASHO Method T 89. The material shall not contain more than 18 percent by weight of particles that pass the No. 200 sieve as determined by Alaska Test Method T 7. The percent of minus No. 200 will be determined on the basis of samples which will pass the 3-inch [7.6 cm] sieve.

Excavated material from roadway cut sections and rock excavation shall be used in the lower portions of embankments with the general provision that such materials are compactible to 90 percent of maximum density as determined by AASHO Method T 99. Silty soil encountered in excavation with a natural moisture content in excess of 5 percent above the optimum moisture as determined by AASHO T 90 shall be wasted unless otherwise directed by the Engineer.

The surface course consists of one course of aggregate with binder placed on a prepared surface in reasonably close conformity with the lines, thickness and cross sections shown on the Drawings or established by the Engineer. Sections of road requiring surface corse shall be as shown on the Drawings or designated by the Engineer. The material shall be obtained from offsite sources to be provided by the Owners.

Material for the surface course shall be pit run gravel (or such other material as may be available and approved by the Engineer) consisting of hard durable particles of gravel, relatively free from soft thin elongated or laminated pieces and vegetable matter or other deleterious substances. The material shall be as designated by the Engineer.

The surface course shall be compacted to a density of at least 90 percent pf maximum density as determined by AASHO Method T 99.

To define where each design method was applicable, Alyeska engineers used actual field observations from performance of existing roads and airfields in the project area, soil maps, disturbed and undisturbed soil samples for laboratory analysis, and cone penetrometer observations made late in the thaw season. Laboratory and field correlations of soil type, moisture content, dry density, cone penetrometer readings and CBR values provided the mechanism for differentiating between competent and incompetent subgrades. Alyeska's studies concluded that generally a cone index of about 80 was equivalent to a CBR of 3. At a particular location, the "design" cone index was usually an average of observations made at 15-cm intervals within the thawed zone. The cone index was also used for construction planning, and whenever an average value less than 160 was obtained, the soils were considered too weak for machine clearing during the thaw season (McPhail et al 1975).

Table 11. Design thickness of Haul Road (Alyeska Pipeline Service Company 1971).

	Design thickness			*Length designed for*			
	Incomp. soils	*Comp. soils*	*Total length*	*Incomp. soils*		*Comp. soils*	
Segment	*(m)*	*(m)*	*(km)*	*(km)*	*(%)*	*(km)*	*(%)*
1	1.8	0.9	94.5	52.3	55	42.2	45
2	1.8	0.9	72.6	44.3	61	28.3	39
3	1.7	0.9	90.9	52.8	58	38.1	42
4	1.5	0.9	48.6	10.6	22	38.0	78
5	1.5	0.9	46.5	26.9	58	19.6	42
6-S	1.5	0.9	64.5	45.2	70	19.3	30
6-N	1.5	0.9	62.0	49.7	80	12.2	20
7	1.5	0.9	97.4	88.5	91	8.9	9
		Total	577.0	370.3	64	206.6	36

Table 11 presents design thickness for competent and incompetent subgrades and the lengths of each per segment. Incompetent subgrade soil conditions were encountered beneath more than 60% of the road, indicating that high ice content subgrade soils predominated.

The design thickness over competent soils, 0.9 m, is less than the seasonal thaw penetration depth over the entire length of the road, except for occasional, extremely cool summers. However, since the competent soils have a CBR of 3 or greater when thawed, they will generally have relatively high densities and low moisture contents and will therefore not subside as much as ice-rich soils. On southern portions of the road, seasonal thaw will penetrate the original permafrost table more deeply than in the northerly sections of the of the road because the thawing index is two to six times larger. As a result more differential thaw subsidence should occur where the road crosses competent soils in the southern sections.

The minimum embankment thickness over incompetent soils was intended to limit the amount of thawing into the underlying permafrost. However, none of the Alyeska Pipeline Service Company documents quantify the magnitude of the limitation. Thermal calculations by

Alyeska indicated that an embankment about 1.9 m thick would contain seasonal thaw during the "average" season near Prospect Creek Camp, and similar computations suggested that an embankment 1.35 m thick would contain the seasonal thaw penetration in segment 7 (Alyeska Pipeline Service Company 1971). Both sets of calculations indicated that the minimum embankment thicknesses recommended by Alyeska were conservative and that seasonal thawing would penetrate embankments over unstable soils only by several centimeters in "warmer than normal" years. As will be discussed subsequently, our measurements indicate considerably more thawing than originally estimated by Alyeska.

Site selection and field procedures

Our principal objectives were to determine the magnitude of thaw under and adjacent to representative portions of the road and to determine the amount of roadway settlement at these same locations. Secondary objectives included a survey of drainage problems associated with the Haul Road and an assessment of the performance of side slopes.

Aerial photographs, field reconnaissance, and information available from soil borings and terrain maps were used to select sites for monitoring thaw penetration. Transects were established across the road and into the adjacent modified or undisturbed areas as well as along the centerline of the road (Berg et al. 1978).

During the period 19 to 24 June 1976, 13 sites were selected by R. Berg, R. Eaton and J. Brown of CRREL and E. Johnson of the Alaska Department of Transportation and Public Facilities (ADOTPF) for the purpose of following thaw penetration under and adjacent to the road. At each site, elevations across the road and along its centerline were determined and referenced to adjacent benchmarks installed approximately every 1.6 km by the National Geodetic Survey and the Alyeska Pipeline Service Company. Descriptions and locations of the benchmarks were assembled and distributed as part of this study (CRREL undated). Depths of thaw adjacent to the road were measured by probing with a thin metal rod.

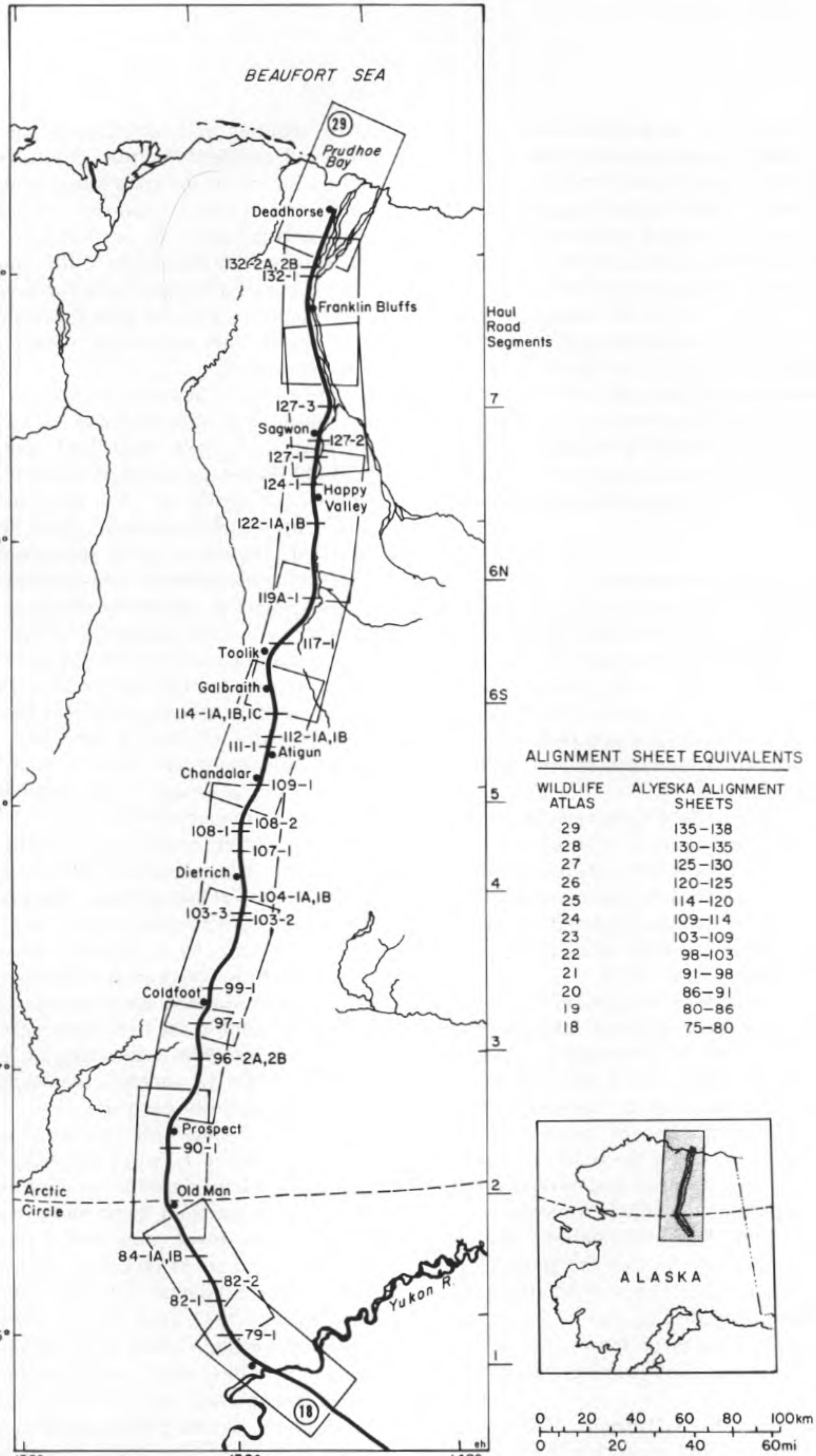
During the period 16 to 21 August 1976, these 13 sites were resurveyed to ascertain seasonal changes in elevation, and thaw depths adjacent to the road were again measured by probing. At that time eight additional sites were established, cross sections and longitudinal sections were surveyed, and depths of thaw measured.

In addition to the road sites, seven adjacent workpad and access road sites and two sites on each of four airfields were established in the 1976 summer as part of the CRREL pipeline program. Several additional sites for thaw measurements across shallow impoundments on the Arctic Coastal Plain and across winter trails were also established.

On 14 and 15 September 1976, a field review of these sites was undertaken by G. Johns (FHWA), L. Darnish (ADOTPF), and J. Brown (CRREL). Based on recommendations from this review, six additional sites were incorporated into future observations. The FHWA and ADOTPF reviewers also recommended that subsurface temperature measurements be made at the centerline and in the shoulders at several sites. We originally planned to install frost tubes (Rickard and Brown 1972) in the road and shoulder in late September and October 1976, and at the same time ascertain summer thaw penetration beneath the road prism. The change requiring placement of ground temperature sensors caused a delay in our installations until spring and summer of 1977.

In all, CRREL established 27 sites along the Haul Road, and subsurface temperature sensors were installed at nine of them. The sites included "typical" construction areas and locations where problems were observed or anticipated. Sites where the aboveground pipeline is in proximity to the roadway were emphasized as they generally contain ice-rich (thaw-unstable) soils which will provide a low bearing capacity if thawed. Table 12 contains the location and a brief description of each site.

Two sets of maps and plans were used for this study: 1) a set of construction record drawings ("as built" plans) dated November and December 1974 for the Haul Road, and 2) a set of construction alignment maps for the oil pipeline (drawing numbers AL-00-G5 for alignment sheets 78 through 138) dated 1969 and 1970 with revisions through 1977. Both sets of drawings were prepared for the Alyeska Pipeline Service Company. Our sites were cross-referenced to the pipeline maps, and our study sites are numbered according to the trans-Alaska pipeline alignment sheet maps. Each alignment sheet covers about 9.7 km and they are numbered from south to north; i.e. alignment sheet 1 starts at the terminal in Valdez and alignment sheet 138 ends at



ALIGNMENT SHEET EQUIVALENTS

WILDLIFE ATLAS	ALYESKA ALIGNMENT SHEETS
29	135–138
28	130–135
27	125–130
26	120–125
25	114–120
24	109–114
23	103–109
22	98–103
21	91–98
20	86–91
19	80–86
18	75–80

Figure 41. Locations of CRREL Haul Road cross section sites and the Haul Road construction segments. Rectangles correspond to the Wildlife Atlas sheet numbers starting at 18 at the Yukon River and ending at 29 at Prudhoe Bay (Hemming and Morehouse 1976).

Table 12. CRREL observation sites along the Haul Road.

CRREL site no.	Old CRREL site no.	Haul Road segment	Station	Dist. from Yukon River (km)	Approx. elev. (m)	Subgrade soil type	Approximate embankment thickness (m)
79-1	0-A	1[T]	560+89	14	162	Ice-rich silt	1.4
82-1	0	1	1341+89	37	166	Sandy silt	1.9
82-2	1	1	1537+49	44	276	Ice-rich silt	1.8
84-1A	2	1	2065+32	59	529	Ice-rich silt	1.9
90-1	3	2	1046+07	124	329	Ice-rich silt	1.9
96-2A	4-B	3	163+49	168	340	Ice-rich silt	1.5
97-1	4-A	3[T]	593+44	181	323	Ice-rich silt	2.8
99-1	5	3	1089+69	197	332	Silt	1.2
103-2	6	3	2277+02	230	437	Silt	1.7
103-3		3[T]	2414+00	233	426	Ice-rich silty sand	2.1
104-1A	6-A	3	2753+98	245	450	Silt	2.1
107-1		4[T]	3560+00	272	560	Silty gravel	2.1
108-1		4	557+00	286	662	Gravelly silt	1.5
108-2	7 New	4	704+84	287	679	Silty gravel	2.3
109-1		4	924+90	292	964	Gravelly silt	2.6
111-1		5	524+00	323	930	Silty gravel	1.8
112-1A	8	5	604+00	325	886	Silt	1.2
114-1A	0	5[T]	1375+19	349	820	Silt	1.0
117-1	10	6-S	862+48	373	948	Silt	1.3
119A-1		6-S[T]	1758+68	404	482	Silt	1.8
122-1A	11	6-N[T]	2828+56	435	402	Silt	1.5
124-1	11-A	6-N[T]	3334+00	451	313	Silt	1.9
127-1	12	6-N	4095+04	473	279	Silty sand	1.2
127-2		6-N[T]	4357+00	482	311	Silt	1.5
127-3	12-A	6-N	4493+76	484	191	Silt	1.3
132-1	13	7	1782+54	532	80	Sandy silt	1.3
132-2A	14	7	1838+04	534	80	Sandy silt	1.5

T—Subsurface temperature sensors installed in 1977.

Pump Station 1 near Prudhoe Bay. The beginning of the Haul Road is at the bridge across the Yukon River located on alignment sheet 78. Figure 41 shows approximate boundaries of the alignment sheets and locations of our test sites. Maps in Appendix C contain detailed site locations. A companion volume to this report contains detailed information for all our roadbed sites (Berg et al., in prep). In our site designation system, the first two or three digits refer to the alignment sheet, and the remaining numbers and letters, preceded by a hyphen, refer to the site on a particular alignment sheet. Site numbers on a particular sheet were also numbered from south to north. For example, site 82-1 is our southernmost site on alignment sheet 82.

Since temperature sensors were to be installed beneath the roadbed and adjacent to the road, long-term clearance from the state and federal land agencies was required. This involved preparation of detailed maps and plans for sites where instrumentation was to be placed. Letters of non-objection were also obtained from the Alyeska Pipeline Service Company and the ADOTPF. Clearance was requested for a total of 19 sites. By late March 1977, the necessary letters and permits had been received. The Bureau of Land Management (BLM) stipulated that holes off the road be drilled using a tracked vehicle while at least 30 cm of snow covered the ground surface. Therefore, a major effort was launched in late March and early April 1978 to install access tubes at off-road sites while the snow cover remained. A contractor was hired to drill the holes.

In July 1977 the ADOTPF provided a drill rig and crew to install access tubes beneath the road and C. Collins (CRREL) supervised these installations. In all cases, 5-cm (2-in.) nominal diameter, schedule 80, PVC pipe with threaded fittings was used for temperature access tubes. During the spring 1977 drilling program, temper-

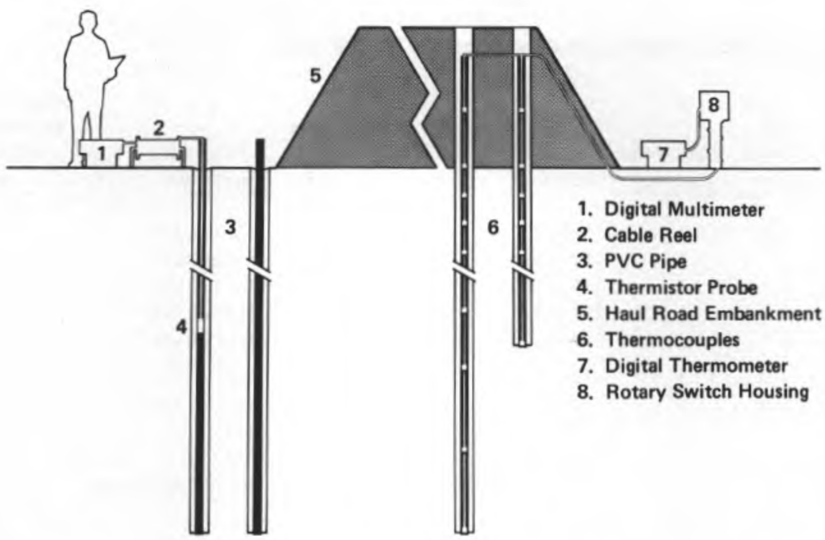


Figure 42. Idealized cross section of subsurface temperature-monitoring installations.

Table 13. Location of Haul Road temperature observation holes.

Date installed (1977)	*Site and hole*	*Depth (m)*	*Sensor type**	*Location*	*Comments*
26 Mar	79-1 (1)	12.2	TP	14 m lt ℄	Undisturbed
26 Mar	79-1 (2)	6.1	TP	8 m lt ℄	Shoulder
12 Jul	79-1 (3)	12.2	TC	3.5 m rt ℄	Road
12 Jul	79-1 (4)	6.1	TC	2.5 m rt ℄	Road
27 Mar	97-1 (1)	6.1	TC	6 m rt ℄	Road
28 Mar	97-1 (2)	12.2	TP	12 m lt ℄	Ditch
13 Jul	97-1 (3)	6.1	TC	2.2 m rt ℄	Road
29 Mar	103-3 (1)	12.2	TP	32 m lt ℄	Undisturbed
29 Mar	103-3 (2)	6.1	TP	19 m lt ℄	Near toe
14 Jul	103-3 (3)	12.2	TC	3 m rt ℄	Road
30 Mar	107-1 (1)	10.4	TP	53 m lt ℄	Undisturbed
31 Mar	107-1 (2)	12.2	TP	40 m lt ℄	Work pad
31 Mar	107-1 (3)	12.2	TP	25 m lt ℄	Work pad
31 Mar	107-1 (4)	10.7	TP	17 m lt ℄	Work pad
31 Mar	107-1 (5)	6.1	TP	10 m lt ℄	Shoulder
15 Jul	107-1 (6)	12.2	TC	3 m rt ℄	Road
15 Jul	107-1 (7)	6.1	TC	6 m rt ℄	Shoulder
1 Apr	114-1A (1)	12.2	TP	30 m lt ℄	Undisturbed
2 Apr	114-1A (2)	12.2	TP	16 m lt ℄	Shoulder berm
2 Apr	114-1A (3)	6.1	TC	7.5 m lt ℄	Shoulder
16 Jul	114-1A (4)	12.2	–	3.5 m rt ℄	Road–could not relocate
16 Jul	114-1A (5)	6.1	–	6 m lt ℄	Road–could not relocate
16 Jul	114-1B (1)	12.2	TC	0.5 m lt ℄	Access road
2 Apr	114-1C (1)	4.6	–		Insulated work pad–could not relocate
3 Apr	119A-1 (1)	3.0	TP	21 m rt ℄	Undisturbed
3 Apr	119A-1 (2)	3.0	TP	21 m rt ℄	Undisturbed
4 Apr	119A-1 (3)	3.0	TP	11 m rt ℄	Near toe
17 Jul	119A-1 (4)	3.0	TC	3 m rt ℄	Road
17 Jul	119A-1 (5)	3.0	–	3.5 m lt ℄	Road–could not relocate
17 Jul	119A-1 (6)	4.6	TP	8 m lt ℄	Work pad
Sept	122-1A (1)	3.0	TP	5 m rt ℄	Rt. shoulder
Sept	124-1 (1)	3.0	TP	8 m rt ℄	Rt. shoulder
Sept	127-2 (1)	3.0	TP	8 m rt ℄	Rt. shoulder

* TP–thermistor probe; TC–thermocouple assembly.

ature access tubes were filled with a nonfreezing liquid and capped to prevent water, snow and ice from intruding into the liquid. The access tubes were terminated above the ground surface so that they could be readily relocated and to prevent surface water flow into the tubes while temperatures were monitored. Since thermocouple assemblies were to be installed in the access tubes beneath the road, these tubes were not filled with a fluid. Access tubes installed within the roadway embankment were terminated about 20 cm below the surface, capped and covered with aluminum foil. In August 1977, these access tubes were relocated with a metal detector, thermocouple assemblies were placed in the tubes, and thermocouple leads were placed in hand-excavated trenches leading to rotary switches contained in terminal boxes adjacent to the road. In September 1977, additional access tubes were installed at three sites when the Alyeska Pipeline Service Company installed the winter roadway delineation markers. A trailer-mounted, rotary-percussive-type rock drill was used for these installations.

Temperature-monitoring installations at a typical site are shown schematically in Figure 42. Temperature measurements beneath the road have been obtained by connecting a portable digital thermometer to the rotary switches. To obtain temperature measurement adjacent to the road, a thermistor is placed in a liquid-filled access tube, lowered to the desired depth, and allowed to equilibrate (for about 1 min); the measurement is then obtained and the thermistor lowered to the next depth. The process is repeated to the bottom of the access tube. Use of this procedure permitted all temperatures adjacent to the road to be made with a single thermistor. Table 13 lists all the sites where subsurface temperature observations were made and the type of observations made at each location. The temperature observations are discussed in a subsequent section and data are contained in Berg et al. (in prep.).

Surface elevations at each test site were determined by rod and level surveys near the end of the 1976, 1977 and 1978 thaw seasons. At the same times, probings were made adjacent to the road to establish maximum seasonal thaw penetration depths. During the 1977 rod and level survey, a cone penetrometer was used to determine the soil strength adjacent to the road. The shaft of the cone penetrometer used for the 1977 observations was slightly over 45 cm (18 in.) long and observations were made at the surface, 15-cm (6-in.) depth, 30-cm (12-in.) depth, and 45-cm (18-in.) depth. The four measurements were repeated at each point where surface level observations were made adjacent to the road. Incident and reflected short-wave radiation measurements were also made during the 1977 survey.

Roadbed performance

Figure 43 illustrates the maximum and average cone penetrometer readings at each site. At all except two sites the minimum reading was zero; at sites 108-2 and 132-1 the minimum values were 10. These low readings were generally in, and immediately beneath, the surficial organic mat. Five of the sites contained at least one location where one or more penetrometer readings exceeded 300, the maximum value which could be obtained with the instrument. In each of the five cases, relatively coarse-grained granular material was encountered, causing the high readings. At most of the test sites the average penetrometer value was between 45 and 75 indicating that the soils have a low bearing capacity, and according to the criteria of the Alyeska Pipeline Service Company, would have been classified as a incompetent subgrade.

Using the average cone index values from Figure 43, the measured approximate embankment thicknesses from Table 12 and the minimum design thicknesses over incompetent soils (those having a cone index less than 80) from Table 11, we note that the embankment thicknesses of sites 79-1, 112-1A, 117-1 and 127-1 are less than the minimum requirement for that location. As will be discussed in more detail later, the roadway surface has subsided more than 10 cm at all of these sites, and it is possible that the road was constructed to the minimum thickness required but settled before our initial set of observations. It is also possible, especially at site 117-1, that the average penetrometer reading made by Alyeska was in excess of 80.

The maximum and minimum seasonal thaw depths observed at the test sites during the three years of observations are presented in Figure 43. In the undisturbed areas, thaw depths at most sites varied less than 15 cm over the three-year period of observations.

Variations in seasonal thaw penetration at the toes tended to be greater than in the undisturbed areas. The magnitude of thawing at the toes was also larger than in the undisturbed areas. At first glance, thaw penetration data in the undisturbed

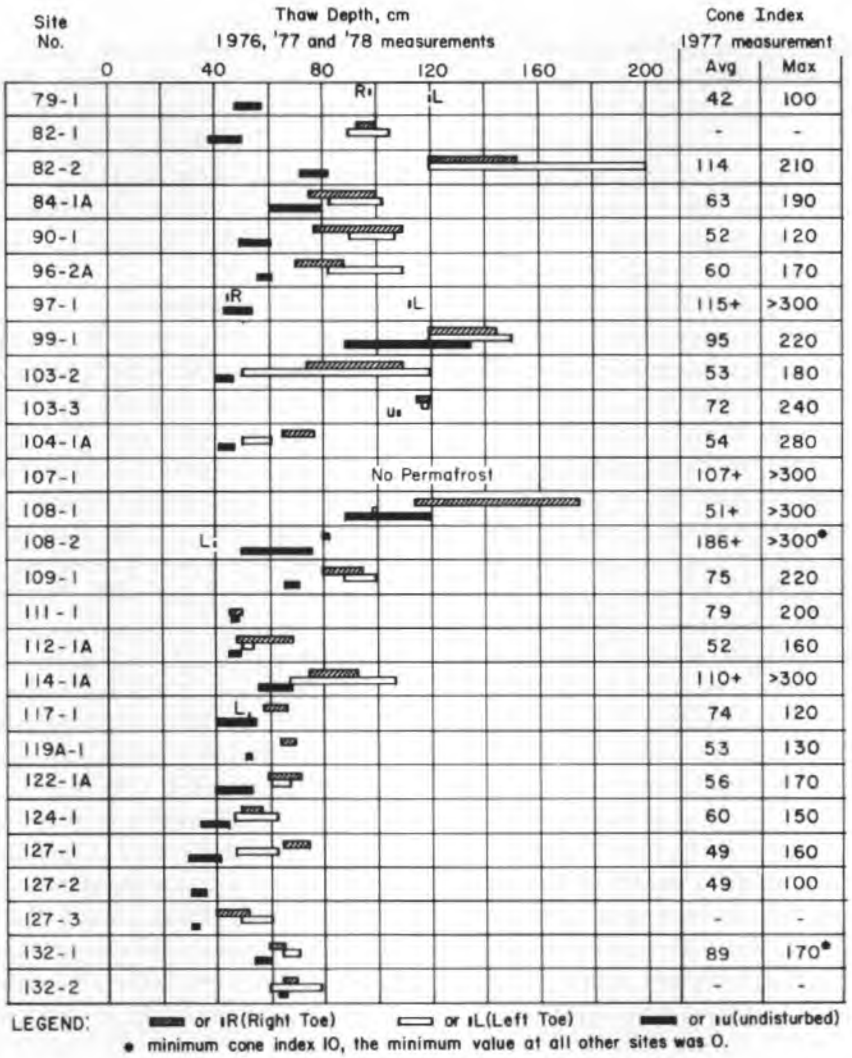


Figure 43. Thaw penetration and cone penetrometer index values of each test site.

areas adjacent to the road show no distinctly decreasing trend when progressing from the south to the north (Fig. 43), but upon close examination of the data, and recalling that Atigun Pass (on Alyeska Alignment Sheet 110) is the imaginary line between the Subarctic to the south and the Arctic to the north, some trends do appear. The first trend we note is a much wider variation in thaw depths at the individual sites in the subarctic region. Site 99-1 exhibited the largest variation in undisturbed thaw depths of the subarctic sites. The thaw depth was 88 cm in 1976 but 135 cm in 1978, a variation of 53%. The greatest variation north of Atigun Pass was at site 117-1 where the thaw depth ranged from 41 cm in 1976 to 55 cm in 1978, a differences of 34%.

The second notable trend is that undisturbed thaw depths from site 111-1 northward average less than those observed at sites 79-1 though 109-1. Another trend is also observed in Table 14, i.e. the average thaw penetration in the undisturbed areas has increased each year. Climatic observations (Table 1) indicate that 1977 was clearly the warmest thaw season south of Atigun Pass and only slightly warmer than the 1976 thaw season north of Atigun Pass. These data also confirm the main reason that thaw penetration depths are greater at the subarctic sites—the air thawing indexes are substantially larger.

These data are substantiated by additional data obtained during the 1977 vegetation transect studies (see *Vegetation* section). Thaw variations at approximate 5-km spacings along the

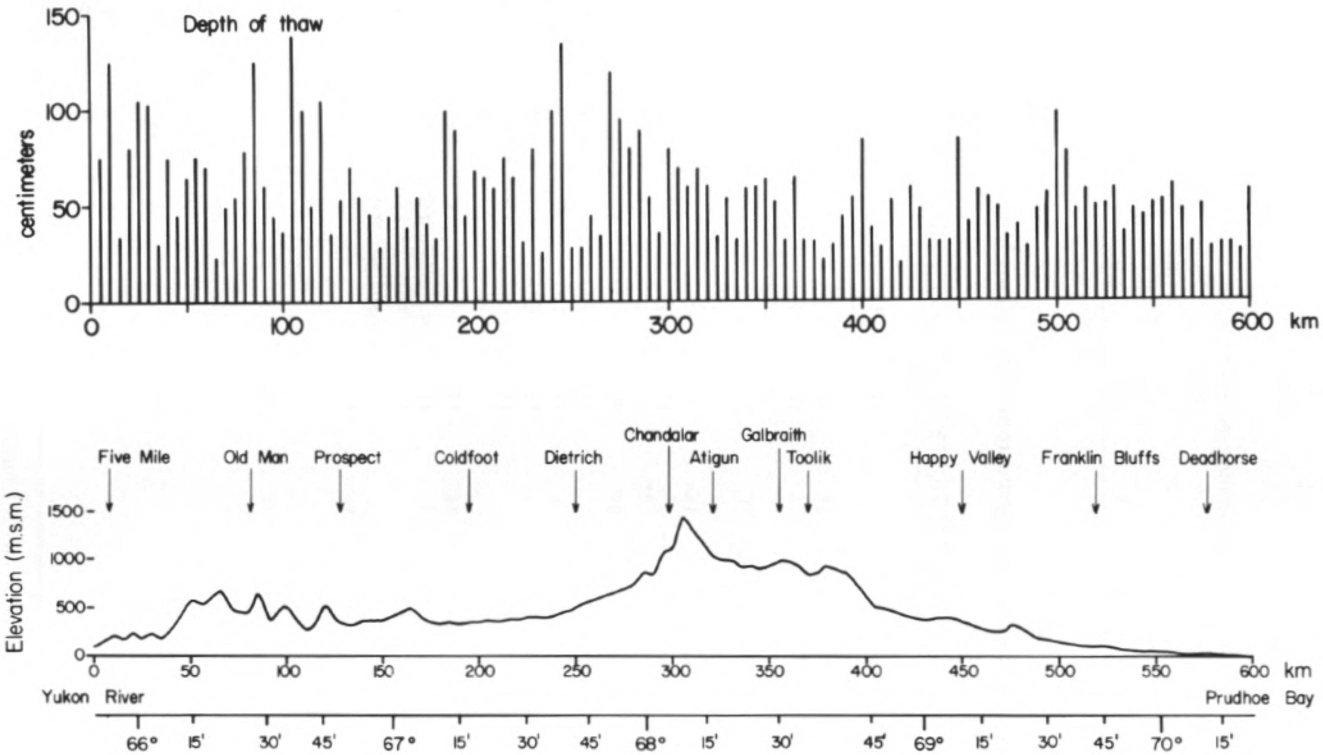


Figure 44. Distribution of thaw depths at 5-km intervals along the Haul Road during summer 1977. (Data from Komárková, unpublished).

Table 14. Average maximum seasonal thaw penetration in undisturbed areas.

Year	*No. of data sites*	*Avg. thaw depth (cm)*	*Std. dev. in thaw (cm)*
Subarctic sites 79-1 through 109-1			
1976	12	54.0	14.1
1977	13	62.5	19.2
1978	14	73.2	29.0
Combined	39	63.7	22.9
Arctic sites 111-1 through 132-2			
1976	9	44.3	12.1
1977	12	47.8	11.0
1978	12	50.0	10.5
Combined	33	47.7	11.0

Table 15. Dates of subsurface temperature observations from the Haul Road sites.

Site	*1977*				*1978*			
and hole	*6-11 Jun*	*28-30 Aug*	*1-2 Oct*	*7-10 Nov*	*2-3 Jun*	*5-7 Jul*	*7-8 Aug*	*22-25 Aug*
79-1 (1)	AP	TP		TP	TP		TP	TP
79-1 (2)								
79-1 (3)		TP	TC	TC		TC		TC
79-1 (4)		TP	TC	TC		TC	TC	TC
82-1 (1)								
97-1 (1)		TP	TC	TC		TC	*	
97-1 (2)	AP	TP		TP	TP	TP	TP	TP
97-1 (3)		TP	TC	TC	*			
103-3 (1)	AP	TP		TP	TP	TP	TP	TP
103-3 (2)	AP	TP		TP	TP	TP	TP	TP
103-3 (3)			TC	TC		TC	*	
107-1 (1)	AP	TP		TP	TP	TP	TP	TP
107-1 (2)	AP	TP		TP	TP	TP	TP	TP
107-1 (3)	AP	TP		TP	TP	TP	TP	TP
107-1 (4)		TP		TP		TP		TP
107-1 (5)					TP	TP	TP	TP
107-1 (6)			TC	TC		TC	TC	TC
107-1 (7)		TP	TC	TC		TC	TC	TC
114-1A (1)	AP	TP		TP	TP	TP	TP	TP
114-1A (2)	AP				TP	TP	TP	TP
114-1A (3)		TP	TC	TC			TC	
114-1A (4)		†						
114-1A (5)		†						
114-1B (1)		TP	TC	TC			TC	TC
114-1C (1)	**							
119A-1 (1)	AP	TP		TP	TP	TP	TP	TP
119A-1 (2)	AP	TP		TP	TP	TP	TP	TP
119A-1 (3)	AP	TP		TP	TP	TP	TP	TP
119A-1 (4)		TP	*					
119A-1 (6)				TP	TP	TP	TP	TP
122-1A (1)								TP
127-2 (1)								TP

* Thermocouple wires apparently cut during road maintenance operations.

† Could not relocate access tubes. They were probably struck during road maintenance operations.

** Access tube covered with about 1-m layer of additional gravel. Could not relocate

AP–used thermistor probe borrowed from ADOTPF.

TP–observations with CRREL thermistor probe.

TC–observations with thermocouple assembly.

Table 16. Seasonal thaw penetration (m) at instrumented observation sites.*

Site and hole	Approx. embankment thickness (m)	Thaw depth 1977	Thaw depth 1978	Subgrade thaw 1977	Subgrade thaw 1978	Thaw adjacent to road 1977	Thaw adjacent to road 1978
79-1 (3)	1.40	2.68	2.36	1.46	0.96	0.52	0.57
79-1 (4)	1.35	3.64	2.56	2.29	1.21	0.52	0.57
97-1 (3)	0.65	2.64	†	1.99	—	0.49	0.54
103-3 (3)	1.80	3.05	†	1.25	—	1.08	1.09
107-1 (6)							
107-1 (7)							
114-1A (3)	0.75	2.05	2.10	1.30	1.35	0.62	0.68
114-1B (1)	0.95	2.21	2.09	1.26	1.14	0.62	0.68
119A-1 (4)	1.85	2.73	†	0.88	—	0.53	0.52
122-1A (1)	1.55	**	>3.0	—	—	0.46	0.53
127-2 (1)	1.70	**	>3.0	—	—	0.31	0.37

* Determined from the location of the 0°C isotherm.

† Thermocouple assembly damaged during road maintenance operations.

** Access tubes installed after maximum thaw had occurred.

road in undisturbed areas are shown in Figure 44. For the 62 sites south of Atigun Pass the average thaw depth was 67.1 cm and standard deviation 31.2 cm. North of Atigun Pass the average thaw depth was 48.0 cm and standard deviation 16.3 cm.

The effects of the warmer air temperatures in the south are partially offset by the additional insulating effect of increased vegetative cover and thickness of organics in the undisturbed areas in southern zones as opposed to colder conditions in the north. Most of the variation in thaw depths in the undisturbed areas can be explained by differences in air thawing indexes, material types, moisture contents and exposure to incident shortwave radiation.

Thaw penetration beneath the road was determined from subsurface temperature measurements made on the dates shown in Table 15. The maximum seasonal thaw penetration depths beneath and adjacent to the road at our instrumented test sites are shown in Table 16. Except at site 119A-1, average thaw penetration values in undisturbed areas adjacent to these sites were greater during the 1978 season than during the 1977 season. Thaw penetration beneath the road was less in 1978 than 1977, but due to damage to many of the thermocouple assemblies, comparable data were only available at sites 79-1 and 114-1A. Thaw depths from all of the instrumented sites indicate that thawing into the original in-situ soil is greater beneath the road than in adjacent undisturbed areas. This is undoubtedly the reason we observed continued settlement of the roadway embankment.

The surface temperature amplitude at site 79-1 is considerably larger than the amplitude at site 114-1A (Fig. 45 and 46). The average temperature at a depth of about 6 m is about -2.7°C at site 79-1 and about -5.5°C at site 114-1A. At Five-Mile Camp, about 7 km south of site 79-1, the mean annual temperatures for 1976 and 1977 were -6.8°C and -6.4°C, respectively. At Galbraith Camp, about 4 km northwest of site 114-1A, the mean annual air temperatures were -9.9°C in 1976 and -9.5°C in 1977. These 4 to 5 C° differences between mean annual air temperatures and mean annual ground temperatures agree with observations reported by Brown (1963) from several Canadian permafrost sites.

Table 17 contains 1977 and 1978 mean annual air temperatures from selected construction camps along the Haul Road; it also shows minimum and maximum subsurface temperatures at the CRREL test sites. The subsurface temperature measurements were made beneath and adjacent to the road. Generally temperature fluctuations beneath the roadway surface are larger than those beneath the surface adjacent to the road due to greater absorption of solar radiation by the road surface and the insulating effect of the surface cover adjacent to the road. Evaporation and evapotransporation adjacent to the road also tend to reduce temperature fluctu-

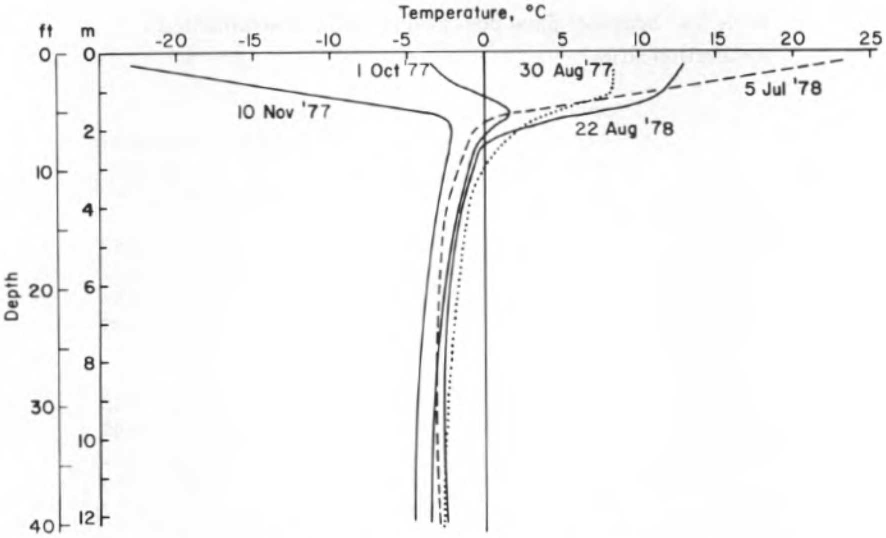


Figure 45. Temperatures beneath the Haul Road measured at access hole 79-1(3).

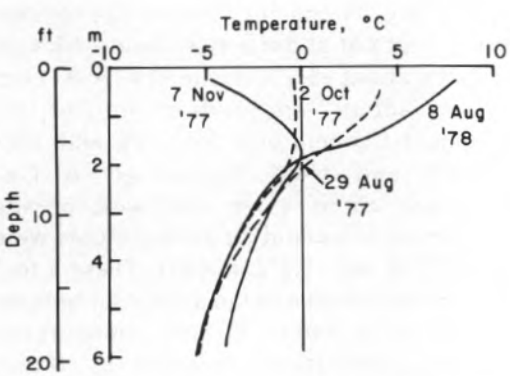


Figure 46. Temperatures beneath the Haul Road measured at access hole 114-1A(3).

Table 17. Mean annual air temperatures and maximum and minimum subsurface temperatures along the Haul Road.

Site	*Yukon River (km)*	*Temperature (°C)* Min. at 6-m depth	Max. at 6-m depth	Mean ann. air* 1977	1978
Five Mile	8			– 6.4	– 4.7
79-1 (1)	14	–2.1	–1.7		
79-1 (3)	14	–3.9	–1.6		
79-1 (4)	14	–3.9	–1.7		
Prospect	130			– 4.8	– 3.7
97-1 (1)	181	–3.6	–0.8		
97-1 (2)	181	–2.5	–1.8		
103-3 (1)	233	–1.5	–0.5		
103-3 (3)	233	–2.8	–1.2		
107-1 (1)	272	+1.0	+6.9		
107-1 (6)	272	+0.4	+5.8		
107-1 (7)	272	+0.2	+8.9		
Chandalar	297			– 5.9	–
114-1A (1)	349	–6.7	–4.4		
114-1A (2)	349	–7.1	–4.3		
114-1A (3)	349	–6.8	–4.2		
114-1B (1)	349	–5.2	–3.6		
Galbraith	354			– 9.5	– 9.0
119A-1 (1)	404	–4.7**	–1.6**		
119A-1 (6)	404	–5.1**	–0.6**		
122-1A (1)	435	+0.9†/**	–		
Happy Valley	448			–11.0	–
127-2 (1)	482	+0.4†/**	–		
Prudhoe Bay	584			–11.4	–10.6

* Data from Table 1.
† Only one observation.
** 3-m depth.

Figure 47. Gravel road showing severe differential subsidence caused by thawing of ice-wedge polygons in permafrost, Umiat, Alaska.

ations in these areas. The slightly different behavior at site 107-1 is caused by the combined effects of the buried hot oil pipeline located about 28 m from the roadway centerline and the high water table at about 2 m below the ground surface adjacent to the road. Oil in the pipeline is probably 35° to 40°C at this location and has caused the temperature beneath and adjacent to the road to gradually warm. Our subsurface temperature observations at this site indicate that the soil temperatures are continuing to increase.

Thaw depths measured adjacent to the road in 1977 were generally slightly greater than those measured in 1976. This agrees with climatic observations (Table 1) which indicate a warmer 1977 thaw season. The 1978 thaw depths were equal to or greater than those observed in 1977 at 18 of the 27 sites where comparisons could be made, and the average thaw depth from all of the sites was greater in 1978 than 1977 (Table 14). The reasons for greater thaw penetrations in 1978 are not entirely clear. The 1977 air thawing index was greater than the 1978 index for most sites (Table 1); however, at most sites, the July 1978 air temperatures were warmer than the July 1977 temperatures. Our experience from other areas shows that a substantial part of soil thawing occurs during July. Therefore, the warmer July 1978 air temperatures may at least partially explain the deeper thaw penetration observed during 1978. The greater thaw could also be due to the combined effect of several climatological conditions.

When design method 1, which permits thawing beneath the embankment, is used in areas where ice-rich soils are present, settlement of the roadway frequently occurs (Fig. 47 and 48). If the road crosses ice-wedge polygons or other deposits of massive ice, the longitudinal profile of the road may tend toward the situation shown in Figure 47. Regrading of the road will reduce the magnitude of differential settlement, but significant quantities of gravel must be added to maintain the original profile elevations. This problem has occurred at several cuts through ice-rich soils on the TAPS road between Livengood and the Yukon River. Differential subsidence of this type has also occurred on a few of the pipeline and material site access roads and very subtle undulations of this type are now becoming noticeable along sections of the Haul Road.

Lateral subsidence of the roadway embankment is usually less noticeable than undulations caused by differential longitudinal subsidence, but may occur more frequently. Figure 48 is a schematic of the progression of this situation. As shown in this figure, the permafrost table beneath most of the embankment may rise slightly after completion of the roadway but beneath the sideslopes it quickly converges on the original

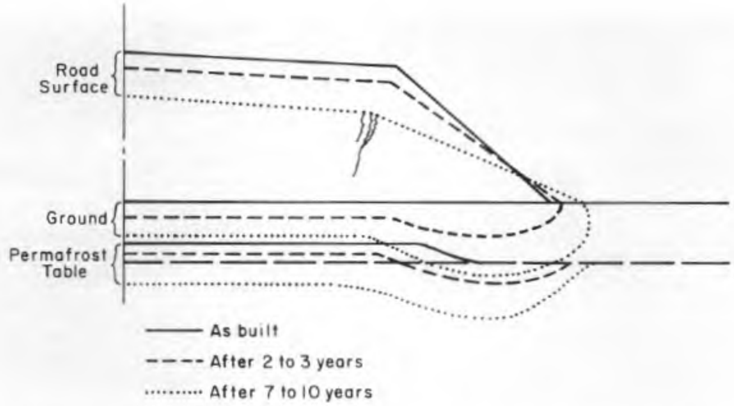


Figure 48. Idealized settlement of a roadway embankment due to thawing and consolidation of ice-rich permafrost.

Figure 49. Longitudinal crack along roadway shoulder caused by settlement of embankment sideslope and toe (TAPS road, mile 54.9, from Clark and Simoni 1976).

permafrost table. After a few years the roadway surface subsides, due primarily to consolidation of the mostly thawed, previously existing active layer. The toe moves outward slightly and the edge of the shoulder shifts slightly toward the centerline. Thawing increases beneath the sideslopes because the gravel cover is not as thick as in the main part of the embankment. Due to greater thawing beneath the sideslopes, they have also subsided more than the trafficked portion of the embankment. After several more years, the active layer beneath the embankment has progressed deeper than the undisturbed permafrost table, especially beneath the sideslopes. The sideslopes become wider and flatter due to thaw subsidence beneath them and the width of the trafficked surface becomes narrower. Cracks may also appear at the edge of the shoulder (Fig. 49). One may ask why the active layer beneath the roadway becomes thicker as

Table 18. Changes in elevation (cm) at cross section locations.

	Difference from					
	August 1976 survey				August 1977 survey	
	1977		1978		1978	
Site	Undist.*	Road*	Undist.*	Road*	Undist.*	Road*
79-1	−7	−11	−10	−16	−3	− 5†
82-1	nd	nd	− 6	0	nd	nd
82-2	−5	− 2	0	− 7	+5	− 5
84-1A	−1	+ 2	− 2	−10	−1	−12
90-1	−7	− 6	−10	+ 3	−3	+ 9
96-2A	−2	0	− 2	− 3	0	− 3
97-1	−4	−24	− 6	−25	−2	− 1
99-1	+1	− 1	+ 1	− 5	0	− 4
103-2	−5	− 3	− 9	−11	−4	− 8
103-3	nd	nd	nd	nd	−8	− 6
104-1A	−3	− 5	− 2	− 8	+1	− 3
107-1	nd	nd	nd	nd	+1	− 2
108-1	nd	nd	nd	nd	+2	− 2
108-2	0	− 2	− 1	− 3	−1	− 1
109-1	nd	nd	nd	nd	−2	− 9
111-1	nd	nd	nd	nd	0	− 2
112-1A	−6	− 7	−10	−16	−4	− 9
114-1A	−5	−16	− 7	−28	−2	−12
117-1	−8	−11	−10	−27	−2	−16
119A-1	nd	nd	nd	nd	−5	−19
122-1A	−4	+18	− 5	+12	−1	− 6†
124-1	−6	− 5	− 6	−12	0	− 7
127-1	−2	−19	− 3	−22	−1	− 3
127-2	nd	nd	nd	nd	+2	− 2
127-3	−2	−14	0	−24	+2	−10
132-1	−4	− 4	− 4	− 6	0	− 2
132-2A	−1	− 3	− 3	− 9	−2	− 6

* Changes in elevations in the "undisturbed" areas adjacent to each site are the average change in 2 or 3 points on the extreme edges of the cross section on each side of the road. Centerline elevation changes are determined from the centerline and the points immediately adjacent to the right and left of the centerline.

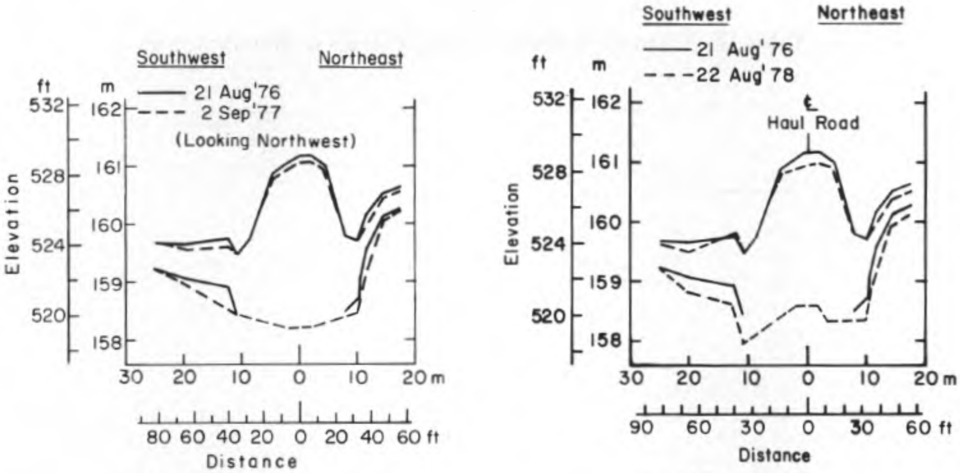
† Survey party observed that additional gravel had been added during the 1977 thawing season.

nd—no data obtained.

time progresses. The answer is that the pre-road active layer and permafrost consolidate as they thaw. The consolidation process also removes water from the subgrade soils, and therefore during the following thaw season a smaller quantity of thermal energy is required to thaw to the previous year's permafrost table. The remaining heat is used to thaw additional permafrost. This process may continue throughout the life of the road, but due to annual variations in the surface energy balance the rate of permafrost degradation varies from year to year. If we assume that a constant amount of heat is added during the summer months and a larger but constant amount of heat is extracted during the winter and that the permafrost is homogeneous, the amount of permafrost degradation and resulting thaw settlement will decrease annually until a stable condition is attained. Our observations of surface elevations on the roadway have provided a method for quantifying the rates at which these processes occur.

Surface elevations and thaw penetration depths in late August 1976, 1977 and 1978 beneath and adjacent to sites 79-1 and 114-1A are presented in Figures 50 and 51, respectively. During the 1977 survey, we noted that additional gravel had been added at site 79-1. The thickness of material added is unknown; however, some settlement of the roadway occurred between August 1976 and August 1977.

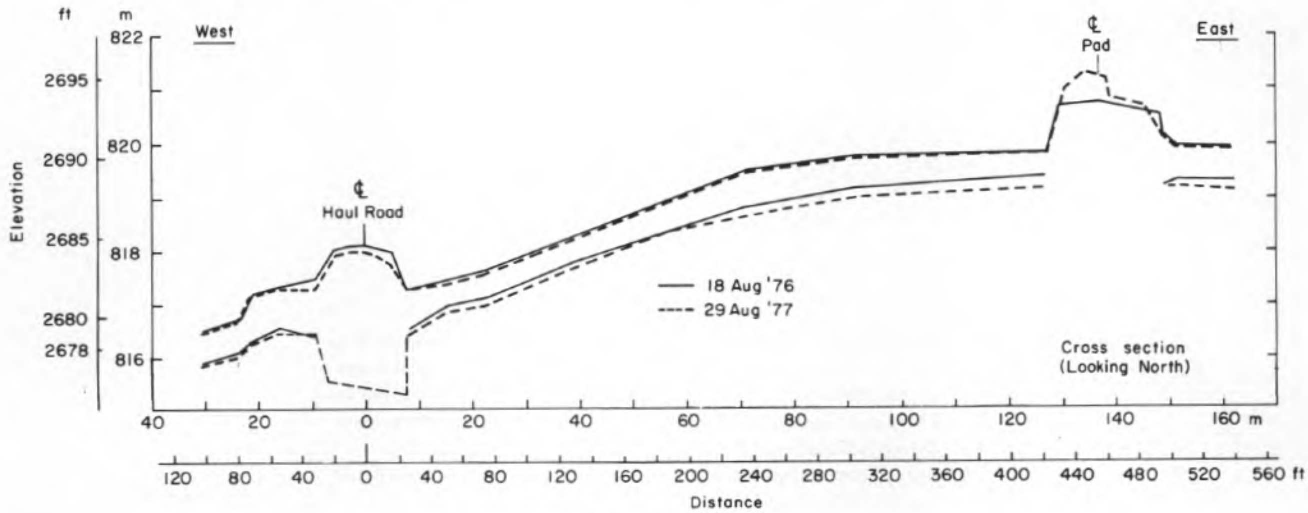
Additional settlement of the roadway embankment was apparent from the 1978 survey. Data in Table 18 show changes in elevations as differences from the 1976 and 1977 surveys. These differences are average values for both



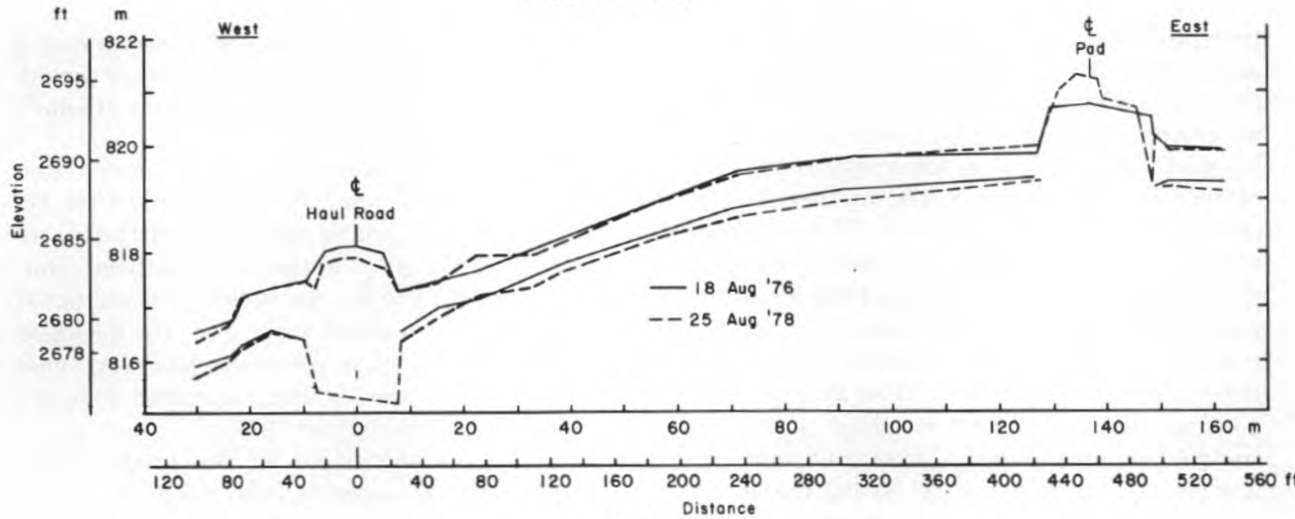
a. 1976-1977.

b. 1976-1978.

Figure 50. Surface and permafrost elevations for site 79-1, 15 km north of the Yukon River.

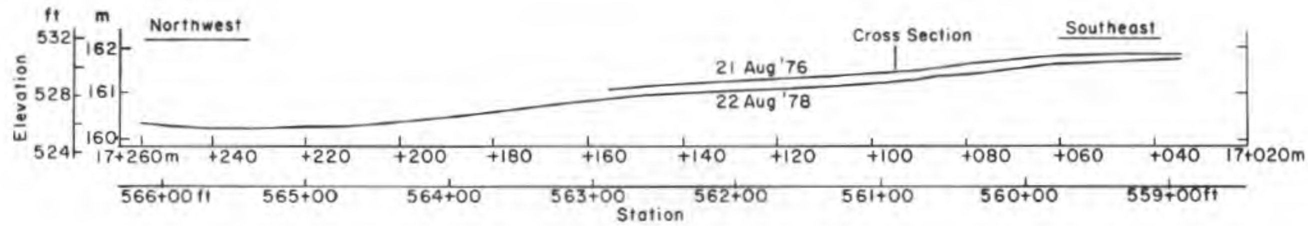


a. 1976–1977.

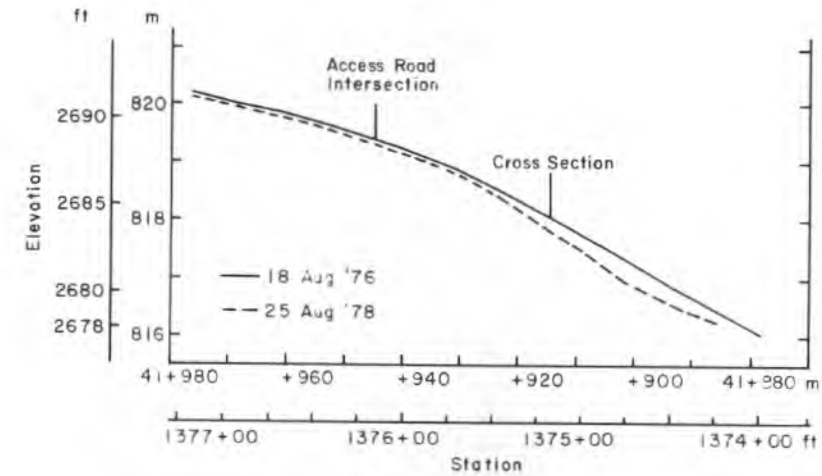


b. 1976–1978.

Figure 51. Surface and permafrost elevations at site 114-1A and 1B, about 349 km north of the Yukon River.



a. Site 79-1.



b. Site 114-1A.

Figure 52. Longitudinal roadway centerline profiles.

the "undisturbed" areas adjacent to the road and three points on the roadway surface. In most instances, the differences in the undisturbed areas adjacent to the road are considerably smaller than those measured on the roadway surface. However, the differences in elevations adjacent to the road were often greater than anticipated. Since steel pins or wooden stakes were used to accurately locate the survey points adjacent to the road, our annual level observations should have been measured within a radius of about 5 cm. Variations in elevation up to 4 cm may occur within this radius. Therefore apparent changes in elevation in excess of 4 cm for the undisturbed areas must be attributed to changes in elevation of the benchmark or general settlement within the entire area surveyed. The allusion to apparent settlement of the road and undisturbed areas adjacent to it is used because we are uncertain whether both have actually subsided or whether the benchmark has been moved upward due to frost heaving, thereby causing our survey data to indicate general subsidence in the test area. Data in Table 18 indicate that subsidence occurred in "undisturbed areas" adjacent to nearly all of our sites. These data also indicate that the apparent settlement of the road has generally been considerably greater than the apparent settlement of the undisturbed areas. Therefore it is safe to say that the roadway surface was lower in August 1978 than it was in August 1976 at most of our test sites.

Apparent settlement of the roadway consists of three components: 1) elevation changes due to actual settlement of the embankment resulting from thawing and consolidation of the original subgrade soils, 2) elevation changes due to regrading of the gravel surface and 3) elevation changes due to movement of the benchmark. We do not know what amount of the observed settlement can be attributed to each component.

Longitudinal profiles along the centerline of the road at sites 79-1 and 114-1A are shown in Figure 52; similar data from the other sites are shown in Appendix D. The profiles show that, in general, apparent settlement of the Haul Road at a particular site was relatively uniform. This

Table 19. Data used in calculating thaw penetration depths.

Dist. from Yukon River (km)	Thickness (m)* Surface course	Base course	Subbase material	Air thawing index (°C-days)	Avg. ann. temp. (°C)	Length of thaw season (days)
15	0.15	0.76	0.53	1542	− 6.7	162
123	0.15	0.76	0.97	1645	− 4.1	161
196	0.15	0.76	0.30	1578	− 4.8	160
288	0.15	0.76	0.25	1011	−10.3	129
348	0.15	0.76	0.34	971	−10.0	120
435	0.15	0.76	0.58	1064	−11.0	115
531	0.15	0.76	0.46	790	− 7.4	109
576	0.15	0.76	0.60	349	−12.2	100

Material	Dry density (kg/m^3)	Moist. cont. (% dry wt)	Thermal conduc. (W/m K)	Heat of fusion ($10^7 J/m^3$)	Heat capacity ($10^6 J/m^3$ °C)
Asphalt pavement	2210	0	1.49	0	1.88
Surface course	2243	6	3.61	4.51	2.01
Base course	2080	8	3.21	5.58	2.10
Insulation layer	32	0	0.03	0	0.07
Subbase material	1922	10	2.76	6.44	1.97
Subgrade soil	1281	25	1.19	10.73	1.92

* Where a pavement was used it was 0.08 m thick.

† To obtain surface thawing indexes the air thawing indexes were multiplied by the following factors: Gravel surface—1.4
Asphaltic concrete—1.8
White-painted asphaltic concrete—1.0

uniformity may be somewhat artificial, however, due to regrading of the road.

Since our elevation measurements were made on the roadway surface rather than on plates embedded below the surface, it is not possible to determine the amount of apparent settlement caused only by regrading the road. However, it is unlikely that the amount of apparent settlement due to grading is greater than 5 to 8 cm. The apparent settlement exceeded these values at many sites (Table 18), and at four sites the apparent settlement of the roadway exceeded 20 cm during the 1976-78 period. Between August 1977 and August 1978 apparent settlement of the road equaled or exceeded 8 cm at eight of the 26 sites where comparable data were available. Although the exact amount of settlement of the road cannot be determined, it is readily apparent that the road is still actively subsiding at most of our test sites.

At several locations along the road, maximum seasonal thaw penetration was estimated by computing the depth using a thawing index measured near the site and representative soil properties. The modified Berggren equation (Aitken and Berg 1968) was used for the computations.

Table 19 contains data which were used to calculate thaw depths beneath the road surface and the calculated depths are shown in Figure 53. Thaw depths beneath the surface of the gravel road (curve B) follow the same general trend as the air thawing indexes, i.e. an increase from north to south.

Data from curve B indicate that considerable thawing beneath the design embankment thicknesses in Table 11 should be expected. The computed thaw depth for the site 15 km north of the Yukon River corresponds to our site 79-1. Our

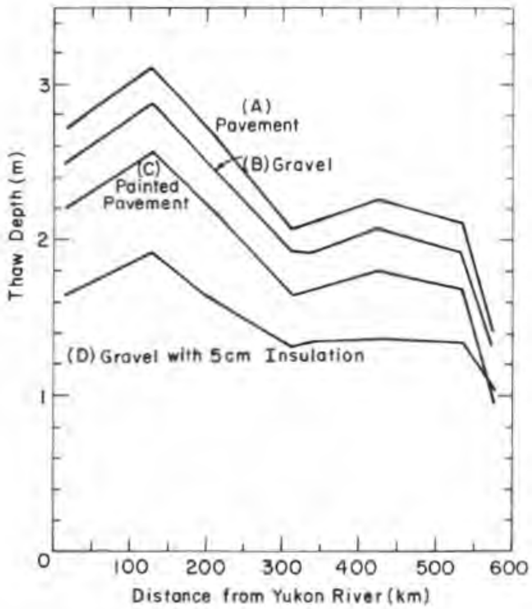


Figure 53. Effect of surface type and insulating layer on calculated maximum seasonal thaw penetration beneath the road surface.

temperature observations indicate thaw depth beneath the road surface to be on the order of 2.4 to 2.7 m. The computed thaw depth for this location was about 2.5 m.

Thaw depths computed for the site 348 km north of the Yukon River correspond to those at our site 114-1A. Subsurface temperature measurements at this site indicate 2.0 to 2.2 m of thawing beneath the road surface. Computed thaw depths for the gravel embankment at this location were about 1.95 m. It must be noted that we used the actual embankment thicknesses at these two sites in our computations (Table 19). Curve D in Figure 53 illustrates the effect of placing a 5-cm-thick insulation layer on top of the subbase course. Computed thaw depths are considerably reduced when this thickness of insulation is used. Had this thickness of insulation been used with the design embankment thicknesses over incompetent soils listed in Table 11 (method 3, Fig. 39c), our computations indicate that thaw would not have penetrated the embankment at nearly all locations. The layer of insulation would have added to the initial cost of the road, but in return may have reduced the maintenance costs. An economic analysis to determine the benefits of including a layer of insulation could be made if cost figures for material, equipment and workers were available. We did not conduct such an analysis.

When a road is opened for public travel, pressure will probably mount to pave it. An excellent example of this is the move to pave some Canadian sections of the Alaska Highway. In arctic and subarctic areas an asphaltic concrete pavement is normally used, which will tend to absorb more solar radiation than a gravel surface, resulting in increased thaw penetration as shown in curve A in Figure 53. Since thaw penetration beneath the paved surface is greater than beneath the gravel surface, additional differential thaw settlement will probably occur after an existing gravel road is paved. Costs associated with releveling an asphalt pavement are generally much greater than those required for regrading a gravel road.

A light-colored surface can be applied to reduce the amount of solar radiation absorbed by an asphalt pavement. Berg and Aitken (1973) report that white paint has been successfully used on a runway at Thule, Greenland, and on highway test sections near Fairbanks, Alaska. Thaw depths beneath a white-painted asphaltic concrete pavement were calculated and are shown in curve C in Figure 53. The computations suggest that thawing beneath a white painted asphaltic concrete pavement would be slightly less than that beneath the original gravel surface (curve B). The difference is due to the reduced absorption of solar radiation by the white painted surface. An obvious drawback to painting an asphalt concrete pavement is the probable necessity for repainting it every few years.

The primary reason for measuring the incident and reflected short-wave radiation was to determine whether the road absorbed more solar radiation at some sites than at others due to its sur-

Table 20. **Incident and reflected shortwave radiation observations made during August 1977.**

Site	*Location*	*Incident (cal/cm² min)*	*Reflected (cal/cm² min)*	*Albedo*
79-1	Road	0.34	0.09	0.27
82-2	Road	0.68	0.11	0.17
	Undisturbed	0.68	0.05	0.08
84-1A	Road	0.61	0.17	0.27
	Cleared	0.61	0.14	0.22
	Work pad	0.61	0.14	0.22
	Forest	0.61	0.10	0.16
96-1A	Road	0.54	0.17	0.31
	Undisturbed	0.54	0.09	0.17
97-1	Road	0.63	0.14	0.23
	Undisturbed	0.63	0.11	0.18
99-1	Road	0.52	0.14	0.26
	Undisturbed	0.59	0.05	0.08
103-2	Road	0.50	0.09	0.18
103-3	Road (wet)	0.59	0.11	0.19
	Road (dry)	0.63	0.14	0.22
	Undisturbed	0.61	0.09	0.15

face characteristics. For comparative purposes we also made similar measurements in undisturbed areas adjacent to the road.

The albedo (reflected shortwave radiation divided by incident shortwave radiation) was determined at eight of the test sites (Table 20). It varied from 0.31 at site 96-1A to 0.17 at site 82-2. For all eight sites it averaged 0.24.

Performance of drainage features*

Design criteria

Design criteria for cross-drainage associated with the Haul Road and other roads along the pipeline route between Prudhoe Bay and Valdez were established by the Technical Advisory Board to the Department of Interior Task Force on Alaska Oil Developments and the Federal Task Force on Alaskan Oil Developments. These technical stipulations can be summarized as follows:

1. Design of all culverts and bridges was to be in accordance with criteria established by the American Association of State Highway Officials and the Federal Highway Administration and endorsed by the State of Alaska Department of Highways (now Department of Transportation and Public Facilities) to pass a 50-year recurrence interval flood or the greatest flood of record, if greater, without overtopping the roadway.

2. Culverts were to be constructed (following the interpretation of stipulation 1 by the Bureau of Land Management) so that the design flood would be passed with a ratio of head water height (culvert to hydraulic grade line height at culvert inlet) to culvert diameter limited to 1.5. This criterion was also approved by the State of Alaska, Department of Highways. Environmental stipulations also influence culvert design and placement. Alyeska agreed to install all temporary and permanent culverts so that calculated 5-year flood levels would not cause velocities to exceed 1.1 m/s through the culverts.

A specific culvert design was achieved by first determining the required design discharge and then by determining culvert diameter and slope to meet the flood passage criteria. If fish lived in the stream, fish passage requirements may have dictated the culvert diameter, slope, and elevation with respect to the thalweg. Finally, structural, bedding and other requirements were determined for individual streams. Two methods were used to determine flood discharges upon which to base culvert size, with the one yielding the largest discharge being used for selecting the final culvert size. The first method, the area-constant drainage method, assumed a flood peak south of the Brooks Range of 0.33 m^3/s per km^2 of tributary drainage area and a flood peak north of the Brooks Range of 0.22 m^3/s per km^2 of tributary drainage area. Such floods were to pass through the culverts at the critical flow level. The culvert diameter and slope were computed to pass the flood peaks at their critical flow capacity. The second method was based on a Bureau of Land Management method which estimated a 10-year and 25-year recurrence interval flood. The 25-year recurrence interval flood was used to design the culvert diameter and slope such that a head water/culvert diameter ratio of 1.25 or less was achieved. These methods were adopted because field data and culvert experience were virtually nonexistent in the region traversed by the Haul Road.

During the vegetation mapping program (see Walker and Webber, this report), the feasibility of using aerial photographs to assess culvert placement and performance was investigated. Sixty culverts, which represented only a small sample of the total number of culverts along the highway, were examined in the areas mapped for

*Prepared by G.L. Guymon, R.L. Berg and J. Brown vegetation. The study concluded that aerial photographs at a scale of 1:6000 are useful in determining the extent of drainage modification and inundation and for determining in advance subtle drainways that may not always be obvious on the ground. The soil mapping approach would produce similar conclusions (see Everett, this report).

Drainage considerations

The design and installation of drainage for surface and subsurface water on and adjacent to roadways and highways constitute a major undertaking. Surface moisture in the form of water or snow and ice is the most visible problem and structural elements that deal with surface drainage include cross slopes, parallel gutters and channels, and cross-drainage structures which usually carry flows under the roadway by means of bridges or culverts. Subsurface drainage may or may not involve special structures such as base course or subbase drains.

Problems associated with inadequate roadway cross-drainage or erosion control may result in roadway washout, ponding and promotion of icing conditions that clog cross-drainage facilities, killing of fish, and destruction of fish and wildlife habitats. Problems associated with parallel drainage include erosion of exposed fine-grained soils in cuts, ponding, promotion of thaw weakening and subsidence, unsightly and erosive gully formation, and downslope siltation producing disturbances of downslope fish habitats. Roadway surface drainage problems on gravel roads are generally related to blockage of drainage and erosion due to gravel berms on the roadway shoulders. The berms tend to keep runoff on the roadway where it progresses downhill and frequently breaks through the berm over a stream. There it carries surface sediment, makes gullies in the sideslope, and silts the stream. Subsurface seepage problems may result in unstable foundation conditions, differential frost heave, icings, and waterlogging of soils with consequent damage to the roadside vegetation.

Problems observed with culverts

Drainage problems along the Haul Road were observed during numerous trips by CRREL personnel. Because most of these problems are associated with culverts, two trips were conducted especially to observe and catalog functional problems associated with culverts. The first field inspection of culverts was during late summer (August 1977) when culverts were completely exposed and flows were presumed to be at their lowest stages. The second trip (May 1978) was timed to be near breakup when it was presumed that flow stages would be near maximum and ice and snow problems would be most visible. However, breakup and flows during the May 1978 trip were either mild or low.

The objective of these two trips was to identify classes of problems specifically associated with drainage in permafrost regions and to select culverts which characterized such problems for possible further observations. It was not the purpose to provide a critical review of design, construction, and maintenance procedures related to Haul Road culverts.

Although fish passage and ice problems were observed at some culverts and are of major concern, they were not thoroughly evaluated by us. Several reports on fish passage associated with the road have been completed (e.g. Gustafson 1977). The Alaska Pipeline Office prepared a list of concerns in late August 1978 which were all essentially related to drainage problems.

During our two trips, corrugated metal pipe (CMP) culverts were observed while traveling the Haul Road by vehicle. Culverts that were considered worthy of closer inspection because of obvious problems were observed on foot. Pertinent details of each culvert visited were recorded in a field notebook and photographs were taken with 35-mm cameras. Eighty photographs for the August 1977 trip and 94 for the May 1978 trip were catalogued and filed. The slides were catalogued according to a system based upon the alignment sheet number and arbitrary numbers within an alignment sheet (i.e. XXX-CY-N, where XXX is the alignment sheet number, C refers to culvert site to distinguish it from other CRREL study sites, Y is the number on the alignment sheet, and N is the photograph number at the particular site). Table 21 contains characteristics of all culverts visited, and Figure 54 shows their locations.

The most significant problems observed and discussed herein are related to:

1. Roadway thaw consolidation causing culverts to bow down on the ends or down in the middle. These conditions generally cause ponding upstream.

2. Culverts with one or both ends partially or completely plugged with gravel due to regrading of the road. In some cases, this caused upstream ponding.

Table 21. All culverts observed during August 1977 and May 1978 field trips.

Station*	Culvert†	CMP dimensions** (m)
Haul Road segment 1		
391+50	79-C1	2.2×1.6×19.5
474+60	79-C2	0.6×22.6
500+00	79-C3*** (Phelps Cr.)	1.7×1.5×20.1
566+00	79-C4	0.6×17.1
598+10	79-C5	0.9×20.7
661+20	80-C1	2.2×1.6×30.5
736+12	80-C2	2.1×1.5×29.9
812+60	80-C3	
947+42	80-C4	
1011+08	81-C1*** (Ft. Hamlin Hills Cr.)	two 3.5×1.7×25.6
2001+50	84-C1*** (So. Br., W. Fork, Dall R.)	4.0×2.4×25.6
2313+24	85-C1	1.2×42.7
2485-18	85-C2*** (Kristie's Cr.)	1.5×27.4
Haul Road segment 2		
115+00	88-C1*** (Alder Mt. Cr.)	2.9×2.0×26.2
1311+32	91-C1	0.6×21.3
1315+16	91-C2	0.6×24.4
1465	92-C1	
1711+43	92-C2	1.2×20.7
2098+18	94-C1 (Abba-Dabba Cr.)	
Haul Road segment 3		
599+00	97-C1*** (Rosie Cr.)	3.8×2.4×33.5
2203+04	102-C1 (Valvesite Cr.)	0.9×16.8
2229+04	102-C2	0.6×16.8
2240+50	102-C3	0.8×21.3
2255+41	102-C5	0.6×21.3
2265+01	102-C6	0.8×19.8
2276+02	102-C7	0.6×19.8
2288+50	102-C8 (One-O-Two No. Cr.)	0.6×21.3
2293+95	102-C9	0.6×18.3
2298+61	102-C10	1.2×29.0
2307+92	103-C1	0.8×18.3
2320+25	103-C2	0.8×18.3
2366+39	103-C3	0.6×19.8
2826+88	104-C1 (Disaster Cr. overflow	0.6×21.3
Haul Road segment 4		
3026+13	105-C1*** (Number Lakes Cr.)	2.3×1.7×17.1
3204+00	105-C2	0.9×19.8
3228+48	105-C3	0.6×21.3
3579+53	106-C1	0.8×24.4
Haul Road segment 5		
1539+50	114A-C1	0.6×19.8
Haul Road segment 6-S		
540+85	115-C1	
Kuparuk R.	117-C1***	two 3.9×2.5×22.6
Haul Road segment 6-N		
2110+	120-C1*** (Oksrukuyik Cr.)	
2498+00	121-C1	0.6×27.4
Charlies Cr.	123-C1***	
3083+98	124-C3*** (Dan Cr.)	2.5×3.7×47.6
3332+98††	124-C2	0.6×21.3
3421+00	124-C3	
3471+49	124-C4*** (Stout Cr.)	
3840+00	125-C1*** (Mark Cr.)	
3921+00	127-C1	
4316+16	127-C2	
Haul Road segment 7		
1645+56	132-C1***	two 0.8×17.7
1655+59	133-C1***	1.2×18.3
	133-C2	
3040+02	137-C1***	3.5×22.0
3118+53	137-C2*** (Susan Cr.)	2.7×1.8×26.2

* Haul road stationing in feet.

† Culvert No. XXX-CY where XXX is the alignment sheet number, C is to distinguish the culvert site from other CRREL sites, and Y is an arbitrary number on the alignment sheet.

** Dimensions of corrugated metal pipe (CMP).

†† Several culverts from 3332+98 to 3335+54 in Haul Road segment 6-N.

*** Fish streams, Julius Rockwell, Bureau of Land Management, Anchorage (Pers. comm.).

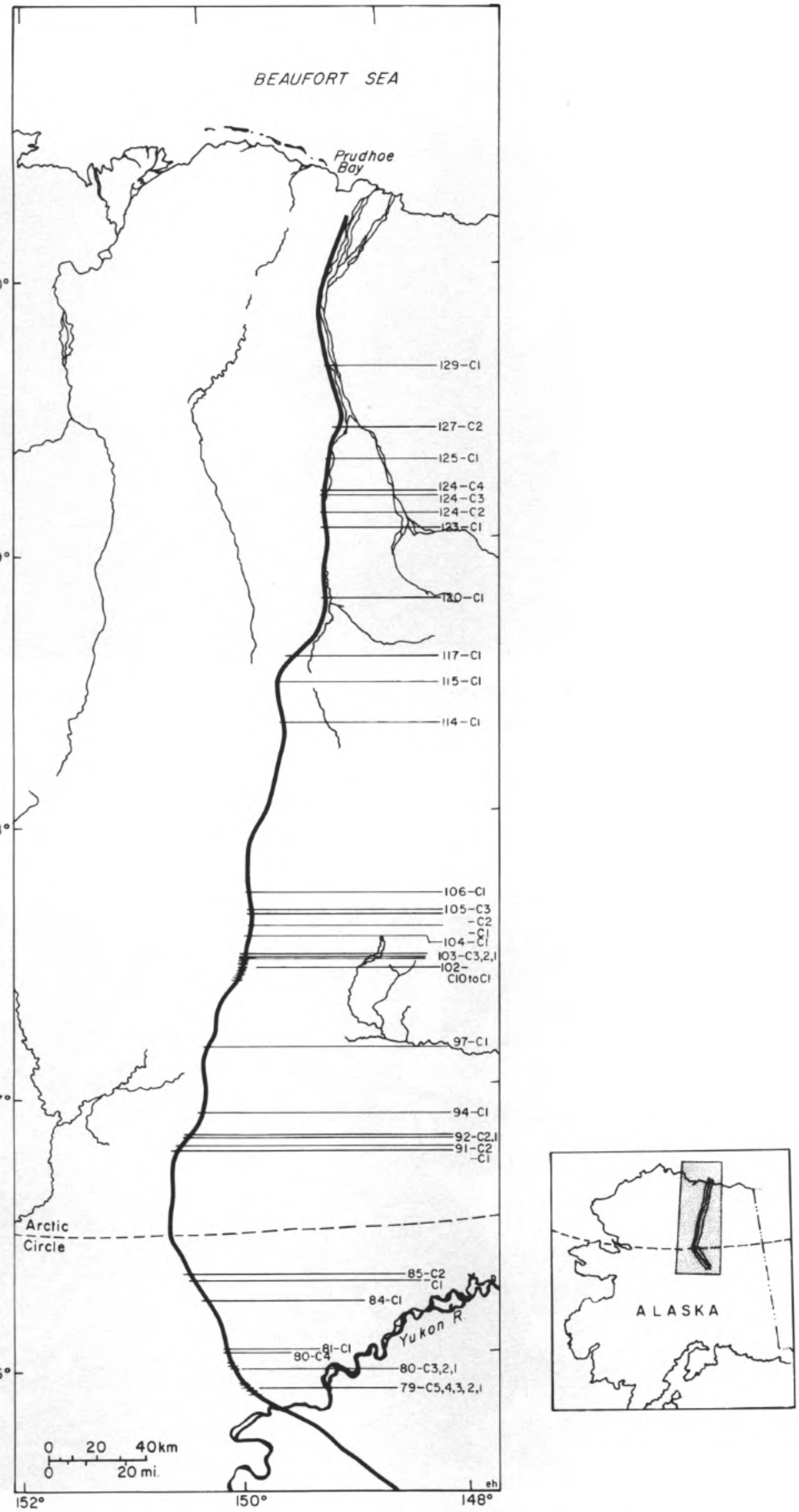


Figure 54. Location of culverts observed in this study.

Figure 55. Upstream ponding caused by shoulder thaw consolidation and bowing of the culvert, site 91-C1, August 1977.

Figure 56. "Maintenance clogging" problem caused by surface material graded down sideslope of road, site 91-C2, August 1977.

Figure 57. Maintenance clogging problem on a deep fill, site 121-C1, August 1977.

3. Culverts that have induced significant thermal erosion downslope from the roadway.

4. Culverts with poor inlet conditions causing erosion of the roadbed and subsequent deposition of eroded material downslope, causing partial blockage of the stream.

In addition to these common problems, induced icings and interruption of fish passage were two persistent problems, but are not discussed in this report.

Site 91-C1 (Fig. 55) is typical of locations where bowing of the culvert was caused by shoulder settlement resulting in upstream ponding.

The problem most frequently observed is termed "maintenance clogging" and results from regrading of the roadbed and related erosion. The regrading tends to lower the roadway surface elevation and at the same time widen it by plowing gravel onto the sloping shoulder. While this problem is not confined to cold regions, it is an important factor in these areas since most of the far northern roadways built in the future will probably remain gravel surfaced. Sites 91-C2 and 121-C1 (Fig. 56 and 57 respectively) illustrate maintenance clogging problems which also generally cause upstream ponding. Alyeska has been attempting to correct many of these problems, even if only on a temporary basis, by adding extensions onto smaller circular-shaped culverts or providing bank protection for larger culverts.

One of the most striking problems associated with drainage was thaw degradation and thermal erosion downslope from the roadway. These processes were induced by concentrating flow through culverts and onto ice-rich soils where nonconcentrated flow previously occurred. Sites 102-C1 and 102-C6 (Fig. 58 and 59, respectively) illustrate the extent of these problems and attempts to correct them. This problem is most pronounced on the ice-rich alluvial slopes along the Koyukuk River. Vegetation here consists of tussocks and black spruce, and the permafrost table is within 0.5 m of the surface. On similar slopes in other nearby areas, these problems were not observed as drainage was apparently directed into pre-existing drainage channels. Likewise, this problem was not observed at other locations where the slope, vegetation and permafrost conditions were seemingly similar. Whether or not this problem could have been identified at a given site prior to construction is debatable.

Inlet erosion problems were much more frequent north of Atigun Pass. In several cases, cul-

Figure 58. Drainage channel constructed to minimize additional thermal erosion downslope from the road, site 102-C1, August 1977.

Figure 59. Half sections of corrugated metal pipe (CMP) used to channel water downslope from culvert. The CMP sections were over a granular fill placed in a gully caused by thermal erosion, site 102-C6, August 1977.

Figure 60. Debris deposit at outlet of culvert, site 132-C1, August 1977.

verts were too short or roadway material was plowed onto the shoulder. During periods of peak flow, velocities at culvert inlets were accelerated and erosion frequently occurred. The roadbed material was carried through the culverts by the high velocities. The velocities rapidly diminished at the culvert outlet, causing material to be deposited. The result of this deposition was the filling of small, incised channels with coarse gravel and the creation of wide, flat streambeds. Water in many instances flowed through this gravel rather than over it, making fish passage difficult or impossible. Site 132-C1 (Fig. 60) illustrates this problem. Alyeska was attempting to correct many of these problems by providing upstream protection.

An example of seasonal ground ice formation induced by road construction is illustrated by the ice mounds that formed on the upslope side of the road a few kilometers south of Galbraith Lake (Fig. 61). They were observed in 1978 and appear to result from 1) downslope flow of water in the stream and/or through the active layer in the fall, 2) freezing of water and gradual blockage of the culvert, 3) freezing of accumulating groundwater at the interface of the permeable organic mat and impermeable frozen substrate, and 4) buildup of ice during the winter causing uplift and rupture of the vegetative mat. Melting of this ice in addition to the normal flow of water in 1978 resulted in increased erosion and loss of much of the vegetation across an area approximately 15 m wide near the culvert inlet. Similar ice phenomena were observed at the base of Slope Mountain and on the west side of the Haul Road immediately north of Pump Station 3. In these two cases, stream flow was apparently impeded and ice growth from blocked drainage lifted large areas of sod and vegetation.

Drainage problems parallel to the roadway

In the course of our observations some drainage problems parallel to the roadway were observed on the Arctic Coastal Plain. A few instances of severely detrimental road interactions with the permafrost and ground ice were observed, and two examples are discussed below.

The road is constructed on the higher terraces of the Sagavanirktok River and, in general, approximately ½ to 1 m of sands and silts overlies more gravelly river deposits. Although polygonal ground is common, the maximum width of the underlying ice wedges is small (<0.5 m). The quantity of segregated ground ice in these sandy and gravelly sediments is not very large.

Access roads to the material sites in the river run nearly perpendicular to the Haul Road. These access roads sometimes serve as dams,

Figure 61. Seasonal ground ice mounds upslope from the culvert at station 1198+50 on Haul Road segment 5 just south of Pump Station 4, August 1978.

Figure 62. Inundation adjacent to the Haul Road on the Coastal Plain was frequently observed on the southeast intersection of road and access road, 30 June 1976. In this case the ponding is overtopping the access road. Ponding generally persisted throughout the summer and eventually culverts or low water passes were installed.

Figure 63. Inundation adjacent to the Haul Road looking upslope to the northeast by access road 133-2, 7 July 1976.

ponding water to 1 m in depth. Generally no culverts were placed under the access roads as they were used for temporary access to material sites. As a result, impoundments occurred at the upslope intersection of the Haul Road and access roads, and the water occasionally overflowed and breached the access roads (Fig. 62, 63 and 64). Some of these impoundments persisted for several summers until low water crossings through the road were constructed or culverts were installed. Thaw depths were measured in the inundated area and on the unflooded and opposite side of the access roads (Table 22). The shallow ponded areas generally show a greater depth of thaw than the undisturbed sites. If these areas had contained large quantities of ground ice, degradation of the permafrost could have been more severe. The influence of flooding on the composition of the vegetation will be discussed in a later section.

An example of channelized flow along the Haul Road was observed about 30 km north of Franklin Bluffs Camp (Fig. 65 and 66). In this instance spring runoff became channeled in the small trench containing the buried fuel gas line, and some headward erosion of pre-existing polygons was initiated. The area was sand-bagged to control erosion and later the entire area was covered with gravel (Fig. 66).

Table 22. Influence of impoundments on thaw penetration adjacent to the Haul Road.

Transect		Depth of thaw (cm) 16 Aug 1976	7 Aug 1977
133-2*	T-2-S	56 (under 20 cm of water)	72 (under 8 cm of water)
	T-2-N	64 (undisturbed)	67 (undisturbed)
132-1†	T-1-S	71 (ponded)	70 (originally ponded)
	T-1-N	61 (undisturbed)	60 (undisturbed)

* Average of 7 probings per line. Intersection of the Haul Road and access road 133-2.

† Average of 31 probings per line. Intersection of the Haul Road and access road 132-1.

Figure 64. Inundation adjacent to the access road for material site 134-3 showing raised edges of ice-wedge polygons, 30 June 1976.

Figure 65. Result of channelized flow over the buried fuel gas line on alignment sheet 133, 24 June 1976.

Figure 66. Area shown in Figure 65 was later covered with gravel, 17 August 1976.

Figure 67. Gravel berms on roadway by site 107-1, 28 August 1977.

Roadway surface drainage problems

Because the gravel-surfaced roadway must be frequently regraded to maintain a relatively smooth surface, small berms of gravel are often created on one or both sides of the roadway (Fig. 67). When it rains the water cannot readily pass through the berms and must flow downslope until the berm is breached. The breach generally occurs in a low spot on the longitudinal profile of the road, and culverts are usually located at these locations. If the volume of water flowing through the breach is large, erosion of the sideslope may occur (Fig. 68). The alluvium from the road surface and sideslope cause siltation of the stream.

Figure 68. Erosion of side slope due to drainage down the road, 28 August 1977. Also, note small berms which have been formed by most recent grading.

Installation of guard rails usually causes more problems associated with the gravel berms. When a berm is created immediately below a guard rail, the only methods of removing the berm are by manually shoveling or by careful manipulation of a backhoe. Either method is time-consuming and costly and therefore frequently is not accomplished. At a few locations on the recently reconstructed Elliott Highway, breaching of gravel berms beneath guard rails has caused major erosion of side slopes. In maintenance grading it is very important that cross slopes be maintained and that even small gravel berms not be permitted.

Performance of sideslopes

The design of cuts in permafrost soils crossed by the road has attracted considerable attention. The TAPS Road (Yukon Highway), constructed in 1969 and 1970, crossed terrain which required several cuts into ice-rich permafrost. Numerous reports and articles have been prepared from observations of these cuts (e.g. Smith and Berg 1973, Lotspeich 1971, Pufahl et al. 1974). Figures 69–74 from Berg and Smith (1976) illustrate the chronological behavior of one of the ice-rich cut slopes along the Yukon Highway. Recession and recovery of this slope is typical of most ice-rich slopes along the Yukon Highway. Generally the slopes were cut nearly vertically, i.e. with slopes of 1:4, to minimize the surface area exposed to the new thermal environment. Figure 74 illustrates the idealized stabilization of an ice-rich cut in interior Alaska. Only a few ice-rich cuts were required on the Haul Road, and test site 97-1, established for this study, is at one of them.

Figure 75 shows the performance of the cut at Test Site 97-1. Slopes on both sides of the road have been relatively stable during the period of these investigations, although the roadbed has subsided. As with the ice-rich slopes south of the Yukon River, most of the sideslope instability occurred during the first year or two after the cut was made. The east slope does not look neat because trees have fallen into the receding face. Minor maintenance, i.e. seeding and fertilizing, would improve the appearance of this cut; however, the slope appears quite stable in its present condition. McPhail et al. (1976) describe the behavior and remedial measures taken at the ice-rich cut approximately 5 km south of Happy Valley Camp.

Performance of the ice-rich slopes at site 97-1 and at other locations along the Haul Road indicates that the recommendations and guidelines made by Smith and Berg (1973) and Berg and Smith (1976) are valid. These are:

1. Cut nearly vertical backslopes on the cuts.

Figure 69. Frozen, nearly vertical backslope exposing large ice masses, left side of TAPS Road, mile 20.25 on 23 April 1970, (from Berg and Smith 1976).

Figure 70. Ice face with overhanging mat and hydroseeded lower portion of slope, left side of TAPS Road, mile 20.25 August 1970 (from Berg and Smith 1976).

2. Provide a wide ditch at the base of the cut to allow removal of material if necessary and to allow deposition of some overlying material during the stabilization process. A wide ditch will also permit a porous revetment to be made to enhance drainage and stabilization of the slope.

3. Clear trees and brush from the top of the slope for a distance about equal to one and one-half times the height of the slope. Stumps should be cut as close to the soil surface as possible; i.e. they should be less than 0.3 m (1 ft) high. Although it was not done on any of these slopes,

Figure 71. Overall view of slope, left side of TAPS Road, mile 20.25, 17 August 1971 (from Berg and Smith 1976).

Figure 72. Tree growth near ditch line on portion of backslope, left side of TAPS Road, mile 20.25, 14 September 1975 (from Berg and Smith 1976).

nailing a coarse wire mesh to the stumps would provide additional tensile strength to the organic mat and reduce the amount of tearing of it, especially on higher backslopes. As melting and subsidence occur during the stabilization process, it might be necessary to remove additional trees from the top of the slope. This cutting, as well as the initial cutting, should be accomplished with hand tools. Heavy construction equipment should not be used outside the lateral limits of the excavation area.

4. Seeding should be attempted only on relatively stable portions of the slopes at selected times. If the slope is exposed in the early spring,

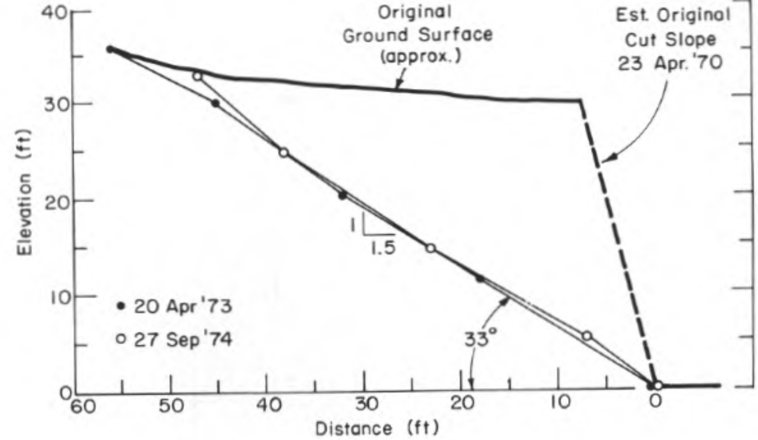
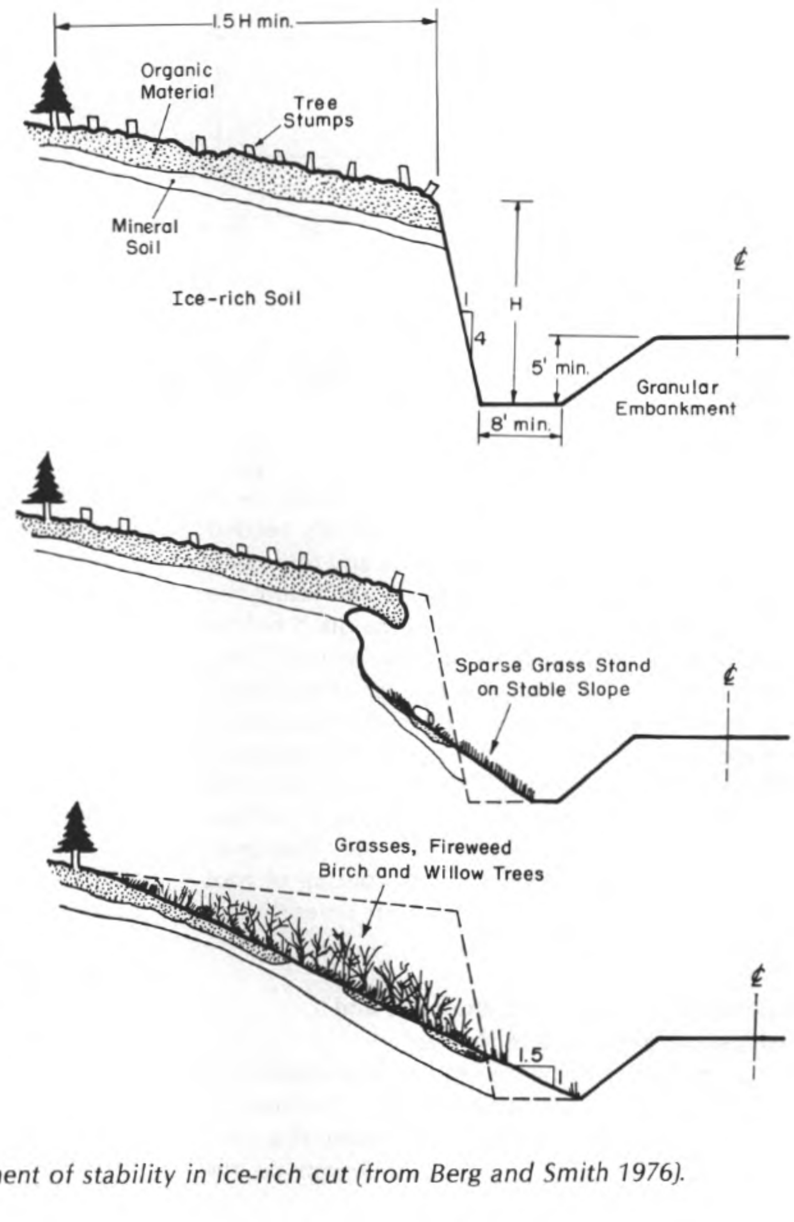


Figure 73. Slope profile measurements, left side of TAPS Road, mile 20.25 (from Berg and Smith 1976).



a. Initial frozen cut profile.

b. End of first thaw season. Slope is mostly unstable and very unsightly; ditch will require cleaning if massive ice is present.

c. End of fifth or sixth thaw season. Slope stabilizes with reduced thaw and vegetation established. Free water from minimal thawing is used by plants whose root systems develop new organic material.

Figure 74. Idealized development of stability in ice-rich cut (from Berg and Smith 1976).

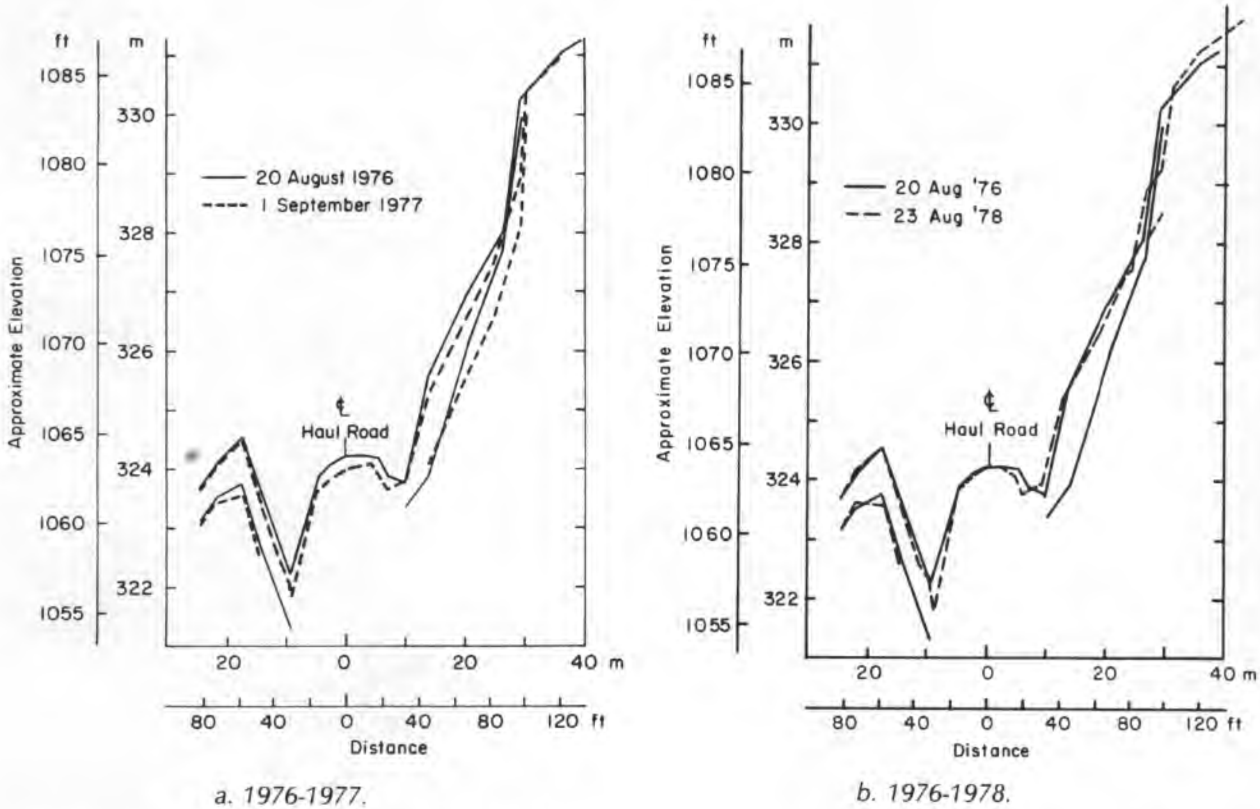


Figure 75. Surface elevations at site 97-1 just south of Rosie Creek, about 198 km north of the Yukon River.

near the end of the first thaw season the lower portion of the slope should be heavily seeded with annual and perennial grasses and fertilized. This will establish a relatively firm and stable toe of the slope down to the drainage ditch before thawing occurs the following thaw season. If this procedure is followed for two or three years, grasses should become established in successive stages up the slope to meet with the subsiding organic mat from the top of the cut. During the second and third summer, seedlings of willow and birch trees could also be set. However, natural invasion by seed or resprouting of root material is likely to occur within several summers.

Conclusions from road, drainage and sideslope performance studies*

1. Seasonal thaw penetration probably exceeds the roadway embankment thickness in most locations. However, it probably does not penetrate the 1.5-m-thick embankment on the extreme north end of the road and at other locations where the fills are extremely thick. The seasonal thaw penetration into the subgrade soils beneath the roadway embankment probably also exceeds the undisturbed thickness of active layer. This was the situation at all of our temperature-instrumented sites.

2. The roadway has subsided to some degree over most of its length. Some of the "apparent subsidence" may be due to regrading of the road during maintenance operations, but at 11 of our 27 observation sites, the subsidence has been in excess of 10 cm and at five of these sites subsidence exceeded 20 cm.

3. No strong relationship between subsidence, embankment thickness and cone index (soil strength) was apparent. Consideration of thaw depth in the subgrade material may produce a more significant relationship.

4. The ice-rich side slopes tend to stabilize after a few years but thaw degradation and resulting subsidence continue beneath the ditches and roadway embankment. This was also the case along the TAPS Road.

*Prepared by R.L. Berg and G.L. Guymon.

5. The most frequent problem related to cross drainage was observed to be "maintenance clogging" of culverts. The problem is caused when short culverts are entirely or partially blocked by gravel deposited downslope from frequent grading. This prevents water movement through one or both ends of the culvert.

6. The most striking problem associated with cross drainage was combined thermal and hydraulic erosion downslope from the roadway that was apparently induced by concentrating flow through culverts and onto ice-rich soils where nonconcentrated flow previously occurred. Future terrain interpretation may result in better placement of culverts to avoid such downslope ice conditions. Most occurrences of this problem were located slightly south of Dietrich Camp on the alluvial slopes along the Koyukuk River.

7. To date only a few drainage problems have been caused by water flow parallel to the road. The most numerous problems of this type result from ponds of various sizes and depths caused by interception of lateral drainage by access roads which generally did not initially have culverts or low water crossings. The most visible problems were caused by thermal erosion due to concentrated flow over the backfilled trench of the fuel gas line.

8. The major roadway surface drainage problem is the creation of small longitudinal berms on one or both sides of the road due to regrading. These dikes inhibit lateral runoff except at locations where the berms are breached. Severe sideslope erosion and stream siltation sometimes occur where the berms are breached. Berms can generally be eliminated by skillful equipment operators during regrading.

9. Performance of the ice-rich slopes substantiates previous recommendations and guidelines:

a. Cut nearly vertical backslopes.

b. Provide a wide ditch at the base of the cut to allow removal of material, if necessary, and to allow deposition of some overlying material during the stabilization process.

c. Clear trees and brush from the top of the slope for a distance about equal to one and one-half times the height of the slope. Stumps should be cut as close to the soil surface as possible.

d. Seeding should be attempted only on relatively stable portions of the slopes at selected times. Natural invasion by seed or resprouting of root material is likely to occur within several summers.

Fuel gas line construction*

During the 1975-76 winter, Alyeska initiated construction of a 25-cm-diam gas line between Pump Stations 1 and 4, a distance of about 230 km. The purpose of the line is to provide fuel for the turbines powering pumps at Pump Stations 2, 3 and 4. The fuel gas line was installed adjacent to the Haul Road over most of its length, but paralleled the oil pipeline in some instances (Fig. 76). Although the installation of this small diameter pipeline was originally scheduled to be completed during one winter season, unanticipated construction problems necessitated a second winter (1976–1977) for completion (Bock 1979, Keyes 1977, Carson and Milke 1976, Mechanics Research Inc. 1977a).

The excavation of the gas line trench, the backfilling of the trench and subsequent erosion control and revegetation procedures provided opportunities to examine the response of permafrost to trenching and burial of a utility line in close proximity to the road. It is expected that knowledge gained from the burial and restoration of this small diameter gas line will be incorporated into routing and scheduling activities for the proposed large diameter gas pipeline. Observations provide valuable information on methods to control erosion, on associated revegetation problems and on the effects of snowpad construction upon vegetation and the underlying tundra.

CRREL personnel observed construction of the fuel gas line several times during the two winters, and observation was also made of the cleanup, erosion control, and revegetation procedures employed during the summers of 1976, 1977 and 1978. Engineering considerations of the snowpad construction are described elsewhere (Johnson and Collins 1980, Mechanics Research Inc. 1977a).

The entire fuel gas line, except for short sections along the oil pipeline workpad and at stream crossings, is generally situated within 5 m of the downslope toe of the Haul Road. At stream crossings the line is offset from the road. Snowpads were used to construct all portions of the line except those on the oil pipeline workpad. Snow was first collected alongside the road by using a truck-mounted backhoe (Gradall) to collect snow from the road shoulder into berms on the edge of the road (Fig. 77). These berms served to catch additional blowing snow. When

*Prepared by L. Johnson and J. Brown

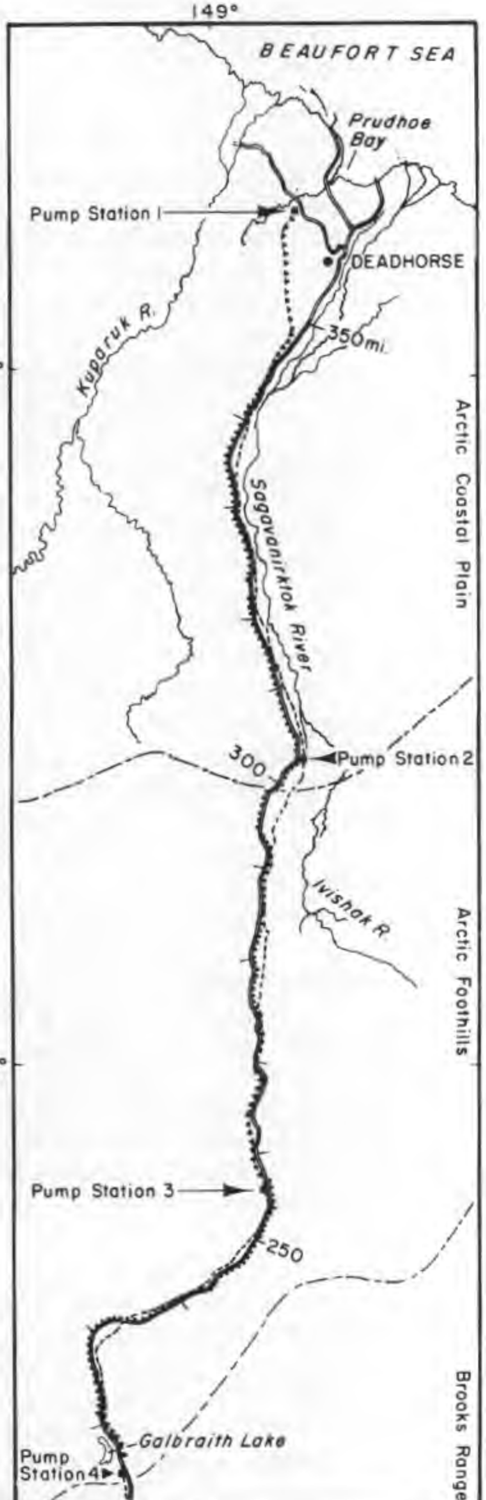


Figure 76. Generalized location of fuel gas line (▲▲) as it parallels the Haul Road and oil pipeline (- -) between Pump Stations 1 and 4.

adequate snow was collected, the berms were leveled by grading and by bulldozers dragging metal net or steel beams for packing the snowpad (Fig. 78). A total of 182 km of snowpad was built between December 1975 and April 1976 between the areas on Alignment Sheets (AS) 114A and 121 and AS 123 and 134. A total of 116 km of snowpad was built the following winter between AS 123 and 134.

Trenching operations involved several different methods and types of equipment. Initially, a small snowblower removed most of the snowpad over the ditch locations. Then either a specially developed trencher (Roc-Saw) or a conventional type of trencher (Barber Greene) began trenching operations. In fine-grained soils, the special trenchers provided a 46-cm-wide × approximately 1.8-m-deep trench in a single pass conveying the pulverized spoil to the edge of the road (Fig. 79). The conventional trencher (Fig. 80) cut a wider (60 cm) and shallower trench. The 8- to 15-cm-diam pieces of spoil were moved onto the snowpad or to the side of the road by a conveyor system. The two machines were occasionally used in tandem, in which case the conventional trencher made an initial pass to remove the surface sod and the upper 0.3 m or so of frozen soil, and the special trencher completed the trench on a second, deeper pass. In this case the spoil was either deposited on the road shoulder by the conveyor system or more frequently, deposited directly on the snowpad. The spoil was subsequently graded into piles and hauled away to disposal sites. This method, unfortunately, left some spoil on the snowpad which during the late spring induced melt and deterioration of the snowpad (Johnson and Collins 1980, Carson and Milke 1976).

The first winter's (1975-76) trenching began in the vicinity of Franklin Bluffs and between Galbraith and Toolik Camps. In the latter area the trenching quickly encountered problems, primarily due to glacial till containing boulders and also due to blowing snow which rapidly filled the open trench. In these bouldery sections between Galbraith Lake and Slope Mountain, it was necessary to blast most of the trench. After blasting, backhoes were used to clean out the trench which was frequently up to 1.8 m wide (Fig. 81). Between Galbraith and Toolik Lakes, large charges of explosives were also used as evidenced by the numerous pieces of debris, up to 25 cm or more in diameter, which were blown

Figure 77. Truck-mounted backhoe making berm beside road shoulders in order to catch additional snow used for snowpad construction.

Figure 78. Bulldozer packing snowpad by dragging steel beams.

Figure 79. Specially designed trenchers (Roc-Saw) excavating the fuel gas line trench through the snowpad. Spoil was deposited on the road shoulder.

Figure 80. Conventional type of trencher (Barber Greene) used for ditching fuel gas line.

Figure 81. View of blasted fuel gas line trench after excavation by a backhoe.

off to either side of the trench to distances up to 30 m.

Prior to deeper trenching, surface organics which contained living vegetative parts and which would provide added moisture holding capacity to the seedbed were to be removed, stored, and later used for revegetation (Carson and Milke 1976). Sod chips were obtained from the conventional trencher which made the initial shallow pass before the special trencher completed the trench. Some operators were able to consistently remove the organic layer with just a small amount of mineral soil, whereas others cut more deeply so that the organics only formed a small percentage of the "sod chips." Chips were usually placed on the snowpad, graded into piles, and were then trucked to irregularly-spaced disposal sites for temporary storage. Ideally, chips should have been immediately collected in containers to avoid mixing with the snow. These materials could then have been returned to the trench in the same general area so as to correspond with the original soil and vegetation conditions. In addition to mixing snow into the chips, the handling also broke the chips up so that the average chip size was relatively small (5 to 8 cm in diameter).

After trenching was completed, gravel was placed in the trench for bedding, the pipe was placed in the trench, and the trench backfilled with additional gravel. Gravel for backfill initially was hauled by dumptruck or belly-dump trailer to the trench, dumped onto the snowpad, and then graded into the trench by a bulldozer (Fig. 82). This method left significant quantities of gravel on the snowpad.

Later in the spring of 1976 and during the 1976-77 winter a cleaner method was developed. The gravel was dumped onto the edge of the roadside, graded into a berm, rocks were removed by hand, and then a "wooly-worm" (consisting of an auger mounted on grader for intake

Figure 82. Gravel for backfilling the fuel gas line trench being dumped onto snowpad prior to fill operation.

Figure 83. "Wooly worm" backfilling fuel gas line trench with gravel from road shoulder.

and a long chute for placement) was used to put the gravel directly into the ditch (Fig. 83). In order to prevent thaw over the pipe and maintain pipe and soil at the same temperatures, strips of rigid insulation were placed below ground level in the trench at a depth of approximately 30 cm. The insulation was covered by enough gravel to form a small berm. Due to the dirty snowpad and the uneven thickness of the snow, it was frequently difficult to detect the soil surface so that insulation at times was mistakenly placed either above or at improper depth below the ground surface. In specified areas, either sod chips or spoil from the special

Figure 84. Crane with clam bucket scraping debris from snowpad. This equipment was also used to place backfill over the trench from the road during the summer.

trencher was placed over the gravel berm before thawing occurred.

Cleanup operations to remove debris from the pad were of several types. Along blasted sections of trench, groups of hand laborers picked up broken snow fence and insulation fragments which had been used to protect the welded pipe during blasting. Self-loading scrapers were used to remove most of the spoil and gravel from the snowpad. Work continued on the fuel gas line into late spring 1976. The snowpad, as it softened, became increasingly contaminated with both spoil from the trench and gravel from backfill. For example, debris 15-25 cm thick was frequently seen on the snowpad right-of-way in May. Later in the spring after meltoff, backhoes and cranes with large buckets scraped debris from the tundra while remaining on the road (Fig. 84). As the cleanup continued in July and August these layers of gravel and spoil were reduced to scattered patches less than 3 cm in depth in most instances. However, the cleanup operations also removed sod chips from the surface of the ditch and often sheared off the tops of *Eriophorum vaginatum* tussocks and other upright vegetation.

Hydraulic erosion became a serious problem along and over the fuel gas line during spring breakup in 1976. Water filled some sections of the ditch which had not been backfilled. Frequently water from culverts washed gravel out of the ditch and in some places water became channelized over the trench. In order to alleviate these problems various corrective measures were taken. Insulation was placed beneath the true ground surface and the trench was backfilled above ground level by the "wooly worm" technique. Half culverts or lined channels were extended across the trench from existing culverts and problem areas were sandbagged to deter water from running down and over the fuel gas line (Fig. 85). The backfill operation continued into the summer 1976 along the blasted trench where subsidence and slumping continued to occur. One area where erosion was particularly severe was entirely covered with gravel during summer 1976 to form a pullout next to the Haul Road (Figs. 65 and 66). Immediately north of the entrance to Galbraith Camp, jute netting was employed in conjunction with seeding, fertilizing, and cross drainage structures.

During the winter of 1976-77 the fuel gas line was completed from just north of Happy Valley Camp to Pump Station 1. Construction activities during the period differed considerably from those of the previous winter. The trench was dug by one of the two types of trenchers, but near

Figure 85. Half culvert in background adjacent to road culvert and lined ditch channel downslope from the fuel gas line.

Sagwon the bottom 1/2 m of trench, in bedrock, was completed by blasting. The top of the ditch in this area was 1 to 1.3 m across as opposed to 2 m across in some blasted sections of trench the previous year. In many instances the spoil from the ditching operations was deposited directly onto the road shoulder by the trenchers. This material was then graded across the road surface. However, when early thaw began, problems with both a slippery road surface and dust occurred. As a result of the dust, the snow cover adjacent to the road melted considerably earlier than the snow cover elsewhere.

Whereas long sections of trench remained open during the 1975-76 winter, in 1976-77 the trench was allowed to rapidly backfill with blowing snow. Later the snow-filled trench was reexcavated, the pipe was placed into it, and the trench was immediately backfilled with gravel. Backfilling relied upon several different methods such as use of the wooly-worm or a small bucket to place gravel directly into the trench. At no time was gravel observed to be dumped directly onto the snowpad as in the previous winter. As expected, this contributed to a much cleaner snowpad and much less debris on the tundra after meltoff.

Erosion and more subsidence continued during the summer of 1977 along portions of the fuel gas line. Backfilling operations using a crane with a clamshell bucket operating from the road were still being observed in early August 1977 (Fig. 84). New half culverts and other cross drainage structures were also installed during 1977. However, the severity and frequency of problems was reduced in 1977 as compared to 1976. During early June 1978, large volumes of water were observed running along the fuel gas line on the Coastal Plain, but no new erosion problems were observed at that time. Some areas were again backfilled during 1978.

There were marked differences in the degree of tundra disturbance due to the various methods of excavating the trench (blasting, using the special trencher, conventional trenching) and backfilling along the fuel gas line. In order to assess differences between the special and conventional trenchers, permanent observations points were established in each of the two major physiographic regions (Arctic Foothills and Arctic Coastal Plain) during both winters. Sites were also selected along the blasted trench between Slope Mountain and Galbraith Lake. Portions of this section were reseeded during early summer 1976, but vegetative cover was generally less than 10% by late summer 1976 and remained low into 1978. Whenever possible, a transect to measure depth of thaw was established in 1976.

Table 23. Depth of thaw (cm), and vegetation cover observation along the fuel gas line pad (see Fig. 17 for position of sample points).
Numbers in parentheses show standard errors of thaw measurements. Cover classes: 1 = 1–10%, 2 = 11–20%... 10 = 91–100%.

		Depth of thaw				Vegetation cover													
						Toe-Trench (A)				Trench (B)		Trench-Snowpad edge (C)				Undisturbed			
Site		*(A) Toe-Trench*	*(B) Trench-snowpad edge*	*(C) Undisturbed*	*Average all snowpad*	*Debris*	*Live vasc.*	*Dead vasc.*	*Live moss*	*Reveg.*	*Max. ht. (cm)*	*Debris*	*Live vasc.*	*Dead vasc.*	*Live moss*	*Debris*	*Live vasc.*	*Dead vasc.*	*Live moss*
										Foothills sites									
Blasted and backhoe																			
116-1	1976	87	65 (13.0)	56.7 (4.3)	70.5 (10.7)	10	0	—	—	1	20	7	3	—	—	—	—	—	—
						10	9	0	0	1	60	4	5	1	1	0	6	1	5
117-1	1976	Too rocky to probe				9	1	—	—	1	5	9	1	—	—	—	—	—	—
	1978					9	8	0	0	3	70	5	3	1	2	1	6	1	6
118-1	1976	Too rocky to probe				0	0	—	—	1	15	6	3	—	—	—	—	—	—
	1978					2	8	1	0	6	50	3	4	2	1	1	4	3	5
Roc-Saw																			
124-1	1976	51.7 (5.0)	57.0 (9.5)	42.8 (3.3)	54.3 (5.2)	8	1	—	—	—	—	6	4	—	—	—	—	—	—
	1978	62.3 (1.7)	54.7 (1.5)	30.3 (1.8)	58.5 (1.9)	3	7	1	3	1	10	1	4	1	8	1	6	2	5
124-2	1976	45.0 (6.7)	45.3 (2.6)	39.8 (5.4)	45.2 (3.2)	6	3	—	—	—	—	1	0	—	—	—	—	—	—
	1978	58.0 (3.5)	34.3 (0.9)	31.7 (2.0)	36.2 (5.5)	6	2	1	1	1	5	1	6	2	4	1	5	1	7
124-3	1976	41.3 (2.3)	42.0 (2.5)	33.5 (6.9)	41.7 (1.5)	4	4	—	—	—	—	1	6	—	—	—	—	—	—
	1978	69.3 (4.1)	38.7 (4.7)	38.7 (2.4)	54.0 (7.4)	6	3	1	1	1	5	1	6	2	1	2	7	2	2
124-4	1976	Unditched		37.5 (9.6)	30.8 (1.6)														
	1978	50.7 (4.8)	45.3 (4.8)	35.7 (2.8)	48.0 (3.3)	7	3	1	1	2	5	6	2	3	1	1	8	2	2
125-1	1976	Unditched		29.5 (1.0)	35.2 (2.3)														
	1978	37.7 (0.3)	38.3 (1.9)	31.7 (1.2)	38.0 (0.9)	2	5	1	6	2	20	1	5	1	8	1	3	3	4
125-2	1976	Unditched, gravel thawed more than 100 cm																	
	1978	80.7 (2.4)	82.7 (1.8)	56.0 (1.2)	81.7 (1.4)	8	2	1	1	1	5	2	3	3	1	1	4	1	5
127-1	1976	Unditched		38.7 (5.2)	37.4 (5.9)	2	3	—	—	—	—	—	—	—	—	—	—	—	—
	1978	65.0 (1.2)	55.7 (6.1)	29.3 (1.8)	60.3 (3.5)	8	2	1	1	1	15	2	4	3	2	1	7	2	5
										Coastal Plain sites									
Roc-Saw																			
128-1	1976	70.3 (5.9)	65.7 (2.3)	51.3 (0.9)	68.0 (3.0)	4	6	—	—	—	—	1	10	—	—	—	—	—	—
129-1	1976	76.5 (0.5)	57.0 (3.5)	40.3 (2.3)	64.8 (5.2)	2	—	—	—	—	—	8	—	—	—	—	—	—	—
129-2	1976	63.7 (0.3)	62.3 (3.7)	63.9 (1.7)	45.3 (2.7)	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	1978	71.7 (6.3)	69.0 (3.5)	40.7 (0.3)	70.3 (1.7)	9	6	2	0	1	15	8	4	5	10	2	4	6	6
130-1	1976	Unditched		48.3 (1.5)	49.0 (1.4)	3	5	—	—	2	—	—	—	—	—	—	—	—	—
	1978	63.0 (3.0)	56.0 (2.3)	51.7 (2.3)	59.5 (2.3)	10	5	2	0	1	2	9	5	5	1	5	5	3	3
130-2	1976	Unditched		58.7 (2.4)	56.4 (1.3)	2	6	—	—	2	—	—	—	—	—	—	—	—	—
	1978	62.7 (2.4)	71.0 (2.1)	58.3 (1.2)	66.8 (2.3)	10	5	2	1	1	7	8	3	5	1	7	4	7	1
130-3	1976	Unditched		64.4 (0.6)	58.6 (4.7)	3	4	—	—	3	—	—	—	—	—	—	—	—	—
	1978	68.0 (0.6)	66.7 (1.8)	72.0 (2.3)	67.3 (0.9)	9	6	4	1	1	10	9	6	6	1	8	5	6	1

Probing was performed between the road and the trench (A, see Fig. 17), the trench and the outer edge of the snowpad (B), and at a number of points beyond the snowpad for control (C) Measurement of thaw was repeated in 1978. Supplemental observations on percentage cover of debris (gravel and spoil), percentage cover of vascular plants, and species differences for vegetation damage were also recorded. A photograph was taken at each site for a permanent record (Johnson 1980).

Data from the fuel gas line are summarized in Table 23 and general comments on the depth of thaw and vegetation damage and recovery are presented below.

1. Beneath the snowpad, microtopography was reduced due to such factors as debris filling the depressions and abrasion of tussock or hummock tops. Areas under thinner snowpad or with more pronounced microrelief were more severely affected.

2. Percentage cover by debris was much greater where gravel for the backfill was first placed on the snowpad. Consequently, the cover of vascular plants was reduced.

3. Depth of thaw was generally greater under the snowpad than in undisturbed tundra. The increase in depth of thaw ranged up to 30 cm. In most cases the depth of thaw was increased between the road and the fuel gas line trench, although it was not easy to differentiate trench and road effects on thaw. The untrenched snowpad in 1976 caused less than 1 cm of average increase in the depth of thaw whereas the same areas in 1978 had an average depth of thaw increase of more than 10 cm approximately 18 months after trenching. It is not known whether this difference is due to the debris deposited on the tundra during trenching and backfilling operations, characteristics of the trench itself, or traffic associated with trenching and backfilling the gas line. In most cases the amount of increased depth of thaw associated with the snowpad was greater in 1978 than in 1976. Since 1977 depths of thaw are not available, it is not known whether depths of thaw are still increasing or whether they have stabilized or begun to decrease.

4. Plant species varied in susceptibility to damage from snowpad construction and debris. Upright shrubs such as willows and birch were frequently sheared off. Some impacted *Betula glandulosa* leaves died shortly after leafout in 1976; however, most of these recovered by 1978. Mosses, possibly due to their low stature, were more susceptible to damage from the debris. In at least several instances, *Arctagrostis latifolia* was flowering more profusely where the snowpad had been than outside it. Percentage cover of vascular plants was very similar under the snowpad and on undisturbed tundra by 1978.

5. The backfilled trench formed a berm which appeared very narrow and well-defined where the Roc-Saw trencher was used, especially where it was backfilled from the road.

6. Although snowpad construction, trenching, and backfilling operations did cause some environmental damage to the tundra, the degree of vegetation damage, and permafrost degradation due to construction activities were relatively minor when the operation was carefully conducted and blasting was not used.

7. The use of sod chips cannot be evaluated because of the subsequent cleanup operations which dislodged most of them. However, in August 1977 some sod chips over the 1976 portion of the trench contained viable growth of cottongrass (*Eriophorum vaginatum*).

8. Success of revegetation over the trench in the first several years was limited. Vegetative cover averaged less than 20% but was higher where the trench was wet.

CHAPTER 3. DISTRIBUTION AND PROPERTIES OF ROAD DUST ALONG THE NORTHERN PORTION OF THE HAUL ROAD

by K.R. Everett

Introduction

The dispersal and composition of dust [generally material less than 200 μm in diameter (West 1968)] over the surface of the earth has been of long-standing interest to geologists and agronomists. The physical processes by which sand-size and finer materials are moved by air currents and the factors that operate to regulate the processes are well known (e.g. Bagnold 1941, and Chepil 1945). Much of the geological research on dust has centered on loess particles (10 to 50 μm) that, for the most part, seem to be transported less than 300 km from their point of origin (van Heuklon 1977, Péwé pers. comm.*). Within the last several decades both geologists and agronomists have become interested in long-distance (intercontinental) transport of dust, which occurs mostly from particles between 1 and 2 μm, (e.g. Jackson et al. 1971, Prospero and Ness 1977). It is recognized that this tropospheric dust may contribute substantially to the mineralogy of distant soils.

Until quite recently, relatively little attention has been directed toward the anthropogenic evolution of dust. Although the phenomenon is as old as man, it has become chronic and widespread only since the advent of mechanized travel. One of the earliest studies of road dust is that of Tamm and Troedesson (1955). These authors sampled dust load (volume and composition) in snow columns taken from a series of eight sites along two transects on either side of an unpaved road to a distance of 150 m. They found a relationship between dust fall and wind direction and velocity, and established that total load decreases rapidly away from the point source. Medium and coarse sand (and gravel) were deposited in the first 5 m, fine sands between 5 and 20 m, and silt and finer fractions beyond 20 m. Water and hydrochloric acid-soluble Ca, Na, K and P all showed regular decreases with distance. From these studies Tamm and Troedesson (1955) concluded that road dust supplied relatively large amounts of nutrients, especially calcium, to the surroundings.

More recent investigations have shown that in addition to silica, a principal component of road dust (Roberts et al. 1975), minerals of local origin (e.g. asbestos) could be significant components of the fine fraction (Rohl et al. 1977).

Recent laboratory simulation as well as field studies dealing with the physical factors involved in dust emission from construction haul roads (Roberts et al. 1975, Dyck and Stukel 1976, and Struss and Milucki 1977) have demonstrated relationships among the soil-water potential of the road surface, road soil type, and vehicle speed and weight. Eller (1977) has demonstrated the effect of road dust in increasing plant leaf temperatures and has postulated effects on net photosynthesis and productivity due to the increased temperature.

With the completion of the Haul Road, for the first time an all-weather gravel road crossed a significant portion of tundra (both upland tussock tundra and wet coastal plain tundra) that had not been subjected to other than tropospheric inputs or local dust fall (loess). Loess along the Haul Road is derived primarily from the Sagavanirktok River, especially in that portion north from its junction with the Lupine River.

During the winter when the roadbed is frozen, evidence of dust is not obvious. However, as the road surface thaws and dries, the presence of dust becomes more apparent as snow-covered

*Personal communication, T.L. Péwé, Arizona State University.

Figure 86. Early melt of winter snow adjacent to Haul Road near the Toolik dust site as viewed to the north, 26 April 1977. Increased melt on west side is indicative of increased dust load and a probable winter dominance of northeast winds in this area.

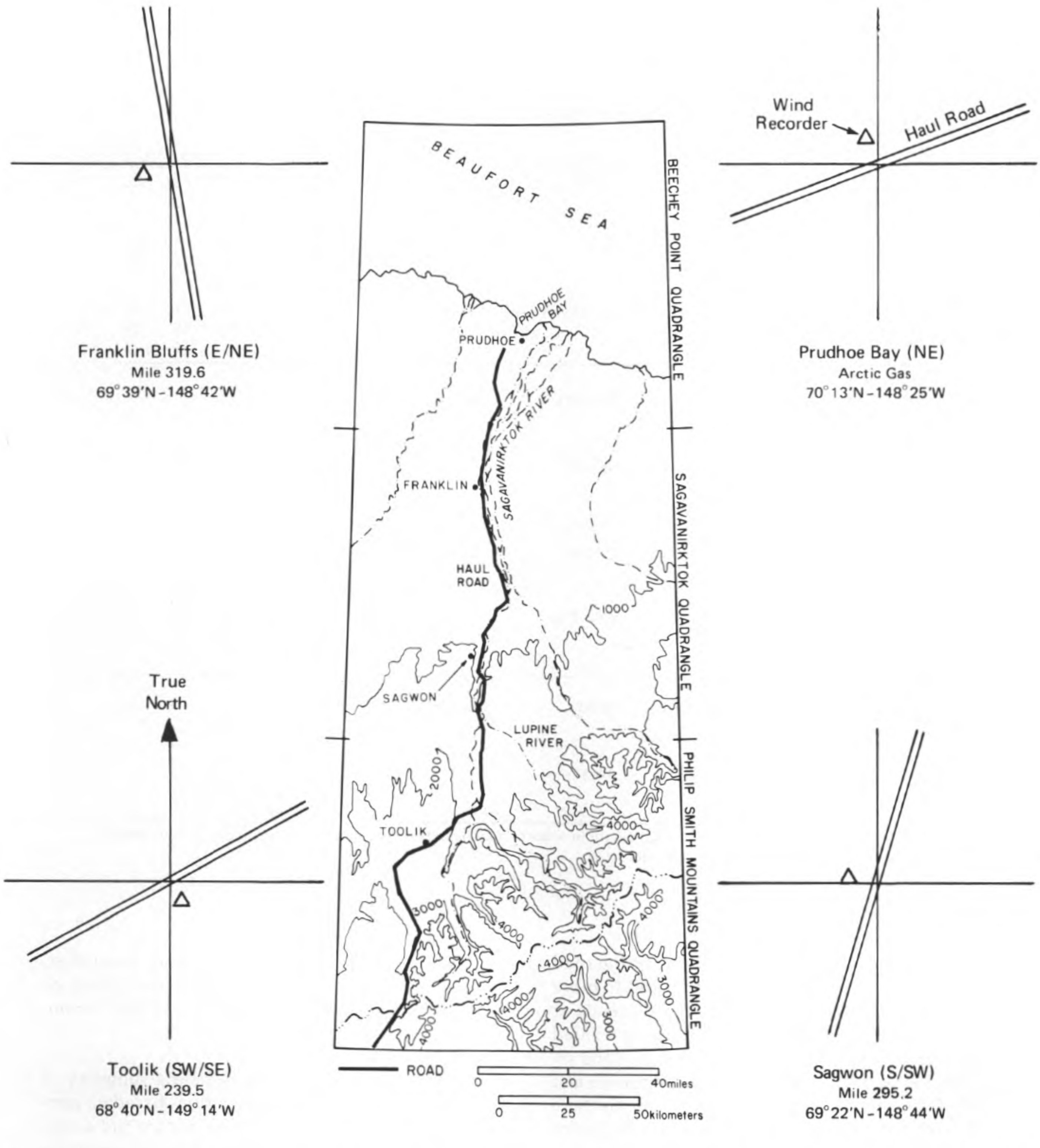


Figure 87. Location and orientation of the four dust transects. Triangle indicates location of wind recorder. Prevailing summer winds are shown in parentheses.

Table 24. Summary of wind data for summer 1977 and 1978 at dust collection sites along the Yukon River–Prudhoe Bay Haul Road north of the Brooks Range.*

	Primary directions (quadrants by month)					*% wind speed by groups (m/s)*				
	June	*July*	*Aug*	*Aug/Sep*	*Month*	*<2*	*2-3*	*>3-4*	*>4-6*	*>6*
Prudhoe Bay (Arctic Gas)										
1977		NE-se	NE-sw	E-S-W	June	–	15	35	23	27
					July	–	23	35	22	20
					Aug/Sep	–	55	36	9	–
1978	NE-(SE)-sw	SE-(SW)-ne	NE-(SE)-sw-nw	E-S-W	June	–	26	29	27	18
					July	–	13	39	19	29
					Aug	4	32	25	32	7
Franklin										
1977	NE-(SE)	NE-(SW)	NE-(SW)	SE-SW	June	4	32	20	28	16
					July	7	50	14	25	4
					Aug/Sep	22	67	11	–	–
1978	NE-SW-se	NE-(SW-SE)	NE-SW		June	6	41	25	19	9
					July	3	45	19	27	6
					Aug	16	37	17	30	–
Sagwon										
1977		SE-(SW-NE)	SE-SW	SW-SE	June	9	41	32	18	–
					July	23	55	16	6	–
					Aug/Sep	42	50	8	–	–
1978	SW-SW-ne	SW-SE-ne	SW-NE-se		June	9	44	34	10	3
					July	–	68	19	13	–
					Aug	17	36	27	20	–
Toolik										
1977		SE-(SW-NE)	SE-SW	SE-SE-ne	June	11	36	38	15	–
					July	26	48	19	6	–
					Aug/Sep	58	42	–	–	–
1978	SW-SE	SE-SW	SW-SE-ne		June	3	55	30	12	–
					July	13	64	20	3	–
					Aug	18	48	17	17	–

* General wind directions are listed, each month in order of dominant direction, subdominant direction in parentheses and significant component in lower case letters.

areas adjacent to the downwind side of the road begin an accelerated melt as compared to more distant terrain (Fig. 86). The obvious presence of spring and summer road derived dust provided an opportunity to study both the direct and indirect effects of fugitive dust on the tundra and to lakes and ponds (Spatt 1978) in northern Alaska. It was anticipated from the beginning that such information would prove useful in decisions regarding the maintenance and use of such roads, as well as future construction of roads which might be built across similar terrain.

Methods

The following sections present a summary of methods, data and interpretations based on summer 1977 and 1978 collection of dust and acquisition of wind data at four sites between the

Brooks Range and Prudhoe Bay (Fig. 87).

Two sites were selected on the Arctic Coastal Plain and two sites on the rolling Arctic Foothills. In 1977 transects were set at right angles to the road and extended out to 1000 m on either side. Prior to establishing the sites, snow samples were collected (23-25 April 1977) at distances extending outward 1000 m from the road, and chemical analyses of the meltwater were performed. Sampling stations along the transects were established at 8, 30, 125, 312, 500 and 1000 m on either side of the road. In 1977, pairs of shielded collectors (241 cm^2 surface area) were placed at each point. Also unshielded collecting pans and static nondirectional dust collectors were employed at various locations on the transects to evaluate effectiveness of the different collectors. In 1978, unshielded plastic basins with an area of 890 cm^2 were used to increase sample yields. A Woelfle-type mechanical wind recorder was positioned at 125 m along the collection transect on one side of the road (Fig. 87). Wind data were extracted from the continuous record on an hourly basis.

Soil samples at 0 to 2.5 cm and 2.5 to 5 cm below the base of the vegetation were collected in 1977 adjacent to each site (8, 30, 125, 312, 500 and 1000 m). Monthly and seasonal samples of dust from the paired traps were collected. In the laboratory, samples were washed, centrifuged and weighed. Dust samples were then treated with 30% hydrogen peroxide to remove organic debris and reweighed. Soil samples were dried, ground, and sieved and leached with ammonium acetate prior to cation analysis. Neutron activation analyses were performed on selected dried samples. Chemical analyses of washed portions of mosses and lichens were also conducted from the Toolik site by I. Iskandar, CRREL.

Results of wind direction and velocity measurements

During the two summer seasons of measurements, a strongly developed northeast quadrant wind component was noted at the coastal Prudhoe Bay and Franklin sites. In both summers, this dominance shifted with winds from the southern quadrants becoming important. A bimodal wind pattern appears at the Franklin site, which is close to the southern margin of the Arctic Coastal Plain; however, northeast winds are still dominant. At the Sagwon upland site, located very close to the northern limit of the Foothills Province, a bimodal wind pattern also occurs but with southwest winds predominating. Winds at the Toolik site, near the southern limit of the Arctic Foothills, are almost entirely from the southern quadrants and show no single predominant direction during the summer.

The predominant range in summer wind velocity at all sites is between 2 and 4 m/s. Average summer season wind speeds decrease generally from north to south (Prudhoe Bay to Toolik). At each site wind speed decreases from early summer to late summer (Table 24). Velocities in excess of 6 m/s were not recorded at Toolik site, and at the Sagwon upland site these were recorded only in July 1977. These and higher speeds, to 11 m/s, are increasingly common northward especially early in the summer. At all sites, but least at Prudhoe Bay, the greatest speeds and most consistent directions occur in the period between 0700 and 1800 hr. These are the hours of greatest use of the Haul Road and therefore greatest dust generation and transport. With respect to the Haul Road, the prevailing winds are from the eastern quadrants. At the Prudhoe Bay site, a significant percentage of winds are parallel to the road in the area studied.

Variations in the seasonal patterns as outlined above do occur and are probably closely tied to the position of the Arctic Front (Fig. 10), with a northward shift giving rise to strong southerly components at the northern sites and southward shifts of the front producing persistent northeast components at the southern sites.

The following sections are detailed summaries of wind direction and velocity at each site which can be referenced directly to the dust load and distribution data that follow.

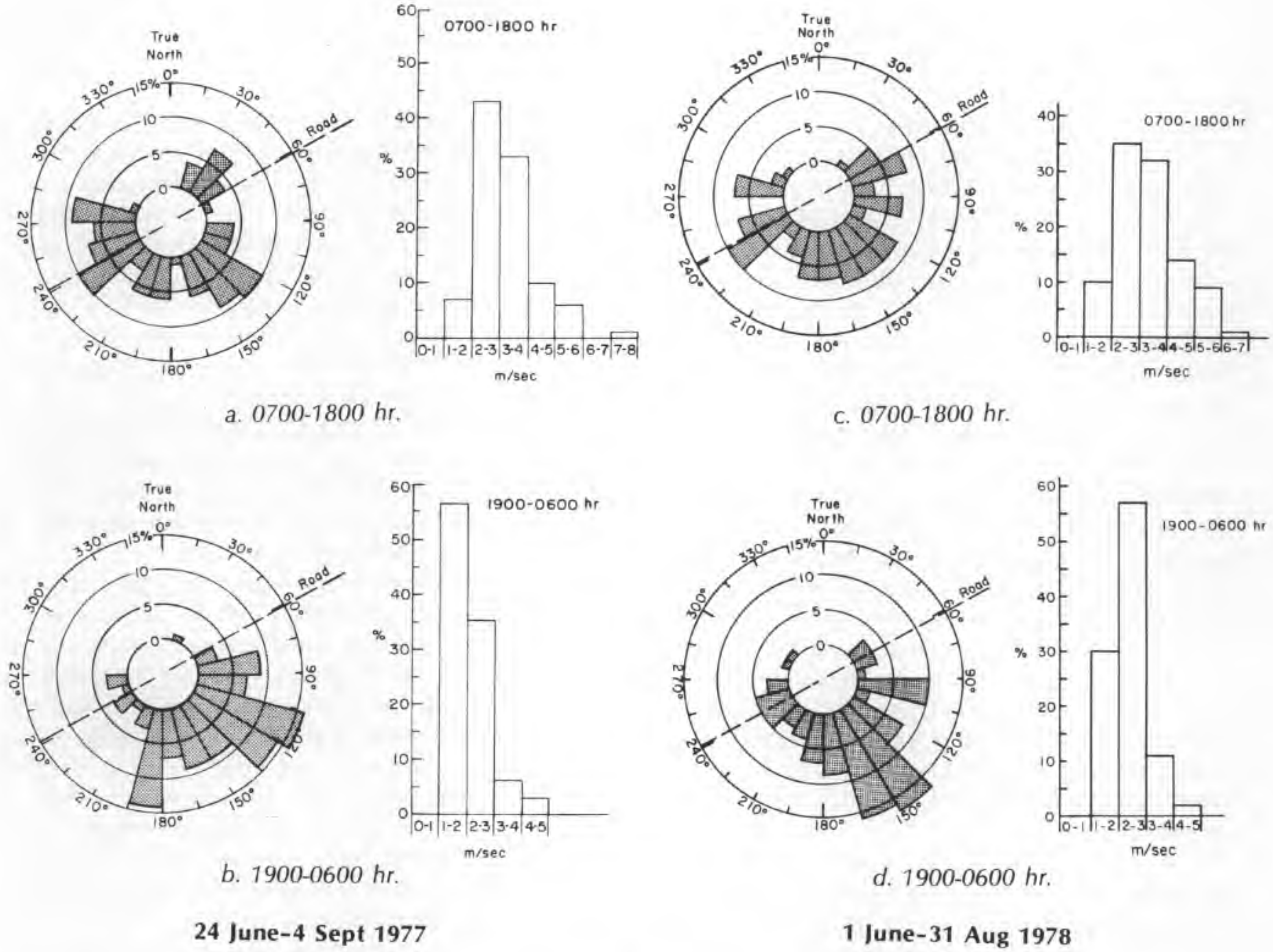
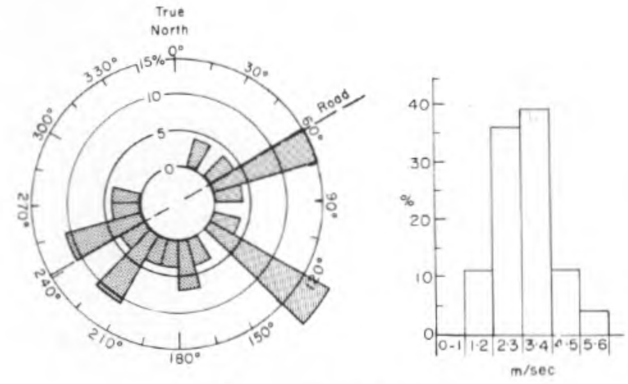


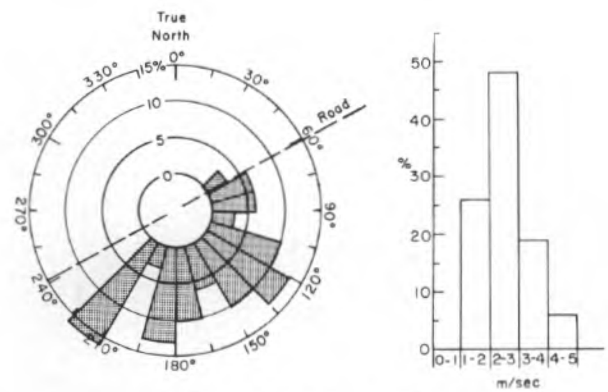
Figure 88. Diurnal wind direction and velocities for the summers of 1977 and 1978 at the Toolik site.

Toolik

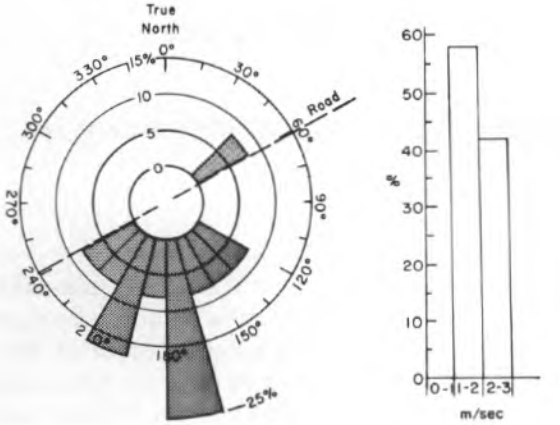
Wind data from this most southerly site for 1978 indicate that nearly all summer winds blow from the south (~ 85% between 1 June and 1 September) and that they are about equally distributed between the southeast and southwest quadrants (Fig. 88 and 89). A similar distribution of winds was observed in 1977; however, in that year the due-south component clearly strengthened as the summer progressed. The strong southerly air flow at this Foothills site is probably the result of katabatic flow from the mountains. Wind velocities during the summer of 1978 were concentrated in the range of 2 to 4 m/s (77%) with 55% of that value between 2 and 3 m/s. In 1977, 61% of the wind speeds were in the range of 2 to 4 m/s. In late August and in early September of that year, 99% of the wind velocities were below 3 m/s with 57% between 1 and 2 m/s. In both years velocity decreased during the summer and in both 1977 and 1978 the wind pattern was more evenly distributed in the southern directions and showed stronger velocity during the period of 0700-1800 hr than in the remaining half day. With respect to the Haul Road, prevailing winds that are parallel or normal to it from the east quadrant occurred about 76% of the time in 1978 and 75% of the time in 1977.



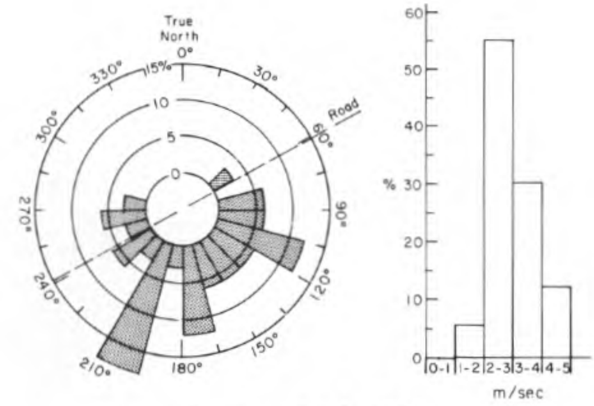
a. 24 June–23 July 1977.



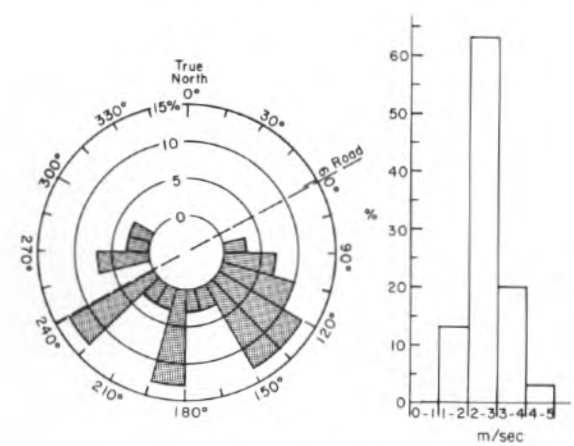
b. 24 July–23 Aug 1977.



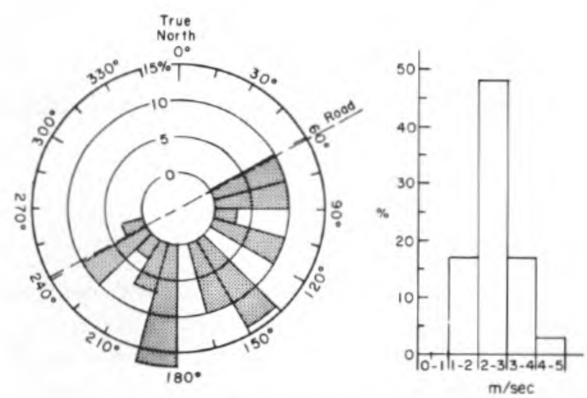
c. 25 Aug–4 Sept 1977.



d. 1 June–3 July 1978.



e. 4 July–2 Aug 1978.



f. 3–31 Aug 1978.

Figure 89. Monthly wind direction and velocities for the summers of 1977 and 1978 at the Toolik site.

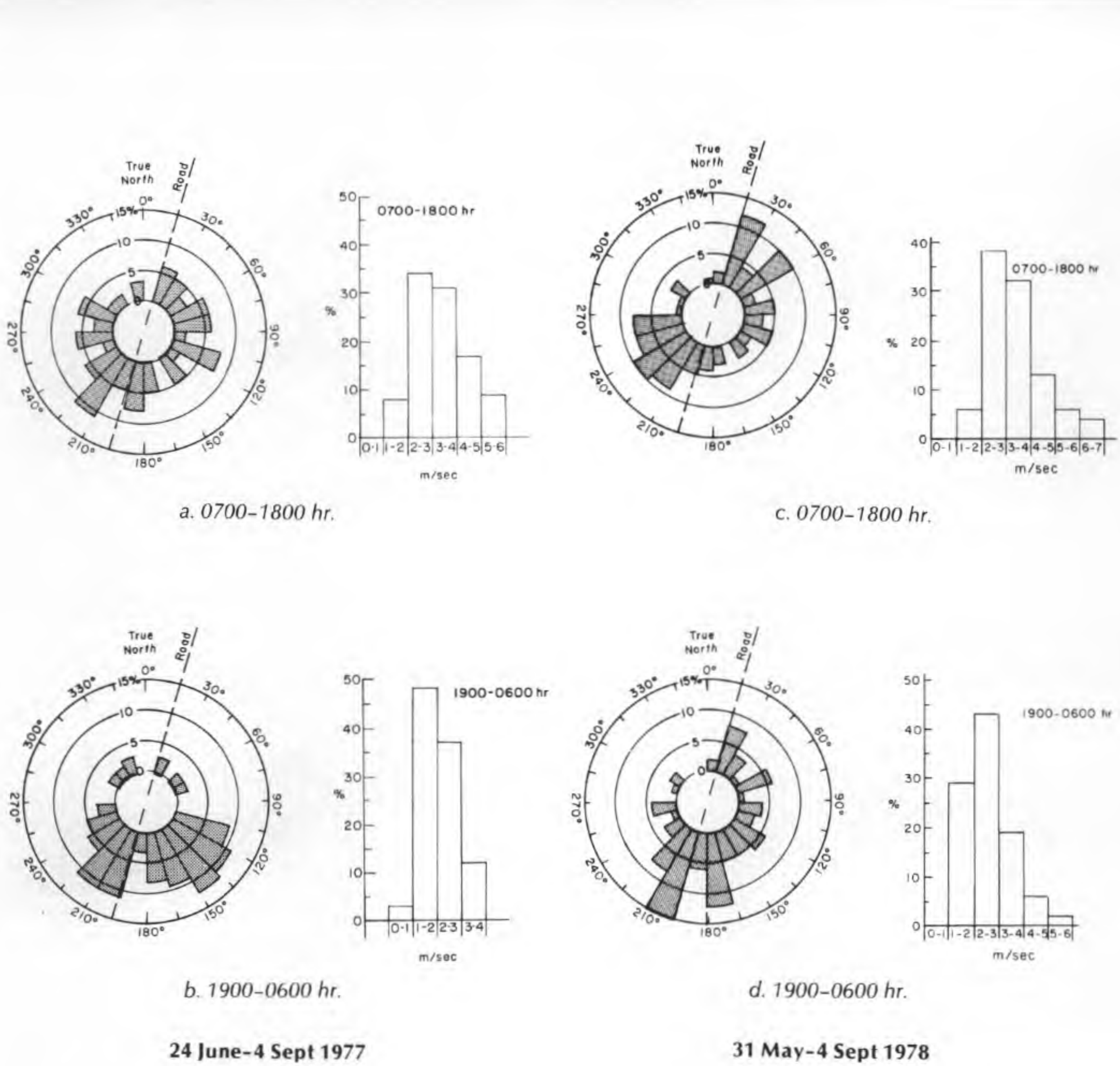
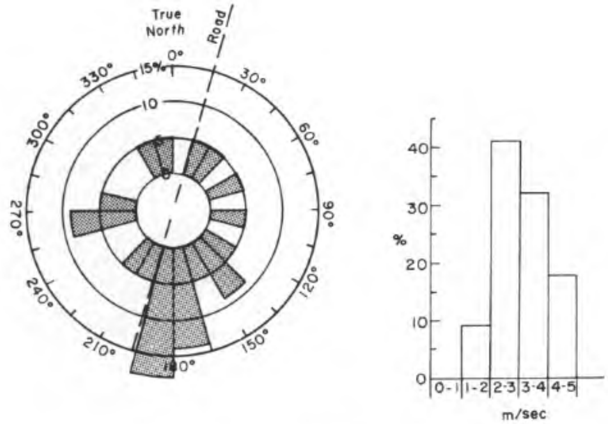


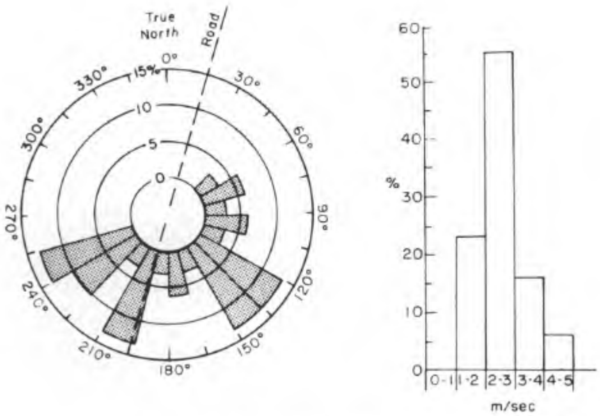
Figure 90. Diurnal wind direction and velocities for the summers 1977 and 1978 at the Sagwon site.

Sagwon

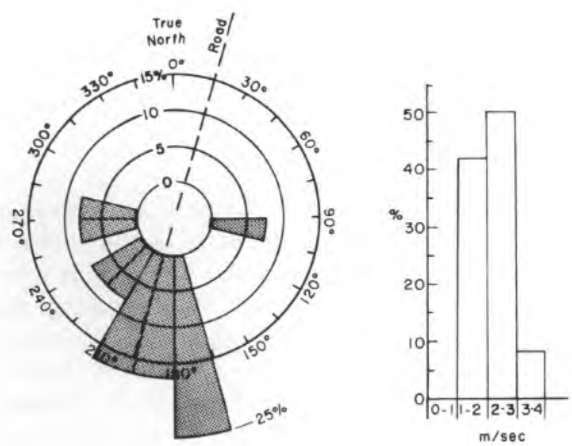
Since the Sagwon site is located near the northern limit of the Arctic Foothills, it is not surprising that winds show both mountain or southern components and those from the northeast or coastal regions (Fig. 90 and 91). In 1978 two prevailing directions developed, one from the southwest (180°-240°) 46% of the time and one from the northeast (0-60°) 25% of the time. Dominant wind directions shifted, however, during the summer probably in response to slight changes in the position of the Arctic Front. As an example, the northeast component was completely missing in July 1978. In the preceding year, winds were mostly from the southern quadrants, implying a strong katabatic control. Wind velocities were primarily in the 2- to 4-m/s range in 1978 (75%) and in 1977 (67%). Highest wind velocities occurred principally during the period 0700-1800 hr. Winds in excess of 6 m/s were recorded only in June of 1978. A pronounced decrease in wind velocities through the summer season was observed both years. With respect to the Haul Road, winds blew at an angle to it generally from the east (20°-90°) 60% of the summer in 1978 and 64% in 1977.



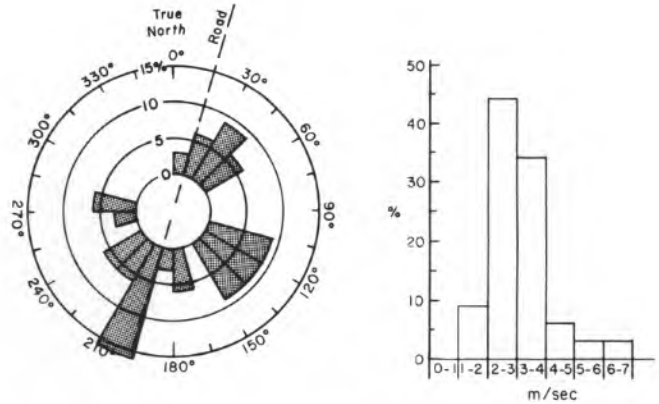
a. 25 June–23 July 1977.



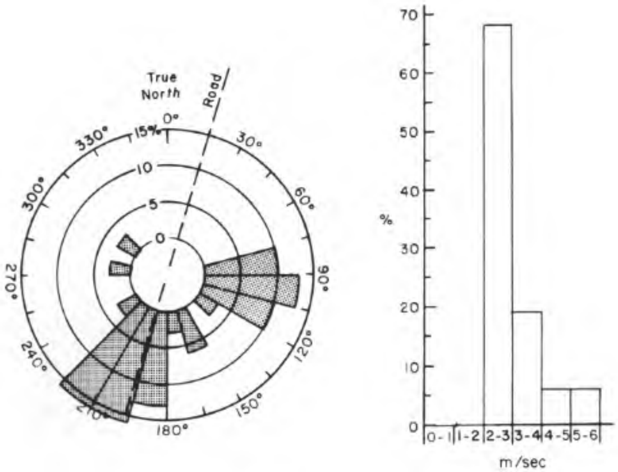
b. 24 July–24 Aug 1977.



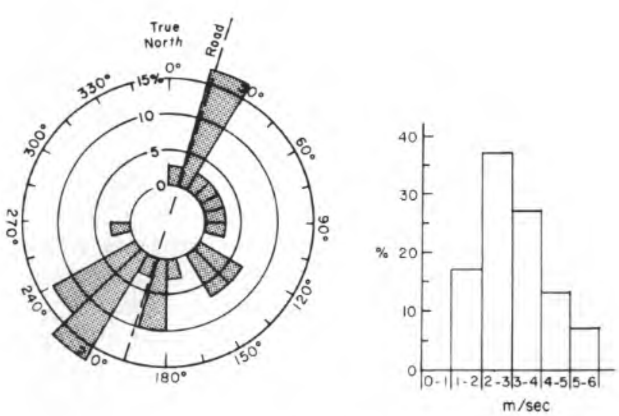
c. 24 Aug–4 Sept 1977.



d. 31 May–1 July 1978.

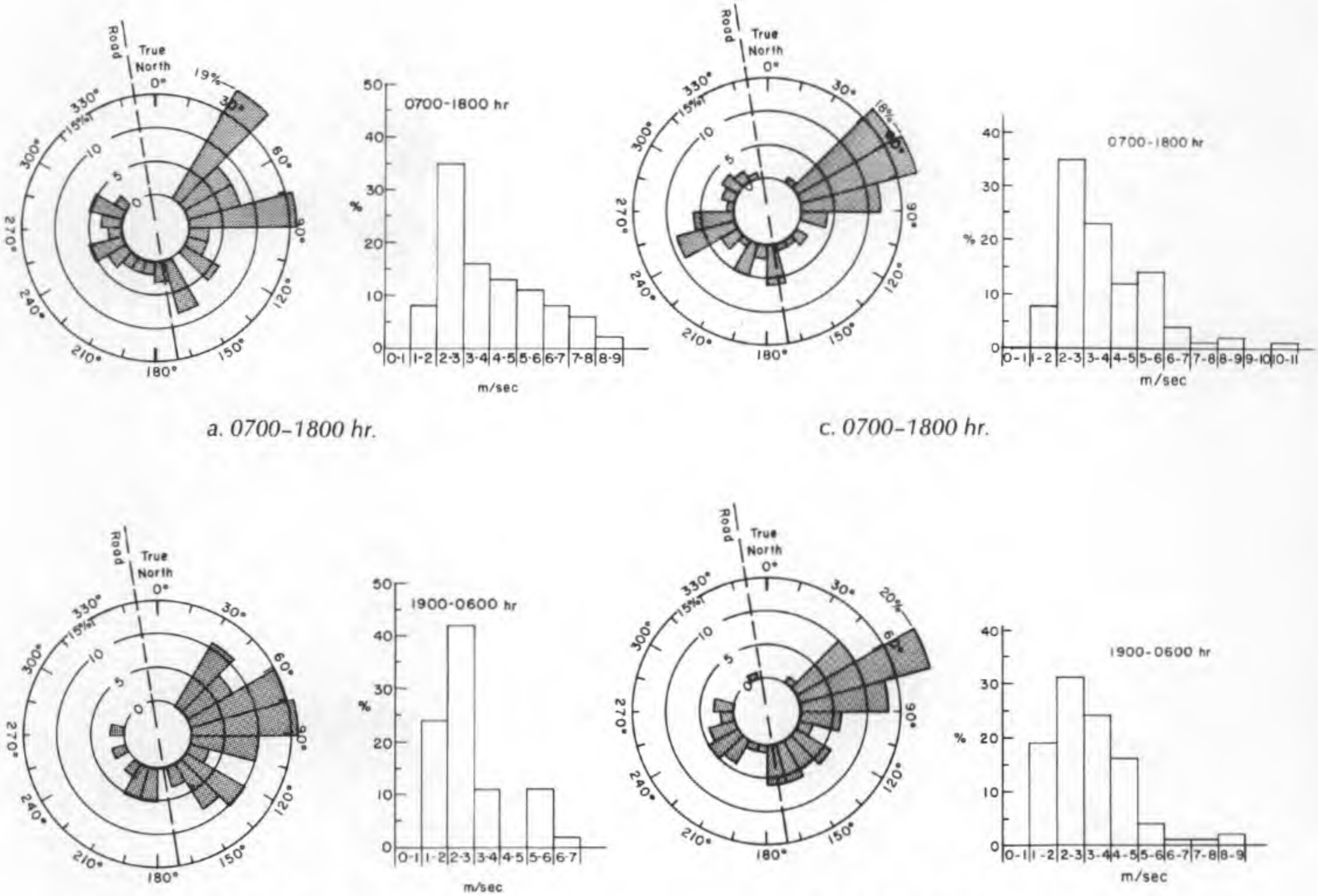


e. 3 July–2 Aug 1978.



f. 3 Aug–1 Sept 1978.

Figure 91. Monthly wind direction and velocities for the summers 1977 and 1978 at the Sagwon site.



a. 0700–1800 hr.

c. 0700–1800 hr.

b. 1900–0600 hr.

d. 1900–0600 hr.

29 June–4 Sept 1977

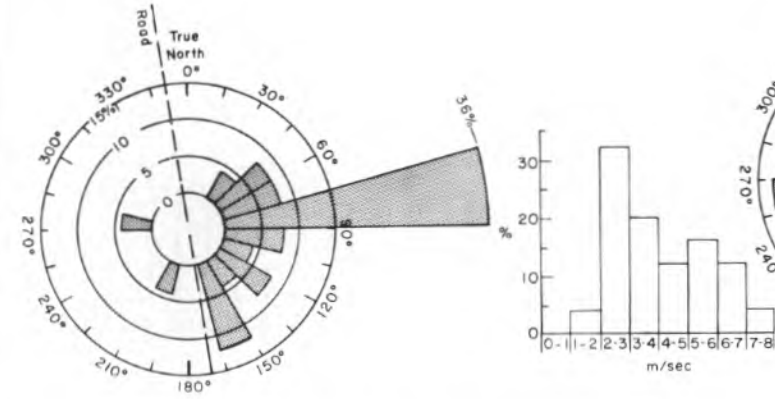
30 May–1 Sept 1978

Figure 92. Diurnal wind direction and velocities for the summers 1977 and 1978 at the Franklin Bluffs site.

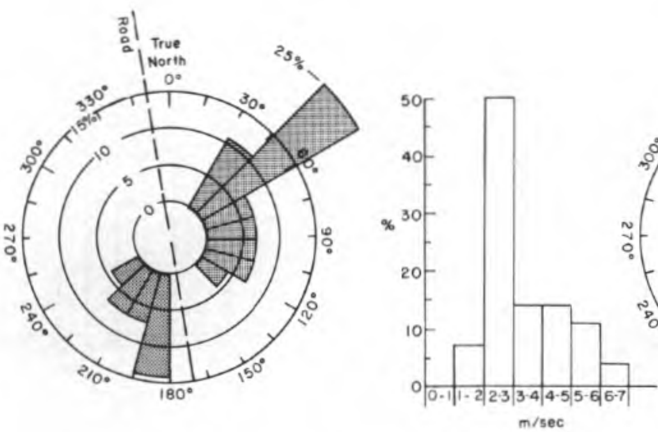
Franklin

Summer 1978 wind data from the Franklin site show a clear predominance (approx. 47%) from the east-northeast quadrant (60-90°) (Fig. 92 and 93). Secondary maxima from the west-southwest (240-270°) and from the south are about equal. The wind pattern during the summer 1977 was similar to 1978; however, a strong southerly component developed late in the summer of 1977. Wind velocities in the two years were generally similar with the greatest percentage between 2 and 4 m/s (60% in 1978, 65% in 1977). In both years winds in the 2-3 m/s range were dominant (40% vs 50%). Winds in excess of 6 m/s accounted for about 8% of the total velocity range and were most prevalent early in the summer (June and early July) in both years. Winds were generally stronger in 1978. Winds during the time period 0700-1800 hr (high traffic hours) were stronger and more prevalent from the NE-SW quadrants than during the period 1900-0600 hr (low traffic hours). This is true for both years but is most apparent in 1978.

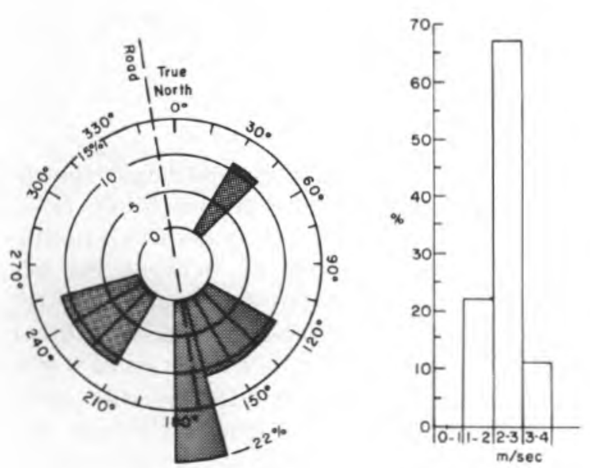
An examination of the dust load distribution for 1977 and 1978 (Table 25) clearly shows the influence of the prevailing east-northeast winds at this site.



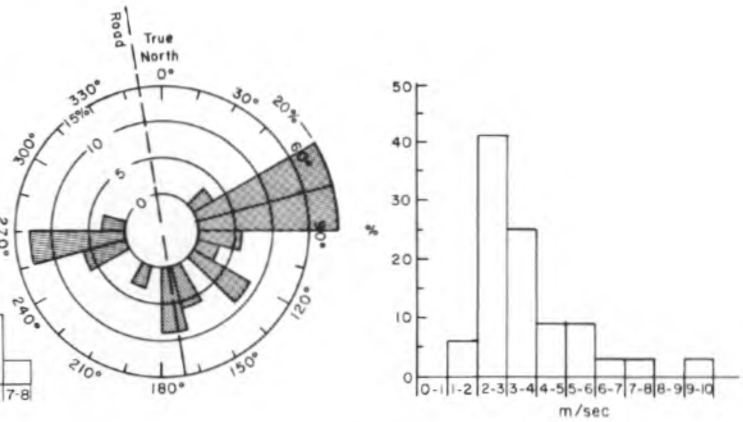
a. 24 June–23 July 1977.



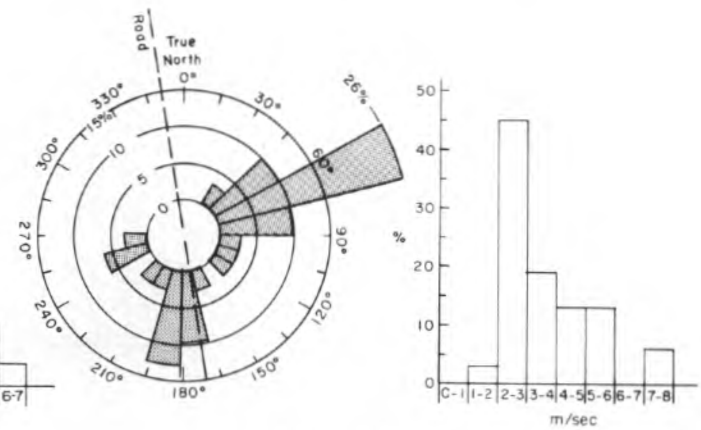
b. 24 July–24 Aug 1977.



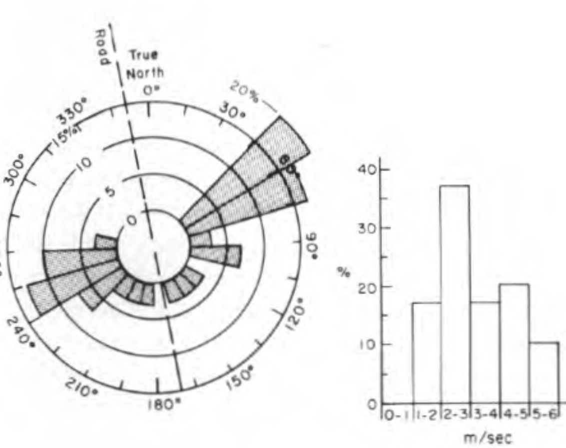
c. 24 Aug–4 Sept 1977.



d. 30 May–29 June 1978.

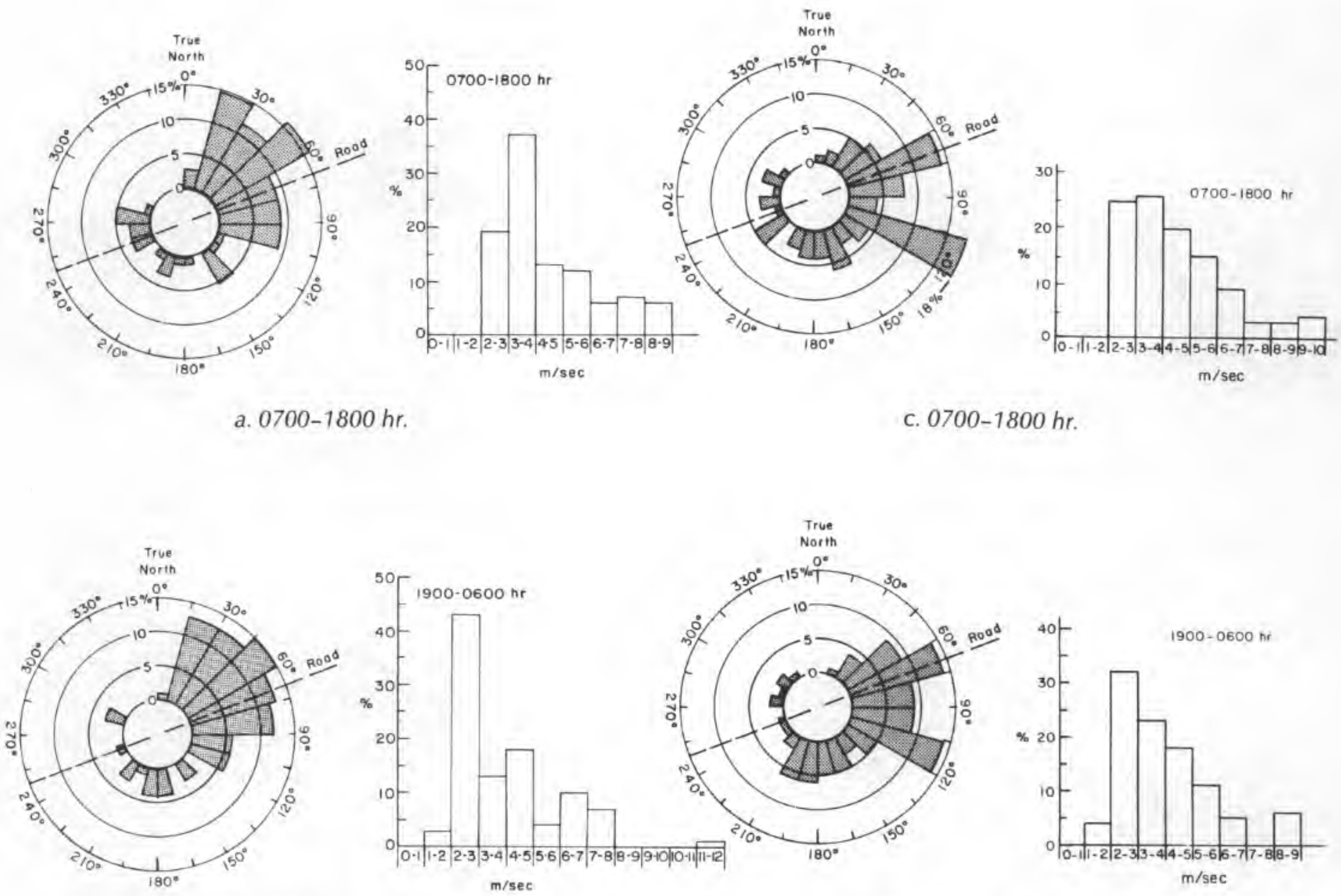


e. 1 July–2 Aug 1978.



f. 3 Aug–1 Sept 1978.

Figure 93. Monthly wind direction and velocities for the summers 1977 and 1978 at the Franklin Bluffs site.



a. *0700–1800 hr.*

c. *0700–1800 hr.*

b. *1900–0600 hr.*

d. *1900–0600 hr.*

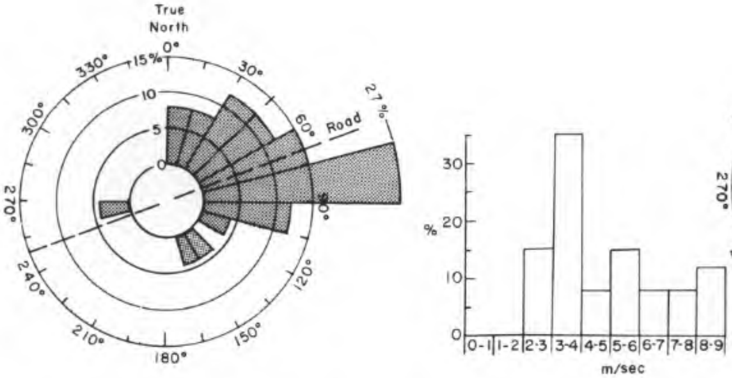
28 June–3 Sept 1977

29 June–31 Aug 1978

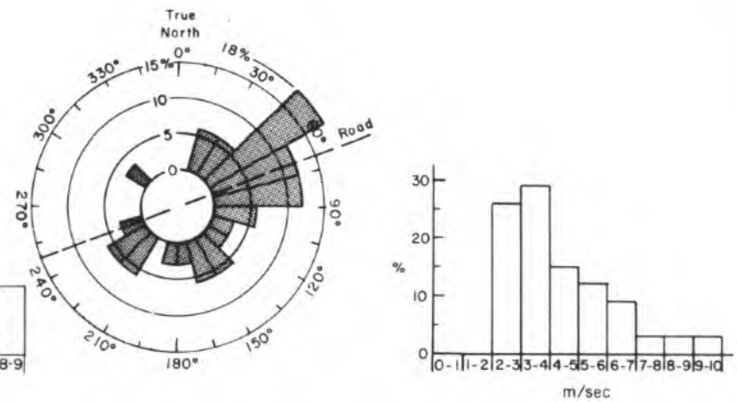
Figure 94. Diurnal wind direction and velocities for the summers 1977 and 1978 at the Prudhoe Bay site.

Prudhoe Bay (Arctic Gas)

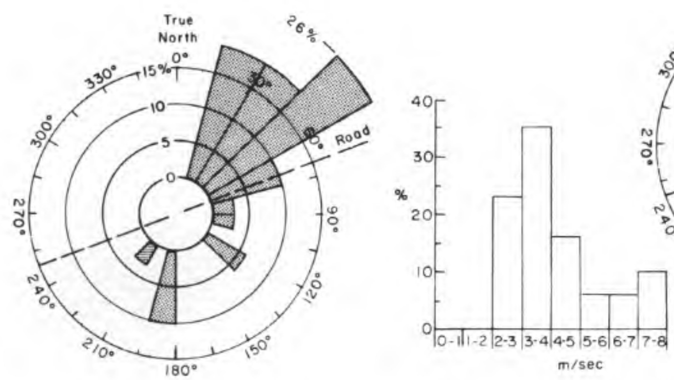
This is the most northerly of the dust sites and is located close to the Beaufort Sea. The site was selected for comparison with the Haul Road sites. The road and related traffic date back to 1969. Wind directions are predominantly from the northeast (approx. 40% in June and August) (Fig. 94 and 95). With respect to the road (oriented N 69°E) the majority of the winds blow parallel or nearly parallel to it. In July 1978 there was a significant wind component across the road (67%). In 1977 winds were also predominantly from the northeast and east. This pattern broke down in late August when the prevailing winds were from the southern quadrants, 190°-270° (56%). Wind velocities are the strongest of any site with 25% of the July and August (northeast quadrant) winds in excess of 6 m/s. However, late August–early September winds (southern quadrants) were mostly between 2-3 m/s (55%). In 1978 the pattern of June and July high velocities (early- to mid-summer) seen at other sites also occurred with 14% in excess of 6 m/s. Unlike the preceding year, high velocities (28%) occurred with winds predominantly from the southeast (in July). No diurnal preference was seen in wind direction in either year. A somewhat higher percentage of strong winds (> 6 m/s) occurred between 0700 and 1800 hours in 1977. In 1978, however, the distribution was about equal.



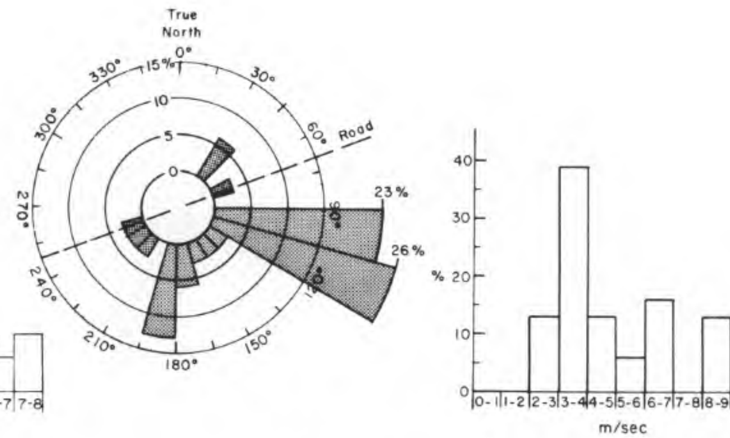
a. 28 June–23 July 1977.



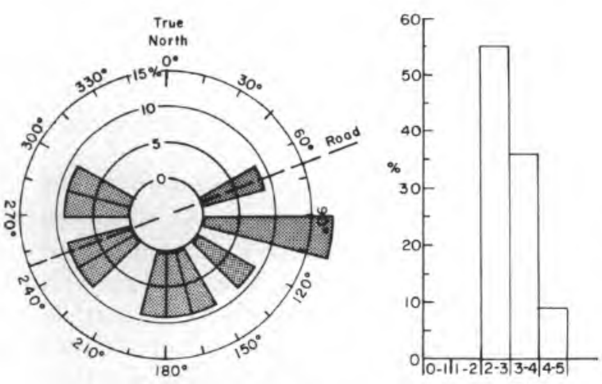
d. 29 May–1 July 1978.



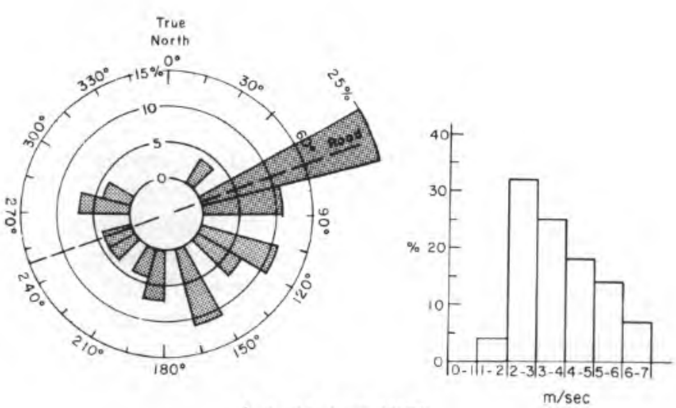
b. 24 July–24 Aug 1977.



e. 2 July–1 Aug 1978.



c. 25 Aug–3 Sept 1977.



f. 2–31 Aug 1978.

Figure 95. Monthly wind direction and velocities for the summers 1977 and 1978 at the Prudhoe Bay site.

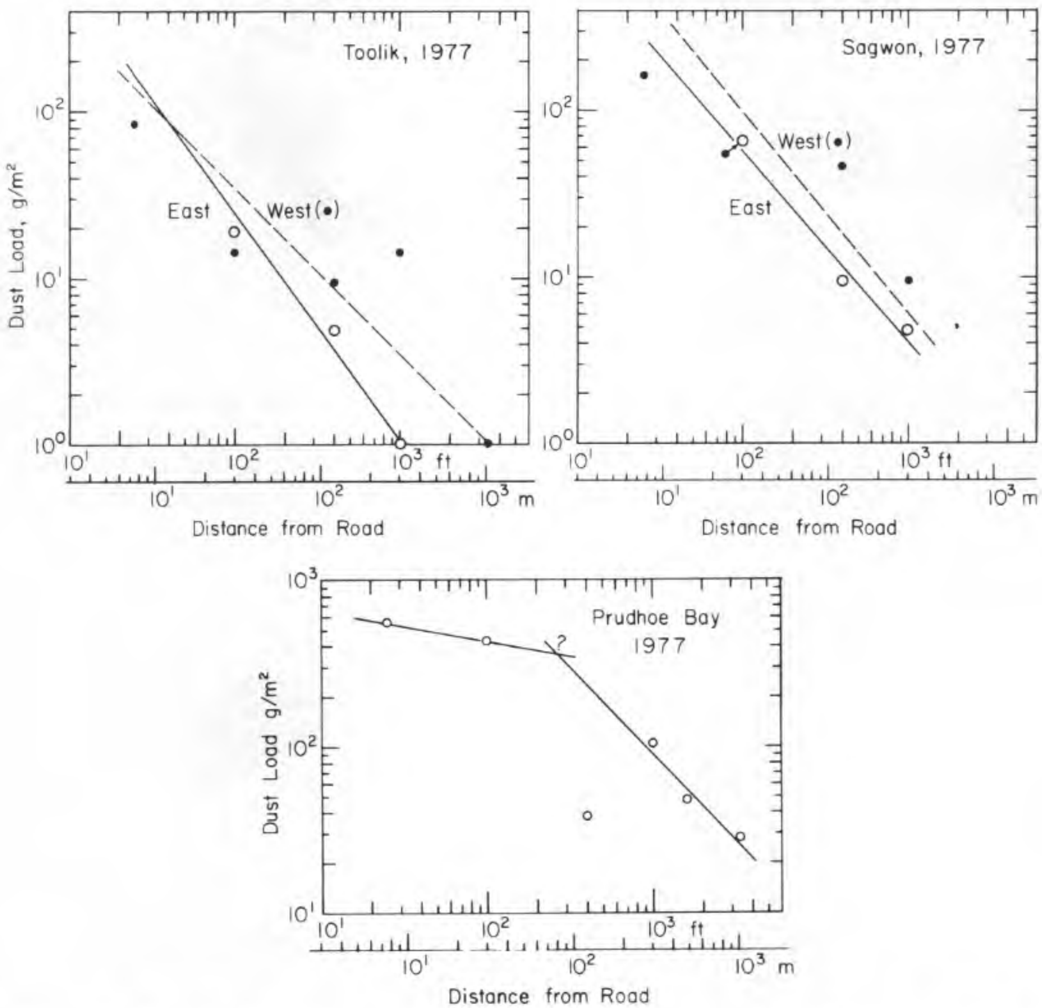


Figure 96. Dust load in snow samples at the Toolik, Sagwon and Prudhoe sites. Samples were obtained from 23 to 26 April 1977.

Dust load and distribution

Although comparison of dust data among sites and between years is desirable, the numerous variables that may influence these data allow only cautious comparisons. Thus interpretation of data from even a single site is difficult. The variables may be grouped into climatic and vehicular conditions and dust control. Within the first group are 1) wind direction, velocity and turbulence as they control particle size distribution, and 2) precipitation and its frequency, as it aids in dust suppression. The second group includes 1) vehicle weight, number of axles, speed, spacing during travel, frequency of passage and tire design, 2) dust suppression program and frequency and uniformity of application of dust retarders, and 3) frequency of road surface regrading.

Table 25 presents a summary of the 1977-1978 dust loads and distribution. Figures 96, 97 and 98 illustrate the logarithmic decrease in dust load with distance from the road. Concomitant with the decrease in load is a decrease in particle size. Comparison of dust loads among all sites indicates a substantial increase between 1977 and 1978 (38% to 59% increase). This occurred even though road use in 1978 was estimated to be only about 10% of that in 1977 (the Prudhoe Bay site is probably an exception). Reasons for this increase in dust loads include 1) dust suppression by watering was much less intensive in 1978 except at the Prudhoe Bay site, 2) the 1978

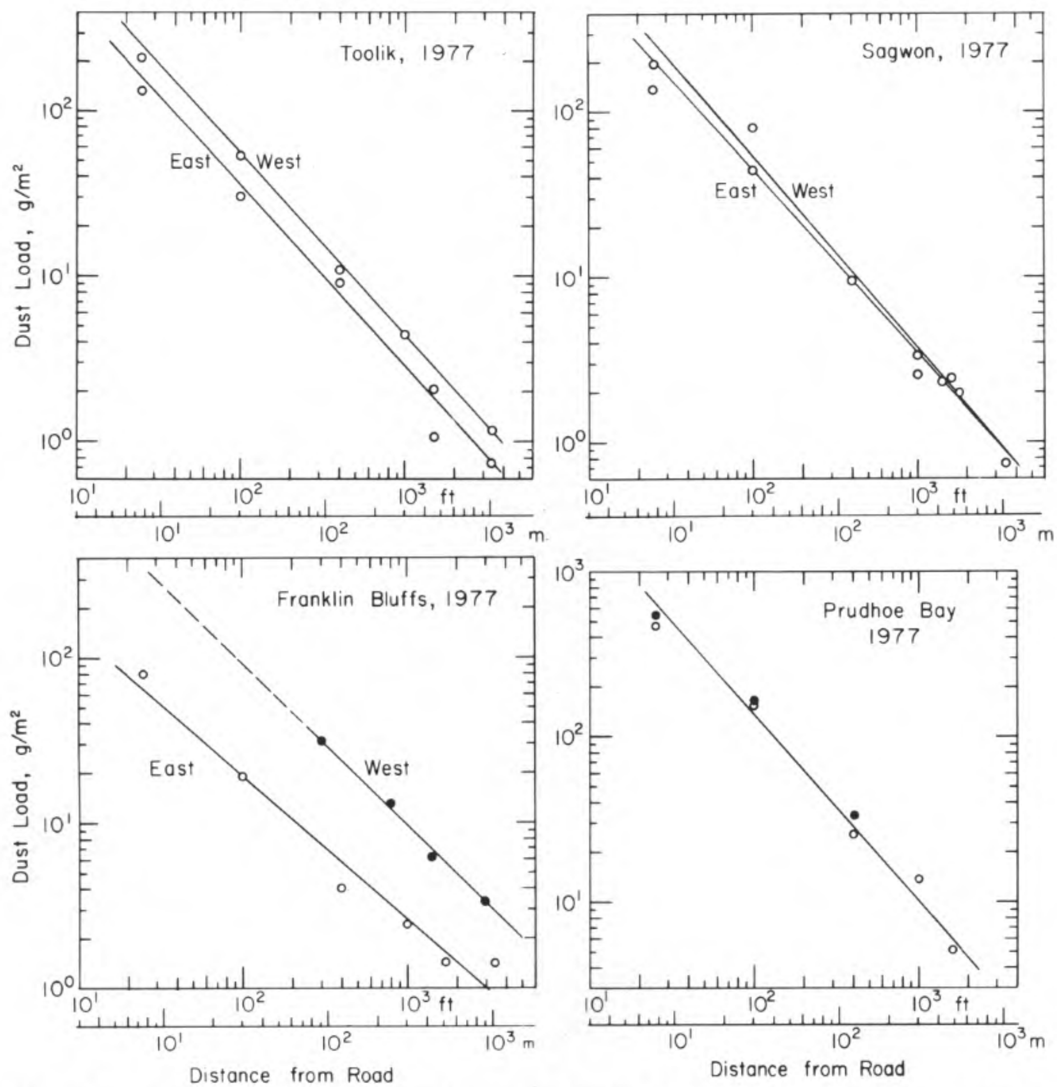


Figure 97. Summer dust loads from the four sites for 1977, period of collection was 67 days.

Table 25. Summer season 1977–1978 dust load (g/m²) vs distance (m) from Haul Road.

	8 m		*30 m*		*125 m*		*312 m*		*500 m*		*1000 m*	
	E	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*	*E*	*W*
Prudhoe	N											
1978	531		111		28		11		5.8		7.6	
1977	463		151		27		14		*		5.2	
Franklin												
1978	*	717	54	129	13	37	5.7	12.8	2.5	5.1	3.1	2.3
1977	81	*	19	—	4	31	2.5	12.9	1.4	6.3	1.4	3.4
Sagwon												
1978	708	520	174	145	32	25	11.4	6	4.4	3.5	3.3	1.7
1977	199	138	45	80	—	—	2.6	3	2.4	2.1	—	0.8
Toolik												
1978	214	221	56	57	11	13	3	4.5	2.3	2.8	1.6	1.7
1977	244	133	30	53	1.3	8	1.7	4.4	1.0	2.2	0.8	1.2

* Collector destroyed or vandalized.

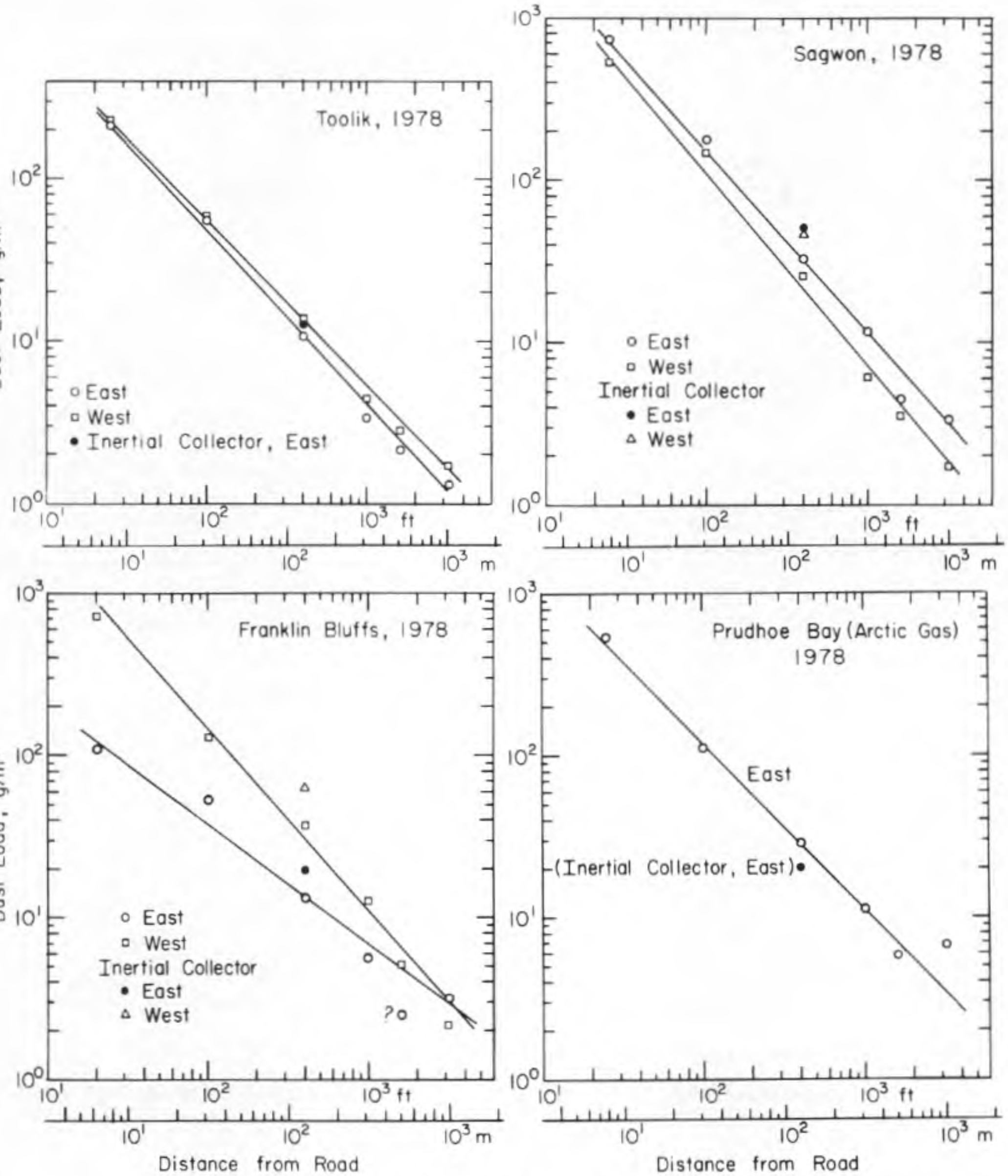


Figure 98. Summer dust loads from the four sites for 1978; period of collection was 96 days.

dust collection period was 25% longer than in 1977, and 3) 1978 was a much drier year than 1977 (Haugen, this report). Also dust collection and processing techniques were improved in 1978. However, there is no indication that the more-than-threefold increase in collection area or the abandonment of the settling well in 1978 had any effect on the efficiency of dust collection. The larger samples collected at each station in 1978 were, however, very much less affected by small losses that inevitably occur in collection and processing. On this basis, the 1978 data are better than those of 1977.

It would be expected that the Prudhoe Bay site might show similar dust loads in the two summers, as variables of traffic and dust suppression probably remained nearly the same. Explanation for differences might be sought in wind speed and direction.

To the extent that between-site comparisons are justified, the 1978 data suggest that the Toolik site produces the lowest total dust load insofar as the larger particles are concerned. This probably reflects differences in particle size of the road materials (three times as much clay content at Toolik as at Sagwon) coupled with any of the traffic variables. The Franklin and Sagwon sites appear to produce the highest total dust loads, again involving the coarser fractions (generally silt and coarser) out to about 500 m. At this distance and beyond, differences among the three Haul Road sites are smaller. The dust load at 1000 m at the Prudhoe Bay site is approximately two to nine times greater than at other sites and is generally higher at 500 m as well. This may in part be due to additions from the road well beyond the immediate site as it turns northwest and normal to the prevailing wind.

In addition to the summer period, significant dust fall occurs during the autumn and winter months before the road becomes snow-packed, with increased dust fall starting again in April. An estimate of the amount of this dust was made from the winter snow pack samples obtained adjacent to the road in late April 1977. The results displayed in Figure 96 indicate a logarithmic distribution with distance similar to that of the summer (Fig. 97 and 98) but with a significantly greater scatter. This point scatter is not unexpected because of repeated drifting and deflation of the snow pack.

Except for the Prudhoe Bay site, the additional 1976-77 winter season dust fall at the 8-m distance contributed between 100 and 150 g/m^2 to the yearly totals. The Prudhoe data for the same distance indicate dust fall at about the same magnitude as during the summer collection period. However, at the more distant Prudhoe collection stations, winter period dust fall is nearly 10 times greater than in the summer. The reasons for this are not understood.

The following sections contain detailed summaries of dust load and distribution for each site (see Fig. 97 and 98 and Table 25).

Toolik

During the two summers of study, dust load decreased logarithmically away from the Haul Road both to the east and west. The amount of dust collected at most of the stations at each site was greater in 1978 than in 1977 by amounts ranging up to 88% (average 38%). In 1977 there was significantly greater dust fall on the west side than on the east with the exception of the 8-m station. This same situation prevailed in 1978 but the contrast was much reduced with only 3% more dust on the west side as compared to 53% more in 1977. The preferential concentration of dust on the west can be explained by the prevailing southeast and south winds blowing approximately normal to the road. The wind data alone, however, do not explain the difference between the years. At the 8-m station significant differences in dust fall between the two sides of the road for a given year or between years are to be expected as total dust fall at this distance is as much a function of saltation or tire throw as wind direction or velocity.

Sagwon

The patterns of dust load and distribution at the Sagwon site are similar to those of Toolik. Dust load was significantly greater in 1978 than in 1977, ranging from 40 to 77% (average 59%). In 1977 a clearly defined preferential accumulation on one side or the other of the road could not be defined. This was due in part to gaps in the data and in part to between-station variability possibly due to microrelief effects. In 1978, however, dust fall was clearly higher on the east side of the road than on the west. Wind data for the entire summer (in both years) show that less than 50% of the total wind was from the west quadrants normal to the road, and that during periods of high dust generation, winds from these directions amounted to less than 35% of the total.

Data obtained from inertial collectors (collecting at a height of 1 m above the ground surface) at 125 m in 1978 show a similar dust load on either side with the west side being somewhat greater (45 vs 50 g/m^2). It is, however, of interest that both these values are significantly greater than those for the corresponding surface collectors (29% higher on the east and 50% higher on the west). This result suggests that considerable dust is moving in the air beyond 125 m (in contrast to the Toolik and Prudhoe sites). This is, however, not reflected in significantly greater accumulations in the surface collectors at the more remote stations. No attempt has yet been made to determine size distribution or composition of the dust from the inertial collectors.

Franklin

Dust loads at this site were greatest on the west side of the road in both 1977 and 1978 and significantly greater in 1978 (approximately 50% greater). The heavy west side dust load reflects the predominance of east quadrant winds that occur more than 50% of the time. The loading on the west side in 1978 was about two times that of the east side except for the station at 1000 m.

The strong contrast in west- and east-side dust loads is further exemplified by the inertial collector data, 63.3 g/m² on the west and 19.4 g/m² on the east. Both of these values are greater than the surface values: 42% greater in the west side and 32% greater on the east. As at the Sagwon site, collectors at the ground at the more remote stations (500-1000 m) do not show dust loads significantly different from Toolik where the inertial collection is nearly equal to the surface collection, i.e. approximately 12 g/m² each. It is possible that much of the airborne dust at the 1-m height moves well beyond 1000 m.

Prudhoe (Arctic Gas)

Dust measurements at Prudhoe Bay were made only on the north side of the road because of the presence of a lake close to the south side. Dust accumulations in 1977 and 1978 were comparable. In 1978, the greatest dust fall occurred in July and coincided with a pronounced wind shift to the southeast quadrant, i.e. blowing more nearly normal to the axis of the road.

The inertial collector, at a height of 1 m above the surface and 125 m from the road, measured 12 g/m² of dust, approximately one-half that measured in the corresponding surface collector. The remote stations, however, have the greatest dust load of any other comparable sites. This might be explained by substantial amounts of dust blowing in from the north rather than normal to the road at the site.

Particle size analyses of dust

Particle size distributions were determined for two sites in 1978, Toolik and Franklin. Not all stations at these sites are represented—only those that had 3 g or more of filtrate retained were included. The data plots (Fig. 99 and 100) indicate significant variation among the sites in the particle size distribution of road materials. The road materials are generally poorly sorted with most particles coarser than coarse silt. Particles in the clay size range constitute between 8 and 15% of the total, with Toolik having the highest percentage. Figure 100 shows the rapid decline in mean particle diameter in the first 8 m from the road for Toolik. The decrease is from coarse sand (1 to 0.5 mm) to very near the upper limit of coarse silt (50 μm). A further, but much less significant, decline in mean particle diameter is noted at 30 m. Beyond 30 m to at least 312 m there is a little significant change in mean particle size of the dust fall with most of it being 50-20 μm in diameter or coarse silt. This supports the findings of Tamm and Troedesson (1955) who reported that beyond 20 m the coarse and fine silt became increasingly dominant.

There is relatively little clay reported in the source materials. Most of the clay either remains airborne well beyond 300 m or the clay particles may be aggregated since the dust is rich in carbonates and fall out with the coarse silt.

In 1977 the small amount of samples collected precluded standard sieve size analysis and only the 16- to 0.5-μm fine silt/coarse clay midranges of the dust were analyzed. Figure 99 indicates a general decrease in mean size of this fraction with distance from the road. The histograms show that in the bulk of the measured fine fraction (98-99%) is less than 3.17 μm in diameter (fine silt/coarse clay). At the Toolik site more than 99% of the measured fraction was smaller than 2 μm.

Although particles larger than 2000 μm compose 30 to 50% of the road surface materials, very few fragments of this size reach the 8-m collectors. Even with the propulsion of particles afforded by the passage of vehicles it is unlikely that the large particles fall beyond 10 m. This conclusion is based on Chepil's (1945) relationship between height of rise (in saltation) vs length of horizontal path.

Chemical composition properties of dust and related samples

Bulk samples of road dust and selected dust samples collected from the April snow cores were prepared by I. Iskandar of CRREL and analyzed by neutron activation techniques at the University of Wisconsin (Koons and Helmke 1978). Forty-seven elements were recorded. From this group nine elements were selected on the basis of their anticipated abundance and their values were plotted as a function of distance from the road (Fig. 101 and 102). Some general interpretations of these data can be made at this time.

With the exception of calcium, most of the elements in the summer dust show either no significant trends with distance, and are thus probably unrelated to particle size, or they increase in abundance with distance. In the latter case they may be concentrated in the finer fractions (fine silt to coarse clay). The principal clay min-

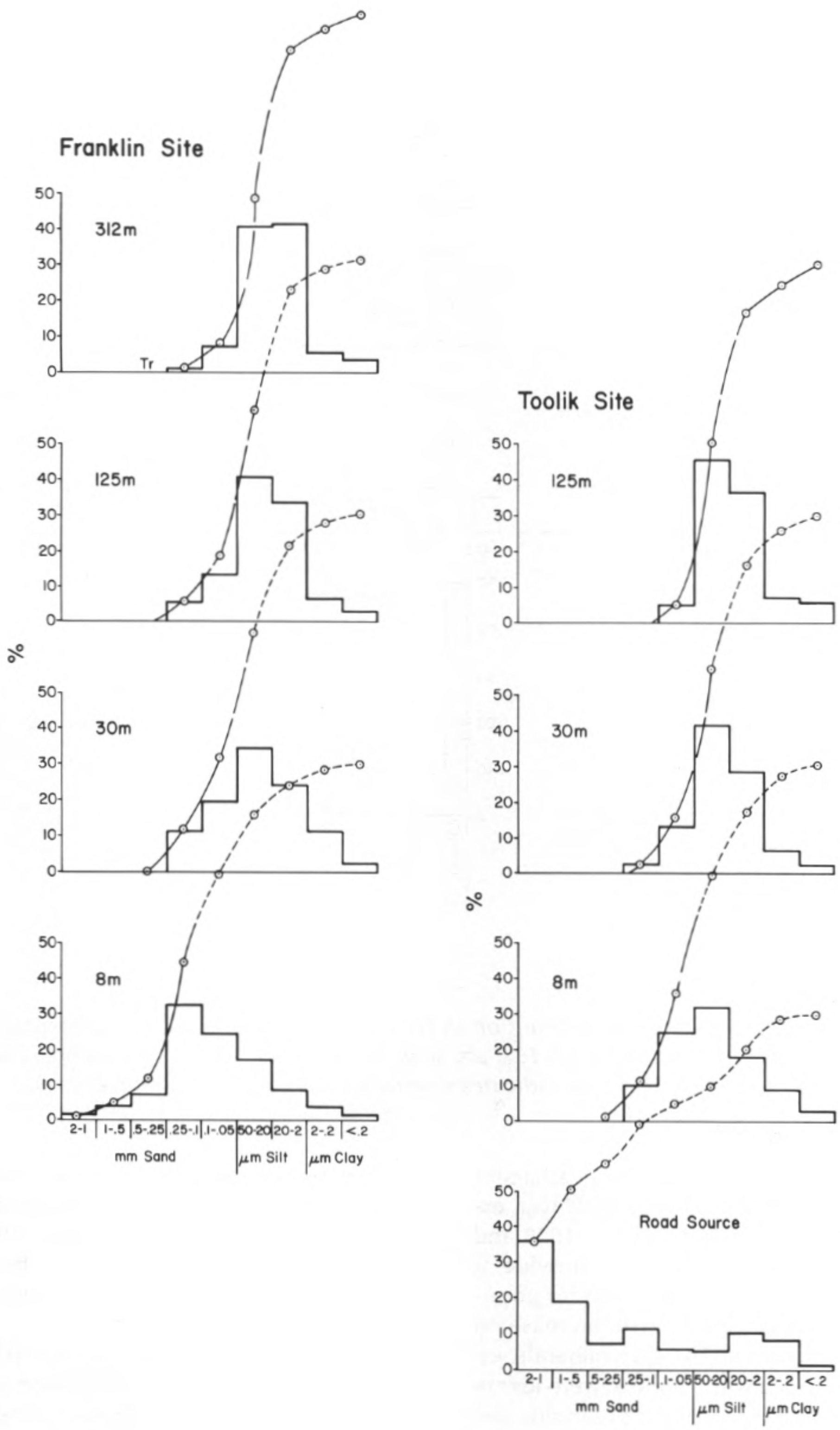


Figure 99. Particle size distribution of road material and road dust collected at 8, 30 and 125 m from the west side of the Haul Road (1978). Median particle diameters read from a cumulative curve.

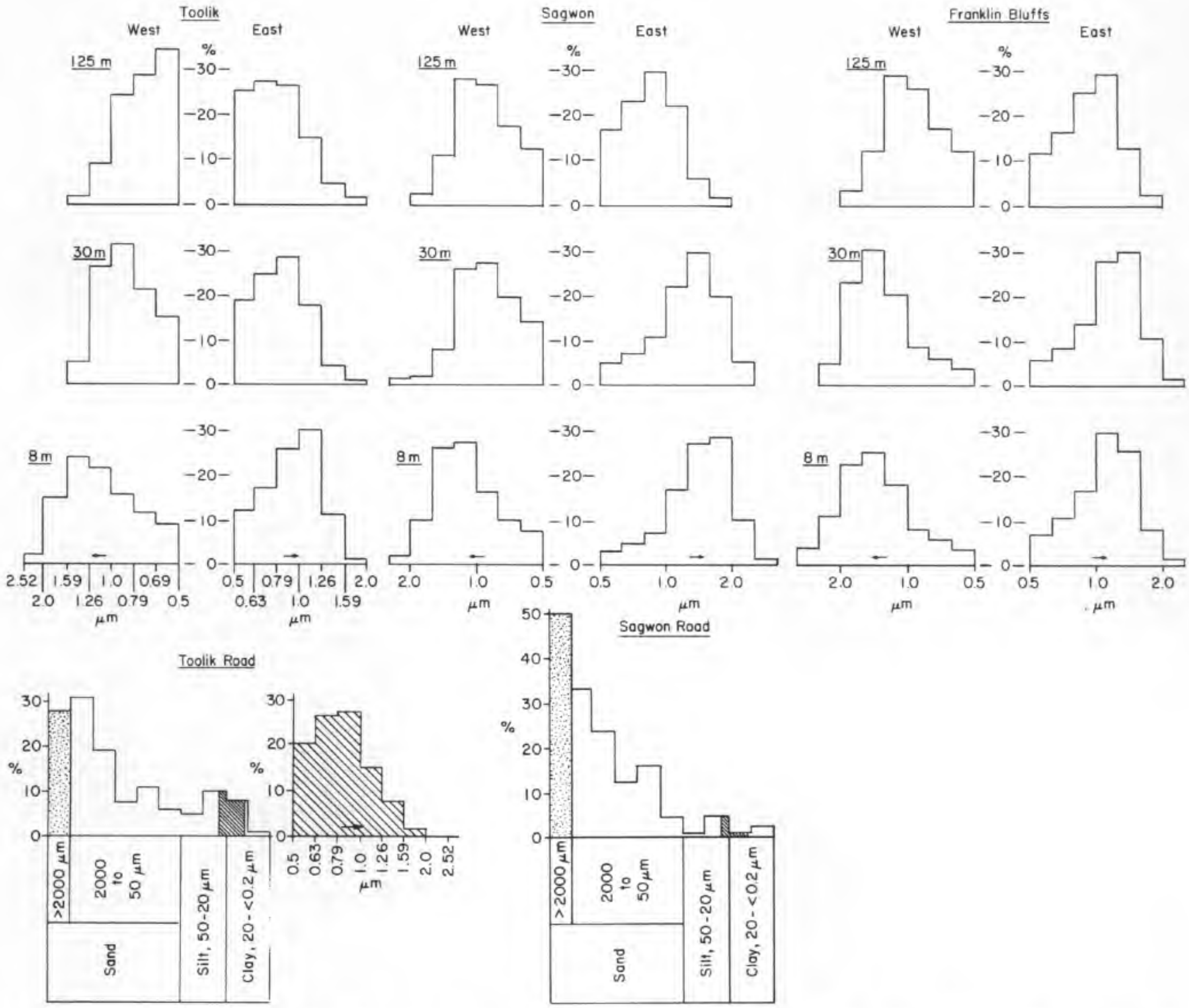


Figure 100. Microparticle (0.5-16.0 μm) distribution in Haul Road dust expressed as percentage of total count. Composite of road surface material in the 0.5-16.0 μm range is shown for Toolik. Dust samples represent a collection period of 66 days. Cross-hatched area indicates size range analyzed for microparticles.

erals in the road material, as well as in adjacent soils, are chlorite, illite and a mixed-layer expandable clay (Reynolds and van Oss 1978 and App. E). These minerals not only provide a source for iron and aluminum but also for potassium and magnesium which also increase in abundance with distance. The clay minerals, especially chlorite along with zeolites, were identified at Toolik and Franklin Bluffs (Reynolds and van Oss 1978) and are potential sources for some of the less abundant elements recognized in the neutron activation analyses. Further study is underway to relate specific size fractions to elemental composition.

It should be noted that the concentrations of most of the elements are within their ranges in the natural environment (Taylor 1964). As shown in Figure 102 cobalt appears to be an exception, being generally lower in the dust samples than the natural environment.

The limited data for winter road dust indicate somewhat higher concentration levels than in the summer for some elements, especially aluminum, silicon, barium and cobalt. The elemental data for the Toolik site show a pattern of general reduction in abundance out to 312 m. Beyond this point, all values decline sharply to far below their natural abundance, especially those for sili-

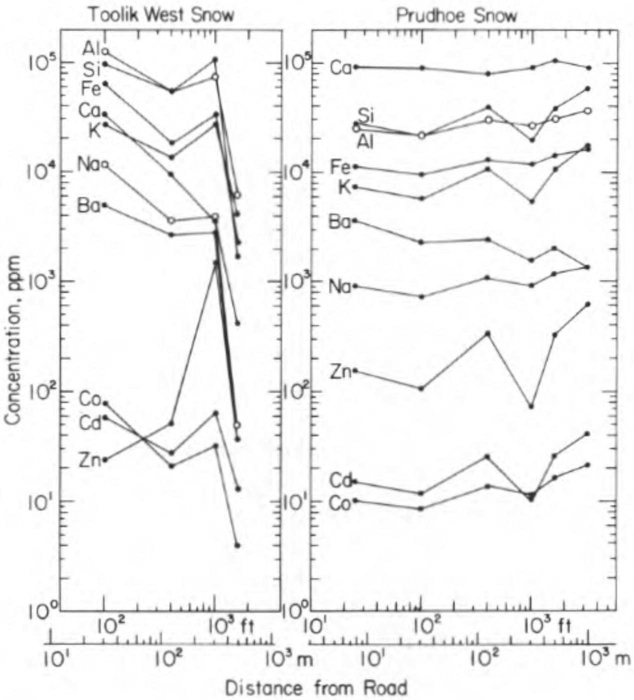


Figure 101. Concentrations of selected elements in the winter 1977 dust as determined by neutron activation analyses.

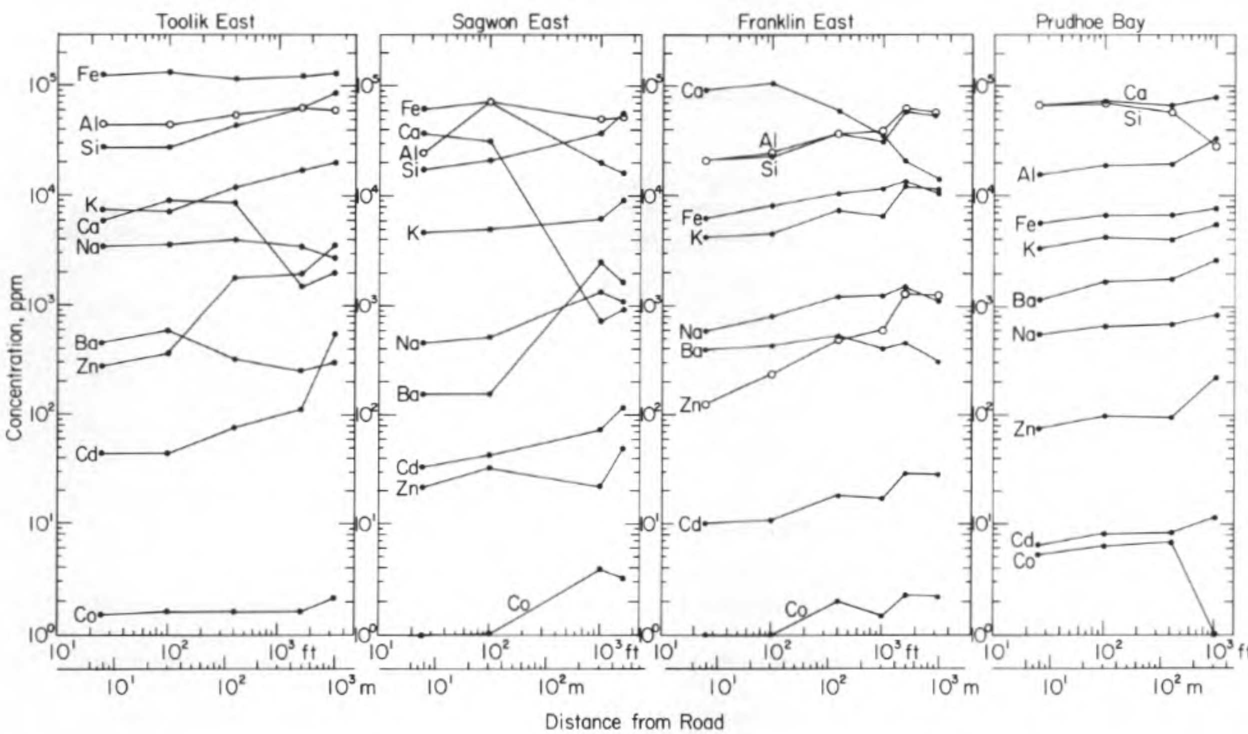


Figure 102. Concentrations of selected elements in the summer dust as determined by neutron activation analyses.

Table 26. Order of abundance vs distance from mountains for selected elements in road dust.

Toolik Dust	Toolik Snow*	Sagwon	Franklin	Prudhoe Dust	Prudhoe Snow*
Fe	Al	Fe	Ca	Ca	Ca
Al	Si	Al	Al	Si	Si
Si	Fe	Si	Si	Al	Al
K	K	K	Fe	Fe	Fe
Ca	Ca	Ca	K	K	K
Na	Na	Na	Na	Ba	Ba
Ba	Ba	Ba	Ba	Na	Na
Zn	Zn	Cd	Zn	Zn	Zn
Cd	Cd	Zn	Cd	Cd	Cd
Co	Co	Co	Co	Co	Co

con, iron, aluminum, barium and sodium. This decrease in abundance coincides with a large reduction in total dust fall beyond 312 m (Table 25). This large decline in elemental abundance in winter dust does not occur at the Prudhoe Bay site where abundance and trends are similar to those of summer dust.

The relative abundance of elements is quite constant from site to site along the northern part of Haul Road (Table 26). The only significant change in ordering occurs at Franklin Bluffs where calcium replaces iron as the dominant element. This reflects the generally high carbonate content of these Coastal Plain sediments, including river sediments used in construction of the road. The general homogeneity of the element abundance is mirrored in the clay mineralogy from site to site as well as along the entire road north of the Brooks Range (Reynolds and van Oss 1978; App. E).

It should be noted that the elemental abundance in the dust as determined by neutron activation does not in all cases parallel that recorded by atomic absorption spectrophotometry. In the latter case plant-available (i.e. soluble plus exchangeable) ions are measured.

Soil cation composition

Soil samples were collected in 1977 at 0- to 2.5-cm and 2.5- to 5-cm depths below the surface at each dust collection station. Table 27 and Figure 103 summarize the soil cation data for the four sites.

Toolik

Uniform trends in soil cation concentration with distance do not occur at this site. However, at the 0- to 2.5-cm depth there is a generally greater concentration on the west side of the road than on the east side. This is consistent with heavier dust loading on the west side. Peak concentrations of soil cations (except calcium) at

Table 27. Summary of soil cation data from dust collection stations along the northern portion of the Haul Road, 1977.

	Distribution of dust load with distance	Dist. (m) to peak soil ion conc.	Trend in soil ion conc. with distance	Depth of greatest ion conc.	Ion of greatest conc. in 0-2.5 cm	Mean concentration in 0-2.5 cm Ca	Mg	K	Na	Prevailing wind from
Toolik—west	Logarithmic	312	None	0-2.5	Ca	12.6*	5.6	1.9	0.71	SW/SE
Toolik—east	Logarithmic	125	None	0-2.5	Ca	12.5	7.3	1.7	0.94	
Sagwon—west	Logarithmic	30 & 312	Decrease	0-2.5	Ca	28	11.9	4.0	0.97	S/SW
Sagwon—east	Logarithmic	30 & 312-500	Increase	0-2.5	Ca	37	7.8	2.8	0.48	
Franklin—west	Logarithmic	30 & 500	Decrease	0-2.5	Ca	75	4.7	1.5	0.58	E/NE
Franklin—east	Logarithmic	None	Slight increase	0-2.5	Ca	54	3.6	0.64	0.29	
Prudhoe—north	Logarithmic	312	None	0-2.5	Ca	3.82	2.4	0.44	1.10	NE

* All ion data expressed in milliequivalents per 100 g dry wt of soil.

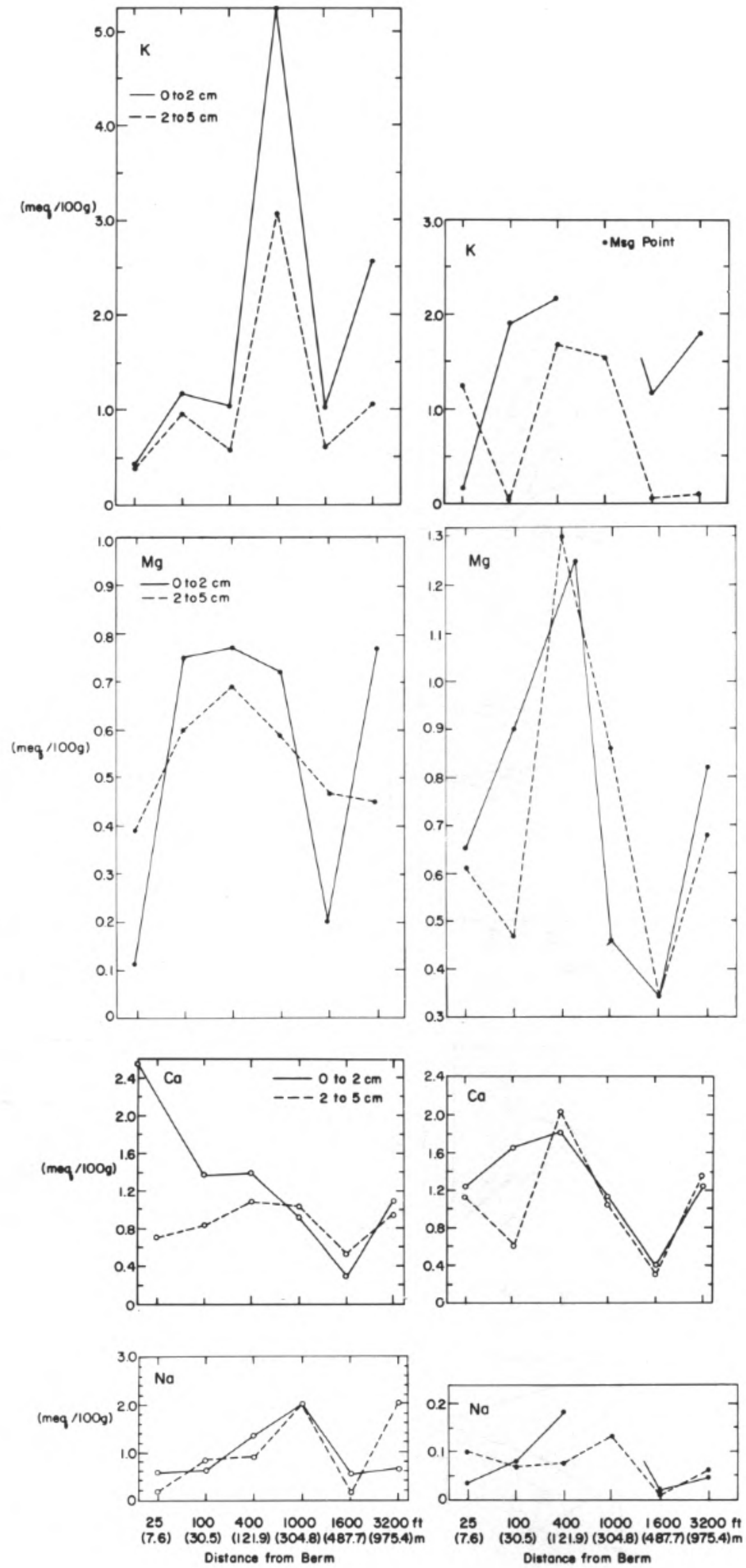
Additional comments on available soil cations in the 0–2.5-cm-depth interval:

Ca—Highest at Franklin; shows no preferential accumulation on either side of the road at any site and shows no trend toward or away from the coast.

Mg—Highest at Sagwon; shows a preferential increase on the west side of the road at Sagwon and Franklin and no trend toward or away from the coast.

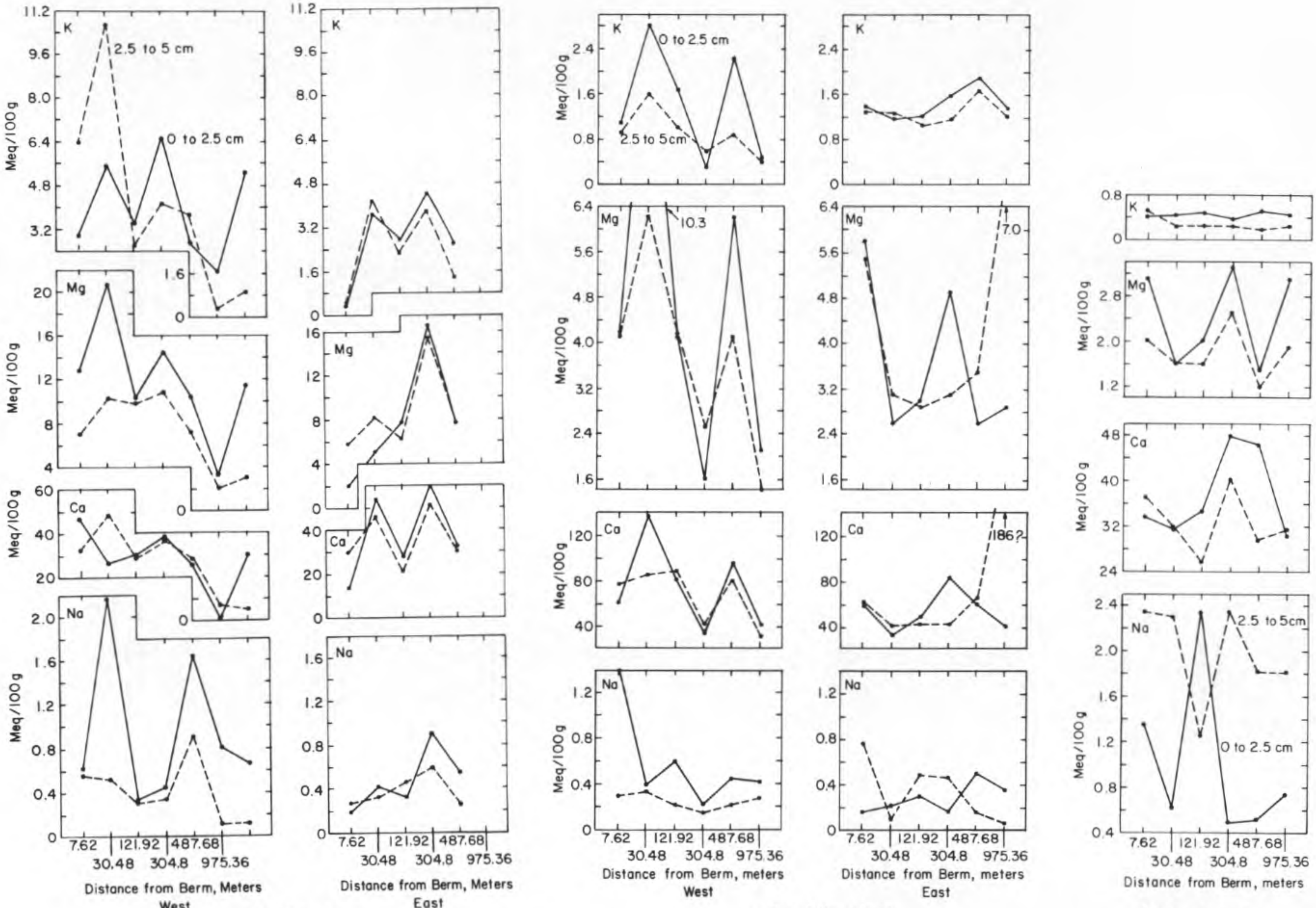
K—Highest at Sagwon; shows a strong preferential accumulation on west side of the road at all sites and no trend toward or away from the coast.

Na—Highest at Prudhoe; shows a strong preferential accumulation on the west side of the road and no trend toward or away from the coast.



a. Toolik

Figure 103. Exchangeable cations from surface samples.



b. Sagwon

c. Franklin Bluffs

d. Prudhoe Bay

Figure 103 (cont'd). Exchangeable cations from surface samples.

Table 28. Major cation concentration of moss and lichens 30 and 830 m from the road at the Toolik site (data provided by I. Iskandar, CRREL).

	Concentration (μg/g) (dry weight basis)				Moisture content (%)
	Na	K	Ca	Mg	
Moss—30 m from road—plant tops	1274	4795	4124	4905	404
Moss—30 m from road—plant mid	1311	2900	2066	2811	697
Moss—30 m from road—plant bottom	1361	2686	4117	1512	777
Moss—830 m from road—plant tops	1458	5667	2139	1270	532
Moss—830 m from road—plant mid	1945	5223	4445	2334	686
Lichens—*Dactylina arctica*—tops	1491	3380	2355	1525	15
Lichens—*Dactylina arctica*—bottoms	2371	4139	2334	2232	15.8
Lichens—*Cetraria cucullata*—whole	1443	3556	6136	1421	14.3
Error	<4%	<3%	<3%	<2%	
Normal range in lichens*	<1000	<8500	<9000	<900	

* Tuominen and Jaakkola (1973).

both measured depths occur at 312 m on the west side of the road and at 125 m on the east side. Pronounced low concentrations occur at 125 m on both sides of the road.

Moss and lichen samples from the Toolik site were also analyzed for major cations (Table 28). Moss samples (30 m and 830 m from the road) were vertically subdivided. Several lichens were also selected from a site 25 m east of the road. The samples were weighed and oven dried, and the total sample was digested in a mixture of 3:1 (vol/vol) of NHO_3 and $HClO_4$ acids. Cations were determined with a Perkin-Elmer 303 atomic absorption spectrophotometer.

The moss samples were collected after relatively heavy rain which resulted in dust being washed from the surface. The Na, Ca and Mg concentrations from the more distant moss samples (830 m) show lower concentrations in the surface layer, suggesting that these cations had been washed downward by the rain. Also K is highest farther from the road, possibly reflecting higher clay content, as is consistent with the neutron activation analyses (Fig. 102). The moss samples closest to the road show higher values of K, Ca and Mg on the surface, which suggests that they are less likely to be leached or are replenished more readily than the more distant samples.

The lichen samples show cation concentrations similar to those of the mosses. However, Na and Mg concentrations are much higher than the normal values reported by several investigators and presented by Tuominen and Jaakkola (1973). It is possible that Ca and K are also higher.

Sagwon

On the east side of the road there is an overall increase in the abundance of exchangeable soil cations with distance as well as a strong double peak in concentration (samples at 30 and 312 m). There is a general trend toward a decrease in the availability with distance of all cations on the west side of the road. Again, however, two peaks are developed, one at 30 m and one between 312 and 500 m. Except for calcium, the absolute difference in cation availability between the 0- to 2.5- and 2.5- to 5-cm depths is greater on the west side of the road.

Franklin

The distribution and quantity of soil cations at Franklin Bluffs indicates that the quantity of available cations decreases on the west side with distance from the road, as was the case at Sagwon. Also, similar to Sagwon, peak concentrations are observed at 30 and 500 m. On the east side there is a weak trend, expressed principally by sodium and potassium, toward an increase in the amount of available soil cations with distance. No clearly defined peaks in abundance are identifiable. Mean values for the 0- to 2.5-cm depth are clearly higher on the west side of the road than on the east. This probably reflects the greater dust loading on this side.

Prudhoe Bay (Arctic Gas)

Soil cations do not show a recognizable trend away from the road at Prudhoe Bay. The surface concentrations (0 to 2.5 cm) are generally higher than those at the 2.5- to 5-cm depth except for Na which is very mobile and easily leached. Because this site has been subjected to dust fall for a much longer period than any other site, it might be expected to show the highest concentration of available cations. However, the data indicate that this is apparently not the case.

Dust impacts on vegetation*

Several investigations were conducted to assess the initial effects of dust on a variety of vegetation types. During the summers of 1976 to 1978, transects were established perpendicular to the road at 17 of the locations for which vegetation maps were prepared (Fig 32). Vegetation was recorded along the transect at 1-m intervals.

From these observations taxa are identified which are apparently susceptible to exposure to dust (Table 29). The cryptogams (i.e. mosses and lichens) are the most susceptible, due in part to their low growth-form, shallow surface anchoring, lack of cuticle, and in the case of most mosses, leaves that are only one cell thick. Unlike trees, shrubs, and herbaceous plants, the low growing cryptogams trap dust and are rarely cleaned by rain so that dust continually collects on the photosynthetic tissues. The dust appears to be toxic to several taxa, particularly members of the moss genus *Sphagnum* and some of the lichen family Cladoniaceae. The most affected lichens are those lacking an outer cortex (e.g. *Cladina)*. Some cryptogams appear to be more tolerant to heavy dust fall. These include members of the moss family Polytrichaceae and the lichen genus *Cetraria*. *Polytrichum* has a more erect growth-form, with thicker leaves than most other arctic mosses. A subjective rating of *Sphagnum* vitality at the Toolik upland site showed very noticeable difference in the health of the moss carpet near the road (Werbe 1980). Likewise, in another study of dust effects on *Sphagnum* from the Toolik upland site, Spatt (1978) observed that total conductivity, pH, and calcium of water extracted from the *Sphagnum* were greatest in the heavily dusted area immediately adjacent to the road as compared to samples at points 125 and 250 m distant. Chlorophyll and photosynthetic rates for *Sphagnum* were lowest in the most heavily dusted sites. It was concluded by Spatt (1978) that a long-term loss in the vitality of *Sphagnum* near the road margin may be expected. Clymo (1973) has examined the effects on *Sphagnum* of high calcium concentrations and found that reduced growth appeared with calcium concentrations above 10 ppm.

Some vascular plants are also affected by road dust. In the Atigun Valley and in the Prudhoe Bay region, four-angled Cassiope (*Cassiope tetragona*) was observed to be dying within the zone of heavy dust loading.

A few taxa appear to increase in relative abundance in roadside environments. These include the cottongrasses (*Eriophorum angustifolium* and *E. vaginatum*) and the moss *Drepanocladus brevifolius*. At Prudhoe Bay, *D. brevifolius* and *Scorpidium scorpioides* are able to tolerate naturally occurring calcium carbonate deposits which often cover all but a few leaves.

At the community level, the vegetation types which are most affected by the dust are those which have a high abundance of *Sphagnum* and/or fruticose lichens. Communities growing in alkaline areas are less affected by dust, since the plants are already adapted to the alkaline conditions.

The eventual outcome and extent of change to plant communities along the Haul Road is difficult to predict since comparable studies have not been conducted along other roads in permafrost areas. In the Prudhoe Bay region, where road dust has occurred for 10 years, there are very noticeable changes to the vegetation. Many mosses, lichens and herbaceous plants have been eliminated from roadside communities, and it is currently difficult to locate undusted stands of vegetation within several hundred meters of the road.

Discussion and conclusions

Dust load decreases logarithmically away from the road at all sites and is closely related to prevailing wind direction. The Toolik site produces the lowest total dust load, especially in the first 125 m. The largest dust load occurs at the Franklin Bluffs and Sagwon sites.

Silt and finer materials constitute between 8 and 15% of the road surface materials available for wind transport. Materials greater than 2000 µm are confined to within 8 m of the road. Beyond 20 m most of the dust materials are smaller than 50 µm. Within this finer fraction there is a significant shift to finer sizes with distance from the road.

*Based on observations by D.A. Walker and E. Werbe.

Table 29. Summary of transect observations regarding dust effects on various plant taxa.

Taxa listed "less tolerant" were observed dying in the areas of heavy dust fall. Healthy specimens of the "more tolerant" taxa were commonly observed in similar areas.

Less tolerant taxa	*More tolerant taxa*
Vascular plants	
Cassiope tetragona ARA, PB	*Alnus viridis* ssp. *crispa* GK, RR
Lycopodium annotinum GK	*Picea* spp. RR
	Betula nana TUR, TUS
	Salix planifolia ssp. *pulchra* TUS
	Rubus chamaemorus TUR
	Eriophorum angustifolium PB, ARS, TUS, FBN
	Eriophorum vaginatum TUR, FM
	Eriophorum russeolum PBS
	Ledum ssp. GK, CF
	Vaccinium uliginosum GK, CF
	Vaccinium vitis-idaea GK, CF
	Spiraea beauverdiana GK
	Braya purpurascens PB
	Dryas integrifolia PB
Mosses	
Sphagnum spp. GK, GL, FM, SMS, TUS, SU	Polytrichaceae CF
Hylocomium splendens RR, CF, ARA	*Drepanocladus brevifolius* PB, FBN
Pleurozium shreberi CF	*Scorpidium scorpioides* PB
Dicranum spp. GK, SMS, ARA, ARS, SU	*Campylium stellatum* SMI
Catascopium nigritum FBM	*Rhacomitrium lanuginosum* SMI
Thuidium abietinella ARS	*Aulacomnium turgidum* ARA, SU
Rhytidium rugosom ARS	*Aulacomnium palustre* ARS, SU
Cinclidium spp. FBN	*Bryum* spp. FBN
Meesia triquetra FBN	
Tomenthypnum nitens SMI, FBN	
Lichens	
Cladina arbuscula RR, GK, GL, CF, WV	*Cladonia pyxidata* CF
Cladina alpestris CF	*Cladonia gracilis* CF
Cladina rangiferina GK, GL, WV	*Thamnolia subuliformis* PB, FBN
Peltigera aphthosa CF, ARA	*Cetraria cucullata* CF, ARA
Dactylina arctica ARA	*Cetraria islandica* CF
Alectoria spp. (on trees) RR	*Cetraria nivalis* CF
Usnea spp. (on trees) RR	

Site location code (see Fig. 32)

YR–Yukon River	AP–Atigun Pass
RR–Ray River	ARA–Atigun River–Alluvial Pass
NN–No Name Creek	ARS–Atigun River–Sand Dunes
GK–Gobbler's Knob	TUS–Toolik Upland South
GL–Grayling Lake	TUR–Toolik Upland Road Effects Study Site
FM–Finger Mountain	SU–Sagwon Upland
CF–South of Coldfoot	FBO–Franklin Bluffs Oil Spill Site
WV–Wiseman Vicinity	FBN–Franklin Bluffs North
SMS–Sukakpak Mountain South	PBS–Prudhoe Bay–Sand Dunes
SMI–Sukakpak Mountain Ice-cored Mounds	PBC–Prudhoe Bay–Coast
DT–Dietrich Treeline	PB–Prudhoe Bay (unpubl. data)

Significant peaks in the concentration of available soil cations occur with respect to distance from dust source and most commonly at the collectors placed 312 m from the road. Other peaks can occur at 30 and 125 m. These peaks are probably related to particle size and/or particle composition and are not simply the result of microsite differences. The quantity of available cations is generally largest in the 0- to 2.5-cm depth as compared to the 2.5- to 5-cm depth. There appears to be a significant increase in the total amount of available soil cations on the west side of the Haul Road. There does not appear to be any trend in the abundance of the available soil cations measured as the ocean is approached.

Concentrations of some elements in road dust (Si, Al, Ba, Co) appear to be greater in winter than summer. Most chemical elements for which data have been evaluated in the road dust tend to increase in abundance away from the road with the exception of calcium. The concentration of most elements in the road dust for which data have been evaluated are within their natural abundance in soil and rock, although cobalt is lower. The relative abundance of elements in road dust is quite constant from site to site along the portion of the road studied.

Soluble calcium in the dust that settles on vegetation is immediately available to be incorporated in the plant—particularly in the mosses, which are organic systems that are little- or non-buffered with respect to hydrogen ions.

The potentially soluble Ca that reaches the soil surface either directly or is washed from plants enters an environment (at the Foothills sites) that is highly base-unsaturated and has a high cation exchange capacity (CEC) dominated by H^+. As an example, the dust at Prudhoe Bay contains something like 1.8 g soluble Ca/kg per m^2. In a volume of soil 1 $m^2 \times 2.5$ cm it is calculated that 2 g of Ca will be required to neutralize 1 meq of H^+—this assumes that all of the Ca is in $CaCO_3$ and that the organic soil has a bulk density of 0.45 g/cm^3. In the Foothills area of acid tussock tundra, the upper 2 to 4 cm of organic soil has an average of 50 meq of exchangeable H^+/100 g of soil. It becomes clear that dust loads even close to the road contain insufficient soluble Ca or Ca+Mg to affect either the pH or nutrient status of the soil. Release of Ca from minerals such as feldspars or hornblende is too slow in the arctic environment to be of short-term consequence. This general conclusion does not minimize the direct chemical effect of calcium on the mosses or in other unbuffered media. A possible result of this is the elimination of moss, especially the acidophylic species such as *Sphagnum*. If other species do not increase in abundance and maintain the insulating blanket, permafrost is likely to be modified. This general scenario has been suggested by Tamm and Troedesson (1955) and by Kryuchkov (1975) quoting P.I. Koloskov.

Sphagnum and lichens, particularly those in the family Cladoniaceae appear to be susceptible to road dust. Other cryptogams appear to be relatively unaffected, especially members of the moss family Polytrichaceae (vertically growing mosses) and lichens of the genus *Cetraria*. Of the vascular plants studied four-angled Cassiope (*Cassiope tetragona*) appears to be greatly affected in the zone of maximum dust fall, i.e. the first 300 m from the road. Some plants such as the cottongrasses (*Eriophorum angustifolium* and *E. vaginatum*) and the moss *Drepanocladus brevifolius* appear to respond positively within the area of maximum dust fall. Dust, however, may be only partly responsible for this.

Early snow melt (2 to 3 weeks) brought about by dust accumulating on the winter snow may extend between 30 to 100 m on either side of the road. The potential for increased use of well-surfaced, high-speed gravel roads in tundra areas is increasing. Thus a thorough understanding of dust effects, some of which are quite subtle, is essential to proper road design, use of dust suppressants, speed control and limits on axle weight.

CHAPTER 4. REVEGETATION AND RESTORATION INVESTIGATIONS

by L.A. Johnson

Introduction

The construction of the Haul Road, the oil pipeline and the fuel gas line along the northern portion of the road resulted in a variety of terrain disturbances. Government stipulations required that erosion be controlled and impacted areas be revegetated or restored. Pamplin (1979) reported that the Haul Road resulted in the permanent loss of 1518 hectares (3751 acres) and that material sites north of the Yukon River occupied approximately 3650 hectares (9000 acres).

A number of terms are frequently used in reference to the reestablishment of plant cover. Revegetation refers to establishment of a vegetation cover on a disturbed surface. Rehabilitation is a broader term that includes revegetation as well as other techniques to control erosion. Finally, restoration is a long-term process which returns the disturbed site to conditions similar to the original ones.

The types of construction activities which required rehabilitation are illustrated in Figure 104. The road itself required numerous cuts and fills. Material sites, opened at irregular intervals on the uplands and in river terraces and floodplains, were connected to the Haul Road by access roads. Some material sites and some undisturbed sites were later used as disposal sites for organic debris and excavated materials before being revegetated and returned to government control. A few were used to stockpile gravels for road maintenance and turned over to the Alaska Department of Transportation and Public Facilities. The oil pipeline parallels the road and in the aboveground and some of the the belowground mode has a gravel workpad which also is connected to the Haul Road by access roads. Upon

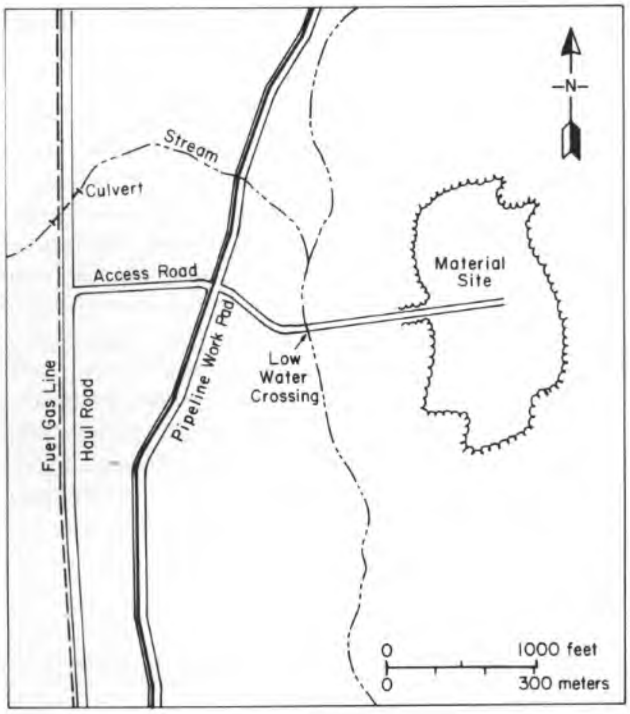


Figure 104. Idealized drawing showing major road and pipeline construction activities.

completion of the pipeline, most of these access roads were blocked by gates or gravel berms and revegetated. The fuel gas line created a linear disturbance which was largely immediately adjacent to the road.

Our CRREL investigations involved both observational programs of Alyeska's revegetation practices over a four-year period and several experimental programs. Since the results of the extensive revegetation program along the Haul Road are not readily available, and since the technology developed is of importance to road construction in the North, we will summarize these results and methods in the following. Additional detail appears in a separate CRREL report on the 1975-1978 observations of revegetation along the entire pipeline (Johnson 1980).

Revegetation approaches

Research on revegetation and restoration within Alaska and northern Canada was limited until the late 1960's. At that time, and for a period of some 4 to 5 years, the Alyeska Pipeline Service Company (ALPS) undertook a revegetation research program (Johnson and Van Cleve 1976). Since commercial seed supplies of native species were few or nonexistent, the basic strategy which evolved was to select from among existing commercial varieties of grasses those which were best adapted to arctic and subarctic growing conditions. Lack of seed is a widespread problem which limits the use of the more desirable native species for revegetation (Sutton 1975). Field tests of varieties of grasses at selected locations along the trans-Alaska pipeline were used as the major basis for selecting both grasses and fertilizer levels (Mitchell and McKendrick 1974a, 1974b; Van Cleve and Manthei 1972, 1973). In addition, extensive surface soil samples from the pipeline route were analyzed for nutrients. This information was then used to formulate fertilizer mixes which would provide both macro- and micro-nutrients to the ALPS grass species.

Native species offer distinct advantages and are potentially very important for arctic and subarctic revegetation (Johnson and Van Cleve 1976, Bliss 1978). Two of these species, bluejoint reedgrass (*Calamagrostis canadensis*) and tall arctic grass (*Arctagrostis latifolia*), were selected and placed into seed increase programs (Mitchell 1979). However, due to the time required for commercial seed production of new varieties and the decision to rely primarily upon seeding for revegetation, Alyeska was, more or less, obligated to use introduced species of grasses (exotic species). Alternative methods, such as resodding with native vegetation (Younkin 1976), or fertilizing undisturbed tundra to provide increased sources of native seed* were either not attempted or were considered uneconomical or otherwise not practical. However, Alyeska did use native shrubs and trees in their willow program and visual impact engineering (VIE).

Alyeska's primary reliance upon a seed mix of introduced grasses followed common practice in the Subarctic, although the exact species composition was unique to this project. However, the relative ease of this approach does not guarantee that it is an optimal solution (Webber and Ives 1978). Studies of a site disturbed in 1949 by early oil exploration in the Arctic have shown that, depending upon soil moisture, ground ice content, and intensity of disturbance, sites will naturally revegetate (Lawson et al. 1978). It may be preferable to let certain disturbances naturally recover or to facilitate reinvasion by native species in lieu of relying upon seeding programs.

Alyeska erosion control and revegetation program

The revegetation program used by Alyeska was an outcome of repeated proposals, counterproposals and eventual approval as a result of discussions between Alyeska and both state and federal regulatory agencies. As such it represented a compromise between Alyeska's design and regulatory concerns based largely upon environmental stipulations.

Alyeska's pipeline and Haul Road revegetation program was employed primarily as a means of erosion control (Lucas 1975); however, Alyeska's stated long-term goal was restoration of all disturbed sites by permitting the reinvasion of native species. These two goals may conflict, at least in the short run. For example, the selection and use of well-adapted agronomic grass varieties in the revegetation seed mix could impede the reinvasion of native species onto a site once it has been successfully revegetated (Younkin 1976, Johnson 1978). Other goals for revegetation include promotion of a stable thermal regime, aesthetic considerations, and production of wildlife habitats.

*Personal communication, F.S. Chapin III, University of Alaska.

Table 30. Revised 1977 seed mixes, locations used, and seeding schedule.

a. Seed mixtures

	Mix 1 North Slope	Mix 2 Brooks Range	Mix 3 Interior
Arctared fescue *(Festuca rubra)*	12.3 (16.5)	4.5 (16.5)	
Nugget bluegrass *(Poa pratensis)*	12.3 (11.1)	10.1 (11.1)	5.6 (0)
Redtop *(Agrostis alba)*	1.1 (5.5)	3.4 (5.5)	
Boreal red fescue *(Festuca rubra)*	10.1 (5.5)	10.1 (5.5)	5.6 (4.4)
Durar hard fescue *(Festuca ovina* lar. *duriuscala* L. Koch)		10.1 (0)	5.6 (4.4)
Climax timothy *(Phleum pratense)*		4.5 (5.5)	2.2 (0)
Meadow foxtail *(Alopecurus pratensis)*		11.2 (5.5)	6.7 (13.2)
Sydsport bluegrass *(Poa pratensis)*			(3.3)
Manchar brome *(Bromus inermis)*			10.1 (5.5)
Annual rye *(Lolium multiflorum)*	14.6 (16.5)	13.4 (16.5)	7.8 (11.1)
Tall arcticgrass *(Arctagrostis latifolia)*	1.1 (0)		
Total	51.5 (55.1)	67.3 (66.1)	43.6 (41.9)

b. Seeding schedule

Construction section	Dormant	Permanent	Temporary	No seeding
4	15 Sept-1 Jun	1 Jun-1 Aug	1 Aug-15 Aug	15 Aug-15 Sept
5	10 Sept-1 Jun	1 Jun-15 Jul	15 Jul-1 Aug	1 Aug-10 Sept
6	1 Sept-1 Jun	1 Jun-15 Jul	15 Jul-1 Sept	None

Numbers in parentheses are the amounts used in the original 1975 mix; units are kg/ha (Lucas 1975).

Alyeska's erosion control program was proposed in three phases. The initial phase, EC-1, involved seeding during the construction period and applied primarily to areas that were judged to pose erosion problems, although areas not to be disturbed again could also be seeded. During phase EC-2, or the cleanup period, permanent measures were to be implemented to rehabilitate construction sites. The third phase, EC-3, involves erosion control maintenance needed to control unanticipated or recurring erosion problems until all sites are acceptably revegetated. EC-3 includes reseeding and refertilizing.

Alyeska utilized seed and fertilizer mixtures and application rates to accommodate the geographical and seasonal variations along the pipeline route. For this purpose three geographical zones were designated north of the Yukon River. For the Haul Road, seed mixture 1 covered Prudhoe Bay to Toolik, mixture 2 from Toolik to Coldfoot, and mixture 3 from Coldfoot south (Table 30).

During 1975, 1976, and portions of the 1977 growing season, Alyeska's revegetation program remained in the initial phase, EC-1. Modifications were made in design specifications but the basic erosion control program remained essentially unchanged. The seed mixes were altered during 1977 in order to reflect changing seed supplies and as part of the post-construction

(EC-2) phase of revegetation. A consistent change in all mixes was a reduction in the amount of annual rye seed, although the rye was still a major component of the mix (16 to 25% by weight). The reduction in annual rye may reflect higher germination rates due to better seedbed preparation after 1975, such as harrowing, or reduced danger of erosion after construction was completed with a consequent reduction of the need for initial rapid growth. Concern that rye growth may be overly competitive with desired perennial growth was also an important consideration in its reduction in the seed mix. A second change in the mix was the addition of a small amount of tall arcticgrass (*Arctagrostis latifolia*) seed to the North Slope mixture. This is one of the two native species from which Alyeska had seed commercially produced. Significantly, this represents the first step in the use of native species for revegetation along the trans-Alaska pipeline.

The percentage composition of fertilizer nutrients used along the haul road was: N (10.9), P_2O_5 (15.1), K_2O (14.5), S (5.2), Mg (3.6), Cu (0.36), Zn (0.48), B (0.12), and Mo (0.0218). This fertilizer was applied at a rate of 715 kg/ha. In order to account for seasonal variation, seeding schedules were devised that would minimize problems such as winterkill (Table 30). Specifically, permanent seeding could only take place early in the growing season, followed successively by periods of temperary seeding, no seeding, and dormant seeding. Temporary seeding for rapid erosion control uses only annual rye. Perennials would germinate and then be winterkilled because they would not have adequate time to become hardy prior to freezeup.

Seeding methods varied, with hydroseeding being the most frequently used method (Fig. 105). Linear areas such as the pipeline workpad were often aerially seeded (Fig. 106), while hand seeding and seed spreaders were used on smaller areas. Fertilizer was applied by similar methods as well as with air injection applicators and specially modified sanding trucks. Fertilizer could be applied in combination with mulches but seeding was done separately from fertilizing. It was planned to check both seed and fertilizer application density and distribution in the field against Alyeska rate check boards for quality control; however, this procedure was probably never widely implemented.

Alyeska predesigned rehabilitation procedures and structures for erosion control. Allowance for local variation and unforeseen conditions was made by permitting Alyeska personnel to modify standard procedures whenever field conditions necessitated these changes. An erosion control field manual was prepared to assist field engineers in determining necessary field changes. This manual contains erosion control procedures which provide guidance on such items as clearing, disposal sites, drainage structures, thermal erosion control, mulches, revegetation, channel liners, fish stream crossings, drainage ditches, and maintenance practices.

In addition to seed and fertilizer mixes, Alyeska specified a number of additional stabilization and revegetation procedures. These include the use of mulches such as straw and wood cellulose fiber, tackifiers, excelsior mats, jute netting, sprigging (the use of woody shrub cuttings), transplants of shrubs and trees and the spreading of previously removed organic materials over disturbed areas.

Special restoration programs were also initiated during 1977. In the spring of 1977 a willow cutting program was established in order to replace wildlife browse lost during construction. Also during the summer of 1977, the VIE program began. This involved the planting of visual screens of trees and tall shrubs at pipeline crossings and other locations (e.g. material sites, etc.) visible from public roads.

Weeds and weedy plants*

Introduction

The building of the Haul Road provides a means for plant migration extending from the Yukon River to Prudhoe Bay and a unique opportunity to study many important questions dealing with problems of plant migration and establishment. This construction project is particularly interesting because it permits the first opportunity for investigation of these problems as they relate to the Alaskan Arctic.

Among the first pioneer species in any disturbed area are the introduced weeds and native weedy species. A true weed is an opportunistic exotic plant which, when introduced into an area, can quickly take advantage of temporary resources, especially space. Many species of weeds have been observed in subarctic regions but few in the Arctic. For example, nearly 200

*Prepared by A.W. Johnson and S.A. Kubanis (p. 132-139).

Figure 105. Hydroseeder, with bales of wood cellulose fiber on trailer.

Figure 106. Aerial fertilizing of pipeline workpad in the vicinity of Old Man, September 1976.

species of introduced flowering plants were reported from the Alaskan Subarctic by Hultén, (1968), but only one such species was observed north of the Brooks Range. Weedy species are native species which act like true weeds to some extent by pioneering on disturbed sites. They are usually generalists, and in the native vegetation may be members of fairly different vegetation types.

Weeds have certain characteristics related to their colonizing ability. Usually, they are relatively light-demanding, xerophytic, frost resistant, deep rooting and unexacting as to soil (Daubenmire 1968). Weed populations have the ability to increase quickly and often have evolved mechanisms to ensure dispersal. Both of these qualities increase the probability that weed seeds will find newly created bare areas. Thus, weeds are adapted for invasion of any open space as long as the environment is within the physiological tolerances of the plant. Introduced weeds generally persist only as long as the disturbed habitat exists. They are intolerant of the conditions that develop with the establishment of dense plant cover (Daubenmire 1968).

On most disturbed sites in the Subarctic, a mixture of weeds and weedy species occurs. In subarctic Alaska, 20 to 30 native invading species are to be expected on disturbed sites, and they may remain as minor components of the vegetation even after the establishment of species belonging to more mature communities.

There are two primary reasons for the lack of weed species in the Arctic. First, few true weeds have been introduced into the Arctic because farming and grazing, the most likely avenues for introduction, are essentially absent. Subarctic Alaska, where agriculture is common, has a substantial weed flora. Weed species are also introduced into subarctic Alaska by means of the continuous road system from Canada into Alaska, which until recently, was not connected with Arctic regions. Prior to this time, introduction of exotic weeds into the Arctic resulted from air or water transport.

In addition to migration, two other weed sources, contaminated grass seed and straw used for revegetation, became important. The road cuts and material sites of the Haul Road were revegetated with this grass seed, and straw, used as a mulch in many places, could contain thousands of weed seeds in a single bale. The straw was obtained from interior Alaska and any weeds occurring there might have been introduced. The grass seed was produced in a number of locations including Oregon, Washington, the Peace River Valley in Alberta, Canada, and in Alaska. It was tested to meet germination and purity requirements, however, even certified seed may contain a low percentage of weed seed.

The second major reason for the lack of weed species in the Arctic is that the characteristic physiology and growth habits of the weeds are not suited for arctic conditions. Many weeds are annuals and the success of an annual weed depends upon its ability to mature and disperse its seeds during the short growing season. Nearly all arctic native species are perennials and do not depend on annual seed set for survival.

Methods

The objective of this study was to monitor the appearance of weeds in areas currently free of them, disappearance or persistence of weed species in areas where they now exist, succession into both bare and reseeded areas by native species, competition between natives and weeds, and persistence of grasses in seeded areas (Kubanis 1980). Permanent transects and plots were established at 98 sites along the Haul Road (Fig. 107). Transects were established to be representative of several situations: 1) bare areas, 2) areas of seeded grasses only, 3) areas of grasses and weeds, 4) areas of grasses and invading natives, and 5) areas of grasses, weeds and native invaders.

One-meter-square plots were established, the number of which varied depending upon the size of the disturbed area. For each 1-m-square plot, all species of plants were recorded and the percentage cover for each species, grasses (collectively), and bare ground was estimated. An area 50 m north and south of the transect was also examined for the species of weeds present. Site differences, the presence of pollinators, straw or netting and last year's growth were recorded. Photographs were taken to document observations.

Phenological data for weed species were collected over the growing season. Vegetative growth, height, buds, flowers, fruits, dispersal, and senescence were recorded. Seeds and plant specimens were collected, but seed collections were fairly sparse because most species had not matured by the time the field studies were ended. Phenological events were also documented with photographs.

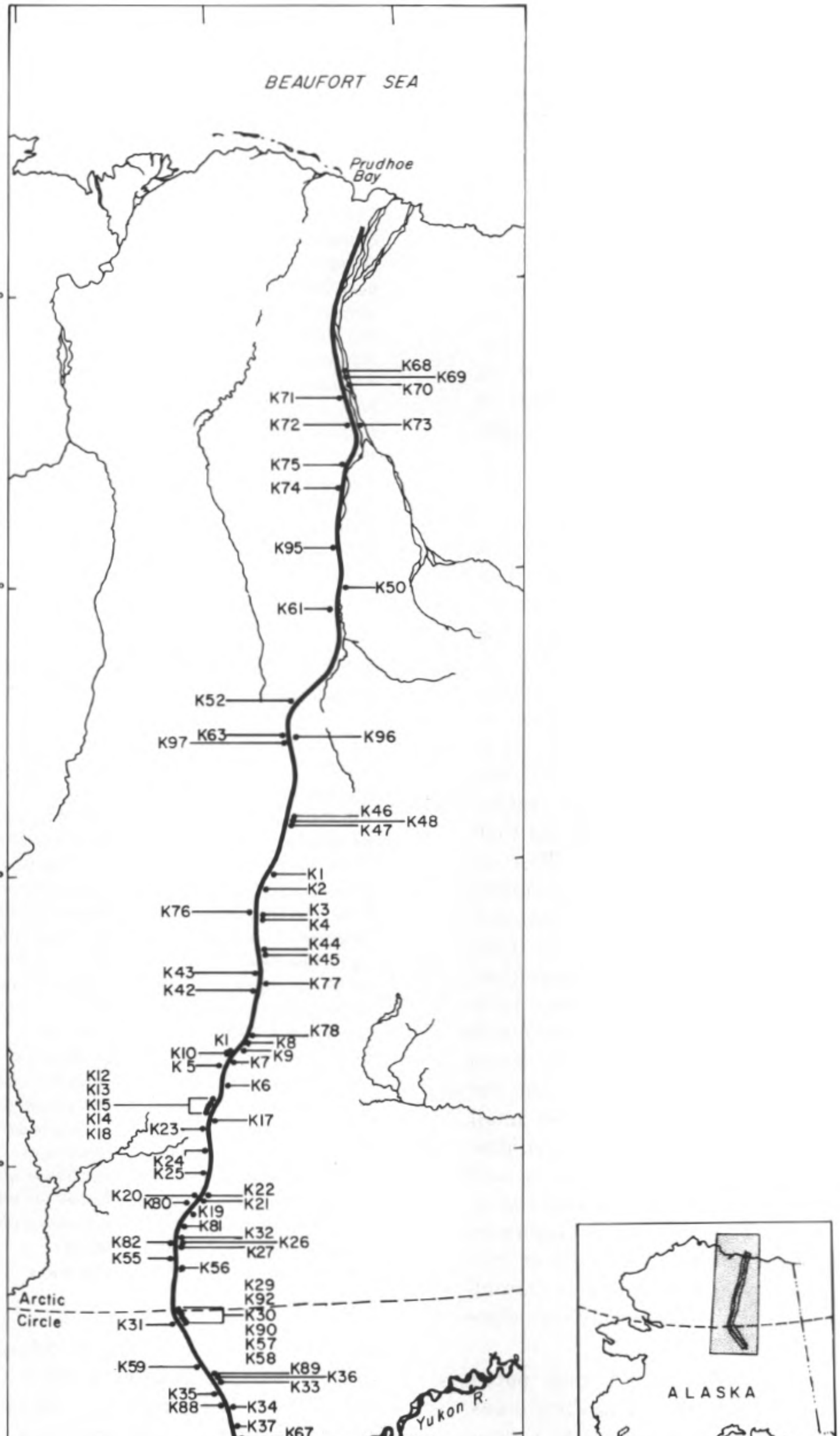


Figure 107. Location of sites for weed and weedy vegetation studies.

Where single species stands or stands of two or three species of weeds or native invaders were found, permanent population observations were initiated using transects, plots, and locating techniques as described earlier. A 1-m-square quadrat was used and the number of individuals of each species per quadrat was determined. Population plots were established for each of 12 species at as many sites as possible along the Haul Road. Dispersal and the presence of straw were also recorded when observed in these plots. Also recorded was whether the plot was of a single species or mixed species. Photographs were also taken.

Results

Species lists of the weeds and native invaders were compiled to summarize the species established in disturbed areas along the Yukon River–Prudhoe Bay Haul Road by 1977 and 1978. The weed species observed are listed in Table 31. Native invaders are listed in Table 32. Some of the native species observed are common in Alaska, including *Vaccinium* spp., *Carex* spp., *Equisetum* spp., and *Polygonum* spp. Of the weed species, some have spread rapidly and extensively throughout other areas in Alaska than those to which they were introduced. These include *Matricaria matricarioides*, *Chenopodium album*, *Capsella bursa-pastoris*, *Polygonum aviculare*, and *Trifolium hybridum*. Some of these appear to have spread north to the Yukon River (a natural barrier), but they had not been introduced north of the river until the construction and opening of the Haul Road and the initiation of the revegetation program. At the other extreme, some of these weeds have quite small areas of known occurrence (*Hordeum vulgare* and *Matricaria inodora*). *Camelina sativa* and *Plagiobothrys hirtus* each show only one site of occurrence in southeastern Alaska according to Hultén (1968). The establishment of these species north of the Yukon River illustrates dramatically how the activities of man may introduce exotic weed species.

Observations in 1978 showed that native species are slowly colonizing disturbed areas. From 1977 to 1978 the native species as a group showed no significant change in percentage frequency and a slight decrease in percentage cover. Two additional species, *Oxytropis maydelliana* and *Selaginella* sp., were found invading in 1978. *Epilobium angustifolium*, *Salix* spp., *Hordeum jubatum*, *Equisetum* spp., and *Carex*

Table 31. Weed species found along Haul Road (summers 1977, 1978).

1977	1978
Avena sativa	*Amsinckia* spp.
Brassica juncea	*Capsella bursa-pastoris*
Camelina sativa	*Chenopodium album*
Capsella bursa-pastoris	*Lepidium densiflorum*
Chenopodium album	*Lepidium perfoliatum*
Hordeum vulgare	*Matricaria inodora*
Matricaria inodora	*Matricaria matricarioides*
Matricaria matricarioides	*Plagiobothrys cognatus*
Plagiobothrys cognatus	*Plagiobothrys hirtus*
Plagiobothrys hirtus	*Polygonum aviculare*
Polygonum aviculare	*Polygonum convolvulus*
Polygonum convolvulus	*Sisymbrium altissimum*
Sisymbrium altissimum	*Thlaspi arvense*
Thlaspi arvense	*Trifolium hybridum*
Trifolium hybridum	

Table 32. Native invader species found along Haul Road (summers of 1977 and 1978).

Achillea borealis	*Hordeum jubatum*
Achillea sibirica	*Ledum palustre*
Arctagrostis latifolia	*Luzula parviflora*
Astragalus alpinus	*Oxytropis maydelliana*
Betula glandulosa	*Petasites frigidus*
Betula nana	*Picea mariana*
Betula papyrifera	*Polygonum alaskanum*
Bistorta plumosum	*Populus tremuloides*
Calamagrostis canadensis	*Rorippa hispida*
Carex bigelowii	*Rorippa islandica*
Carex scirpoidea	*Rosa acicularis*
Chenopodium capitatum	*Rumex acetosa*
Cornus canadensis	*Salix* spp.
Corydalis sempervirens	*Selaginella* sp.
Descurainia sophioides	*Senecio congestus*
Dryas octopetala	*Senecio pauperculus*
Empetrum nigrum	*Spiraea beauverdiana*
Epilobium angustifolium	*Stellaria* sp.
Epilobium latifolium	*Vaccinium uliginosum*
Epilobium palustre	*Vaccinium vitis-idaea*
Equisetum arvense	*Wilhelmsia physodes*
Erigeron acris	mosses
Hieracium triste	liverworts

spp. are particularly rapid colonizers. Some species observed in plots in 1977 were not present in 1978. These included *Astragalus alpinus*, *Hieracium triste*, *Luzula parviflora*, and *Bistorta viviparum*. Individual ranges along the latitudinal gradient as represented in the established plots increased for some species and decreased for others.

All weed species identified in this study occur south of the Brooks Range, but north of the

Brooks Range only 6 of the 15 weed species occurred in 1977, and 4 of the 14 weed species occurred there in 1978. The numbers of species generally decrease from south to north along the 577 km of road between the Yukon River and Prudhoe Bay. Among the reasons for this difference, the relationship of plant development to climatic gradients is probably most important. For example, germination of weed species north of the Brooks Range in 1977 was considerably later than it was south of the Brooks Range. By 18 July 1977, 13 weed species were seen in areas south of the Brooks Range, but by 26 July 1977, no true weeds had germinated north of the Brooks Range. North of the Brooks Range 10 days later, six weed species and several annual native species had germinated. It was observed near the end of the season that many species apparently would not set seed in time to reproduce successfully.

In addition to fewer species north of the Brooks Range, weeds and annual native invaders occurred less frequently. North of the Brooks Range, *Hordeum jubatum* was observed scattered fairly frequently along the road, but other species were found far less frequently. Aside from *Hordeum jubatum*, weeds and native weedy species occurred in approximately 15 sites north of the Brooks Range in 1977.

Although percentage frequencies of weeds are lower than those of native species within established plots, it is probably not because of competitive interactions with native plants. In most plots, densities are low and competition does not appear to be a significant factor in determining which species are present or survive. Weeds often disappeared from plots, but were found in the same disturbed areas outside the plots in densities as great as those recorded in the plots the previous year. The low plant densities recorded in the plots suggest that this difference is not due to interspecific competition; apparently, the weeds disperse seeds outside the plot boundaries. The percentage frequencies for the total number of plots, for example, show that one of the four plants with the greatest percentage frequency is a weed, *Chenopodium album*, which is not losing out in interspecific competition with native species.

The extension of the range of several native species was observed. Several other species are also being examined for possible range extensions. *Achillea sibirica*, which had been recorded only as far north as the Brooks Range, was observed in a newly seeded material site 482.6 km north of the Yukon River or roughly 160 km north of the Brooks Range. This material site was seeded, and in 1977 the observed growth of grasses covered 19% of the area. *Achillea sibirica* was healthy and flowering there. Its occurrence at this new site appears to be directly related to Haul Road activities because it was present only in the seeded area of this material site. Other species with range extensions included: *Chenopodium capitatum*, *Corydalis sempervirens* and *Hordeum jubatum*.

Observations comparing the 11 sites where second- and third-year observations were made in 1977 and 1978 are summarized in Table 33. *Chenopodium album*, *Achillea borealis* and *Hordeum jubatum* reappeared in 1977 and 1978 in most of the sites in which they were observed in 1976. Other species also reappeared in some sites in 1977, including *Plagiobothrys cognatus*, *P. hirtus*, *Descurainia sophioides*, and *Avena sativa* but with less consistent success. Other species not present in 1977 in the sites established in 1976 include *Barbarea* sp., *Amsinckia* sp., *Polygonum convolvulus*, *Capsella bursa-pastoris*, and *Thlaspi arvense*. It was observed that at site XI, as well as at other sites along the road, stalks from the previous year's growth of *Thlaspi arvense* remained standing with their silicles intact. Their seeds were not dispersed. These seeds were used in germination tests which showed that they were still viable.

The third-year comparison, in 1978, revealed that some of the native annuals and weeds are persisting while others have disappeared. Again, *Chenopodium album* was seen to be a persistent weed. A few weeds, *Avena sativa*, *Brassica juncea*, and *Camelina sativa*, were lost entirely from the Haul Road by 1978. On the whole, a large number of weed species survived the winter of 1976-1977 and reproduced successfully in the second summer. A few weeds were found to have survived a second winter (1977-1978) since initial observations were made in 1976. These weeds are: *Chenopodium album*, *Achillea borealis*, *Polygonum convolvulus*, and *Plagiobothrys cognatus*. Some of the *Chenopodium album* populations which had high densities (612 and 235 plants m^2) in 1977 did not reproduce successfully, and these populations became extinct. In 1978, a species which had not been seen earlier, *Lepidium perfoliatum*, was observed in several disturbed areas both north and south of the Brooks Range, and it was seen dispersing in

Table 33. Three-year comparison (1976-1978) of species in selected sites along the Haul Road.

Species	Site number I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Achillea sp.						76			76		
Achillea sp. (1 leaf)		76			76						
Achillea borealis					77	77,78	77,78		78		
Amsinckia sp.							76				
Avena sativa				76			76			76,77	
Barbarea sp.					76		76				
Capsella bursa-pastoris									76		
Chenopodium album		76,77,78		76,77	76,77,78		76,77,78	76,77	76,77,78	76,77,78	
Crucifer									76		
Descurainia sophioides							76,77,78		76		
Epilobium angustifolium				78			78				
Hieracium sp.											
Hieracium sp. (?)						76					
Hordeum sp.							77			76	
Hordeum jubatum				76,77	76,77,78		76,77			77,78	
Hordeum vulgare										77	
Matricaria inodora			77,78								
Plagiobothrys sp.		76							76		76
Plagiobothrys cognatus			76,77,78								
Plagiobothrys hirtus			76,77,78								77
Polygonum alaskanum				78							
Polygonum convolvulus							76,78	76	76		
Rorippa sp.				78					76		
Rorippa sp. (?)							76				
Rumex sp. (?)					76						
Rumex acetosa					77,78						
Thlaspi arvense			77,78								76
grasses	76,77,78		76,77,78			76,77,78					
no weeds	76,77,78										

Site descriptions:

I—culvert 503+72, 1.4 miles north of BM Y155, large range area, no straw.
II—near BM M148. Roadside ridge, seeded, covered s/straw.
III—winter trail crossing road near pipeline crossing just south of Old Man.
IV—No Name Creek, straw in 1976.
V—just north of MS 1941. Straw in 1976.
VI—culvert 3058+25. Seeded 1975.
VII—culverr 2809+90. At DS 104. Straw in 1976.
VIII—PM 3156. Small ridge east of road.
IX—BM 5155, near culvert 781+56. Seeded 1975, straw in 1976.
X—culvert 543+OD. Three bales of straw present in 1976, weeds were growing out of bales. Straw in 1977.
XI—BM T154, near CRREL 122-1A.

Table 34. Species observed dispersing seeds in 1977 and 1978 along the Haul Road.

1977	1978
Avena sativa	*Achillea borealis*
Camelina sativa	*Achillea sibirica*
Capsella bursa-pastoris	*Capsella bursa-pastoris*
Chenopodium capitatum	*Chenopodium album*
Corydalis sempervirens	*Chenopodium capitatum*
Descurainia sophioides	*Corydalis sempervirens*
Hordeum jubatum	*Descurainia sophioides*
Hordeum vulgare	*Epilobium palustre*
Rorippa spp.	*Erigeron acris*
Senecio congestus	*Hordeum jubatum*
Sisymbrium altissimum	*Lepidium densiflorum*
Thlaspi arvense	*Lepidium perfoliatum*
	Matricaria inodora
	Matricaria matricarioides
	Plagiobothrys cognatus
	Plagiobothrys hirtus
	Polygonum aviculare
	Polygonum convolvulus
	Rorippa spp.
	Senecio congestus
	Sisymbrium altissimum
	Thlaspi arvense

some areas. Many of the areas in which it was found were dormant-seeded late in the summer of 1977. Apparently, it survived the winter as viable seed and germinated in the 1978 field season, dispersing seeds in some areas. This is one of the few introduced species found in several locations north of the Brooks Range.

Some of the areas which were free of weeds in 1977 remained weed-free in 1978. In others, introduced or native species appeared. *Hordeum jubatum, Chenopodium album, Achillea borealis, Epilobium angustifolium,* and *Capsella bursa-pastoris* were among the species appearing in these plots. Many of these areas were not seeded or mulched in 1977, and appearances of these species must have been due to migration or delayed germination in previously seeded plots.

The species which were dispersing seeds during 1977 by 24 August are listed in Table 34. North of the Brooks Range, dispersal was observed for *Chenopodium capitatum, Hordeum jubatum, Hordeum vulgare,* and *Senecio congestus*. A few other species, including *Achillea borealis, Avena sativa, Capsella bursa-pastoris, Descurainia sophioides* and *Rorippa hispida*, had nearly mature fruits and may have dispersed viable seeds before being killed by frost in late August or early September.

Obviously, some species of exotic weeds and native weedy species are capable of setting seeds despite the short growing season. Thus, it may be possible that some will be perpetuated from year to year for a few years. Some species may also be perpetuated by means of vegetative reproduction. Native and weedy species observed dispersing seed in the summer of 1978 are also presented in Table 34.

All the native species listed in Table 32 were observed invading plots in the seeded disturbed areas and in some bare areas. Approximately 65 of the permanent sites had natives invading the disturbed area plots. The continued invasion of native species will be followed in these plots to learn more about succession of native species in both seeded and bare disturbed areas.

This study adds to information on plant persistence, migration and reproductive success, phenological development, and plant population dynamics in subarctic and arctic environments. It has examined the relative success of perennials compared to that of annuals under harsh growing conditions. The differential success of weeds and natives has also been illustrated through these field investigations. The results should prove of some predictive value in the colonization of disturbed areas.

Performance of revegetation

A number of revegetated sites were selected for observations of revegetation performance (Fig. 108). Sites included those established in 1975 (Johnson et al. 1977) and new areas revegetated during 1976, 1977 or 1978. Sites were selected to represent a variety of substrates, latitudinal and altitudinal locations, vegetation types, and categories of construction (e.g. pipeline workpad, road cuts, disposal sites, material sites). Sites are listed in order, from the Yukon River to the Prudhoe Bay, and are identified by the alignment sheet number and the number within that alignment sheet.

Photographs of the late season growth for all sites for all four years are presented by Johnson (1980). In addition, estimates of percentage cover of vegetation, established species, maximum height of vegetation, and presence of seed heads were recorded. At a few sites biomass samples were taken annually. The approach of observing the entire length of the road, rather than selecting a few intensive study sites, was employed to obtain a qualitative evaluation of the success of revegetation techniques through

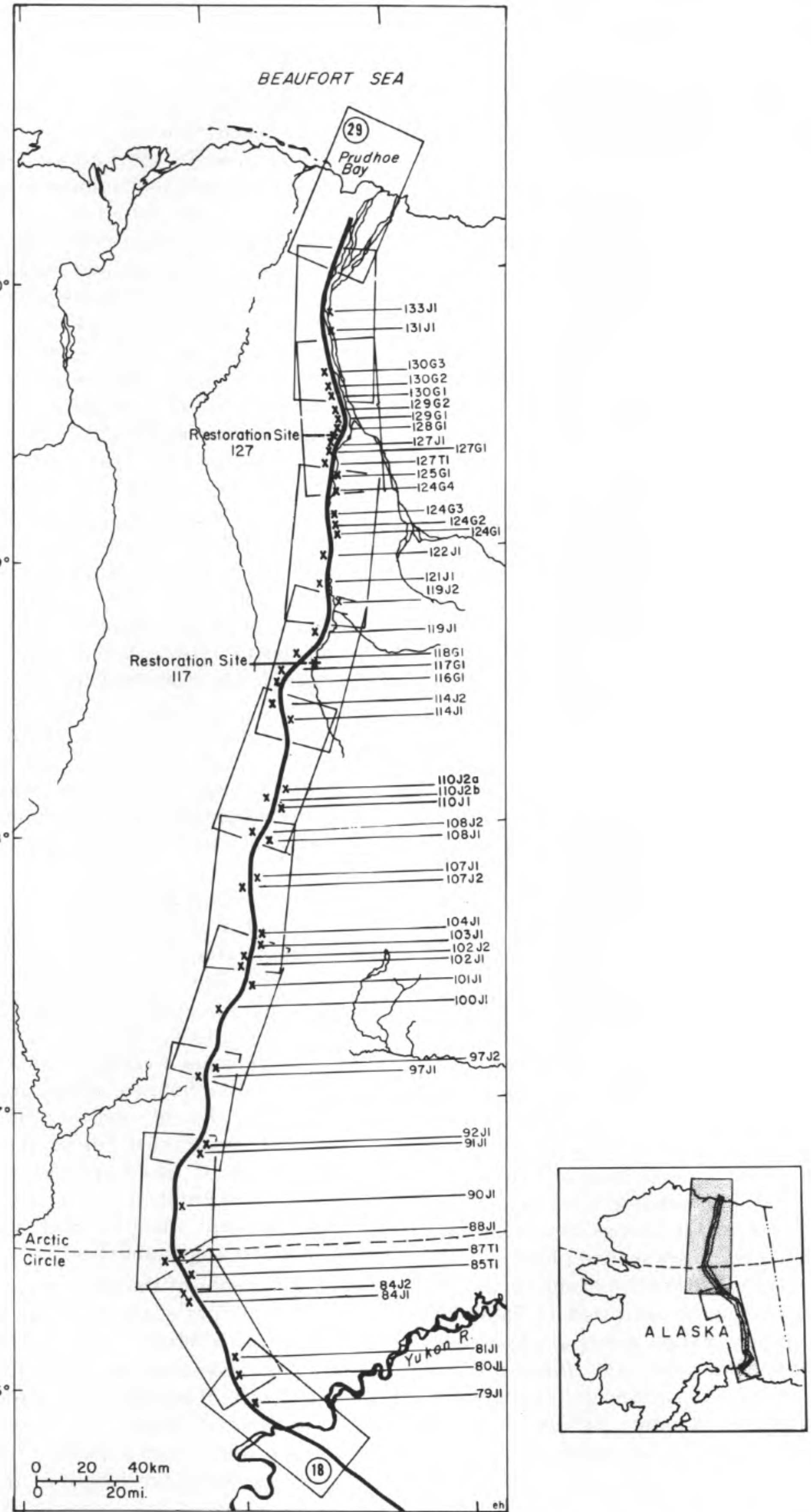


Figure 108. Location of CRREL permanent revegetation sites (G = fuel gas line, T = trails, J = other revegetation sites).

Table 35. Observations at permanent revegetation sites along the Yukon River-Prudhoe Bay Haul Road.

		1976 (1975)			1977			1978			Species setting seed*					
Site	Year seeded	Litter†	Live†	Max ht (cm)	Litter	Live	Max ht (cm)	Litter	Live	Max ht (cm)	Brome	Bluegrass	Annual rye	Foxtail	Fescue	Timothy
Road cuts																
79J1	1975, 1976	1	6	–	5	7	100	—	—	—		c	b	c	c	
80J1	1975, 1976	1	10 lower 1 upper slope	120		8	160		8	152	d	c,d	b	b,c,d	c	
84J2		Destroyed by new construction														
88J1	1975, 1976	2	6	120	4	4 from 1975 8 from 1976	150	5	2	130	d	c	b	b,c,d	c,d	
90J1	1975	1	10	120		8	100	9	4	122	d	c	b	b,c,d	c,d	
92J1	1975		9	120		10	160		9	181	d	c	c	b,c,d		
97J1	1975, 1976	1	7	100		6	130	6	2	82	d		b	b,c		
97J2	1976		—	—	—	10	130		10	143	d			c,d	d	
101J1	1975		5	90	4	8	130	8	7	77		c		b,c,d	c,d	
107J1	1975	9	9	70	9	9	120	9	8	81		c	b	b,c,d	c,d	
110J1	1975		1			2 (patchy)	60		3	50		c		c,d	d	
110J2a	1975		1	30		1	30		1	30				c	c	
110J2b	1975		4	65		3	75		2	73		d		b,c,d	c,d	
114J1	1975	1	6	80		1	60		2	60				d	d	
122J1	1975		4	80		8	80		9	80		d			d	
Material sites																
84J1	1976		4	30	4	3	60	2	2	30	d	c	b,c,d	c,d	c,d	
87J1	1977	—	—	—		5	100	2	5	135	d			d	d	
91J1	1974 probably	1	3	65		2	100		2	120	c,d		b	b,d	b	
103J1	1975, 1977	1	1	65	Regraded	—	—		3	78			b,d	b	b	d
104J1	1975	10	10	120	—	9	110		6	83				b,c,d	c,d	d
119J1	1975	9 (straw)	1	20	8 (straw)	2	30		2	85		c,d			b,c,d	
119J2	1976		1	45		4	40		1	35		c,d			c,d	
127J1	1975, 1976	1	5	65		trace	10		4	30		d			d	
Old trail sites																
81J1	1976	—	—	—		5	120	4	5	139		c		c,d	d	
100T1	1975, 1976	2	8	10	8	4	75	7	4	60		c	c			
108J1	1974 probably		7	65		7	80		7	103		d	a,c,d		b,c,d	
Workpad																
85J1	1976		1	8		7	100	2	2	95	d	c,d	d	c,d	c	
102J1	1975		1	30		2	100		4	101		d	b,c	c,d	c,d	
107J2	1976		—			4	8	6	5	111		d	b,c	d	d	
109J1	1977					2			6	87		d		d		d
133J1	1977		—			3			5	15		d			d	
Disposal sites																
117G1	1976					4	6		4	96		c,d	b,c		c,d	
121J1	1976					4	20		4	80		c,d			c,d	
Other sites																
78J1	Unseeded	—	—	—	—	—	—	–	2	–						
102J2	1976		8	65	10	4	100	8	2	153			b	c,d	d	
108J2	1975 probably	10 (straw)	6	65	5 (straw)	7	130		7	90		c	c	b,c,d	d	
114J2	1975		7	80		8	70		9	72		c	b	b,c,d	c,d	
129G1	1976		6 test plot 1 uncleared	15 3		8 5	50 15	3 5	8 8	75 35						

* a = 1975; b = 1976; c = 1977, d = 1978.
† 1 = 1-10% cover; 2 = 11-20% cover;... 10 = 91-100% cover.
— not observed.

the several major climatic and vegetation zones as well as differing construction activities.

Summary of seeding performance

Observations from the 1975-1978 revegetation program are summarized as follows and are based in part on data presented in Table 35.

Topsoil. In both 1975 and 1976, the use of topsoil and organic material was minimal. Topsoil was used at selected locations during 1977 and 1978. Attempts were made to recover stockpiled topsoil from material sites. However, some topsoil was unrecoverable because it had been buried or pushed downslope from material sites. The importance of topsoil and fine-grained subsoils was especially evident in the northern areas. Some material sites north of Toolik exhibited a rapid decrease in grass cover as one

Figure 109. Contour harrow used for seedbed preparation.

Figure 110. Harrowed ground in which seeds are buried, resulting in increased germination.

moved from the edge of the site, where organics and mineral soils were spread, to the middle of the site, which had no fine-grained soils on the surface.

Surface preparation. Following the initial year (1975), much more attention was placed upon surface preparation. In many areas special harrowing equipment, such as a contour harrow (consisting of a large wire mesh with heavy wires protruding downward) was towed over the surface both before and after seeding (Fig. 109). Contour harrows were first used north of Toolik during 1976. By 1978 the practice was employed along the entire Haul Road. Harrowing appeared to result in greatly increased germination rates and a subsequent increase in vegetative cover, probably primarily due to burial of the seed which increased available moisture (Fig. 110).

River training structures. A number of river training structures were constructed during 1976 along the Koyukuk River. These were mulched with straw and seeded, resulting in an excellent cover by the end of the initial growing season. Most of the cover, however, was produced by either barley or rye, both annuals. In 1977 living vegetative cover was greatly reduced and it continued to decline in 1978 (see 102J2, Table 35).

Variability in methods. There seemed to be greater conformity in methods between construction sections during the 1976 and subsequent growing seasons. Generally areas were hydroseeded using seed, fertilizer, and wood fiber mulch. The amount of straw mulch and excelsior mesh used was much reduced in later years as compared to the 1975 season.

Native species. A number of native species and some introduced weeds were observed on some of these revegetated areas. Fireweed was very abundant and the flowering heads of *Corydalis sempervirens* and *Senecio congestus* were prominent on many sites, especially in the Interior. Some shrubs, primarily alder (*Alnus crispa*) and willow (*Salix* sp.), entered revegetated areas by seed. Finally, in at least some cases, native grasses (bluejoint reedgrass south of Atigun, tall arcticgrass north of Atigun Pass) were flowering more profusely adjacent to the road and other disturbances than in undisturbed areas.

Dominant species. Whereas annual ryegrass was the dominant species on almost all sites during 1975, meadow foxtail was the dominant species on most sites south of Toolik during 1976. Fescue was the dominant perennial species in Section 6 where foxtail was not used. In 1977 and especially 1978, foxtail was still dominant on many sites but timothy, bluegrass, and fescue were a major component, if not dominant on at least some sites. Foxtail frequently produced a high density of seed heads on favorable sites, even if other species did not flower. In areas which were reseeded, annual ryegrass sometimes was dominant over foxtail.

Test plots. Alyeska established some test plots in 1976 to evaluate commercially produced seed of the native species, tall arcticgrass, (*Arctagrostis latifolia*). These plots produced abundant seed heads and a good cover (greater than 80% by the end of 1977).

Atigun Pass. This area poses perhaps the ultimate challenge to biological methods of erosion control. The cold, abbreviated growing season conditions allow only minimal plant growth. This area was seeded during 1977, and by the end of 1978 there was 40% live cover on the north side of the Pass. However, the cover was patchy and some areas had been regraded due to settlement over the pipe.

Arctic. Reduced growth was observed at sites north of the Brooks Range during 1976, but the contrast with other areas was less than during 1975. Sites were seeded earlier in the season during 1976-1978 and, of course, previously seeded sites already had some established vegetation. Maximum height of the vegetation was still less than in southern areas but percentage cover was comparable in at least some areas (Johnson 1980).

Animal grazing. Various populations of native mammals and birds have been observed grazing upon revegetated areas. They include microtines at numerous locations, caribou north of Toolik and especially at site AS127-1, dall sheep along the workpad near Galbraith Camp, and moose in the Interior. Birds such as ptarmigan and migratory waterfowl extensively grazed revegetated areas north of Toolik. Presumably these animals were attracted by factors such as the delayed senescence of introduced species and the higher nutrient content of vegetation within the fertilized areas.

Scheduling. During 1975 and also during 1976-1978 seeding was not completed on schedule in certain sections. This meant that erodible areas were left unseeded for longer periods than desired and that introduction of an adequate vegetative cover was delayed.

During 1978 the Alaska Pipeline Office (APO 1978) formulated criteria for determining the success of restoration of disturbed sites along the trans-Alaska pipeline. Depending upon the location and the soil type existing at a particular site, minimum requirements for vegetation cover were specified. No revegetation was required on those sites that 1) were covered with undecomposed plant matter, 2) will have continued disturbances for pipeline operations and maintenance such as traffic lanes, 3) are located in active floodplains, or 4) possess inadequate fines (sands, silts, and clays) in the soils. Sites with less than 15% silt- and clay-sized particles in the upper 15 cm of soil must have a 30% plant cover over 80% of the areas. For sites with fines greater than 15% there must be at least 50% plant cover over 80% of the area. Plants must

Figure 111. Birch transplants (VIE) near Old Man, 4 August 1977.

show adequate vigor so that nutrient deficiencies or physiological stress are not apparent. If sites did not meet these requirements, then remedial measures such as reseeding were required. Some sites were evaluated by APO personnel during 1978 on the basis of these criteria. Those sites that fulfilled the criteria were then returned to the Bureau of Land Management, relieving Alyeska of future liability.

Visual impact engineering

In the latter part of the summer of 1977 and continuing through the 1978 growing season, Alyeska began to transplant trees and shrubs at pipeline-road intersections and at a few material sites as part of its VIE program. The purpose of the program is to provide visual barriers which will help conceal the pipeline and disturbed areas from the public view, thereby meeting federal stipulations.

Species used varied depending upon the local vegetation. They included birch (*Betula papyrifera*, Fig. 111), white and black spruce (*Picea glauca* and *P. mariana* respectively, Fig. 112), willow (*Salix* spp.), aspen (*Populus tremuloides*), and alder (*Alnus crispa*). Plants were generally taken from nearby undisturbed areas. In most cases plants were removed and planted with a tree spade so that a ball of soil was taken along with the tree or shrub. A mulch such as hay or woodchips was often placed at the base of the transplant.

Visual and scenic considerations mandated that special measures be taken at the Sukakpak Mountain site which had been temporarily used for material borrow. This was the only site observed where large amounts of fine-grained soils and topsoils were transported to the location and spread over it to create an enhanced seedbed. Then, in addition to the normal seeding and fertilizing, transplants and nursery raised seedlings of white spruce were planted along the access road. The appearance of the area was markedly improved by August 1978, the end of the first full growing season (Fig. 113). Grass growth was noticeably better around the base of tree transplants, probably due to improved moisture conditions associated with the transplanted ball of fine-grained soils around the tree roots.

The VIE program is important for ecological as well as aesthetic considerations. As previously mentioned, the fine-grained soils, mulch, and microclimate associated with the transplanted shrubs and trees can create very favorable microsites for vegetation growth on otherwise poor growing sites. Furthermore, the transplants act as islands of seed dispersal onto the site for the transplanted woody species. The transplants can accelerate the re-establishment of native woody

Figure 112. Spruce transplants (VIE) near Prospect camp on alignment sheet 96, 15 August 1978.

Figure 113. View looking at Sukakpak Mountain material site (103-0.1) from the road, 15 August 1978.

species by decreasing the distance that seeds have to travel in order to cover the entire site.

Transplant survival generally appeared very high. In August and September 1978, a survey of 12 VIE sites indicated better than a 93% average survival rate. The lowest observed survival was 88% for birch at one site. However, many of the transplants had not overwintered and increased mortality may occur in subsequent years.

Alyeska willow cutting program

Government stipulations required 1) restoration of wildlife habitat and browse lost during construction of the trans-Alaska pipeline system, 2) methods for inducing large mammals toward big game crossings, and 3) restoration of habitat to near-natural conditions. Alyeska undertook a major transplant program of feltleaf willow (*Salix alaxensis*) cuttings during the 1977 construction season. The plan was for these cuttings to be first rooted indoors and then planted on 2-m centers over some 365 ha of disturbed areas. These areas were primarily material sites and sections of the oil pipeline workpad. Since this technique offers considerable potential for road and material site restoration, some details of the 1977 program are described.

Willows were collected from a number of locations in the general vicinity of the pipeline route, mainly in river bottom areas. Collection sites included areas near Slope Mountain (AS-119), the Toolik and Atigun rivers, Galbraith Camp, and several other locations including some south of the Brooks Range. However, less than 20% of the more than 1 million cuttings were collected from such southern sites. Willows were collected according to a set of guidelines designed to maximize success while minimizing the impact of the collections upon existing willow communities. Guidelines included a minimum diameter (1.25 cm) and a maximum cutting rate per shrub and per stand. Most collections were made in May and all collections stopped as of 5 June 1977. Higher success was expected with dormant (hardwood) cuttings, but collections began so late that some willows had already begun flowering when collected.

In the field, willow stems were initially cut into 1.2- to 1.5-m-long whips. Smaller branches were trimmed off before packaging the whips in burlap bags for transport to Dietrich Camp. At Dietrich the whips were stored outside in snowbanks until they could be processed. After snowmelt, the whips were watered daily to prevent desiccation while they remained outside. The whips were subsequently cut into 15- to 22.5-cm lengths (20 cm average) on a band saw. The thin diameter tips (1976 growth) were generally discarded so that most material for cuttings was two to four years old. Except for a small number of early cuttings, the proximal (basal) end of each cutting was dipped in a preparation of 4,000-5,000 ppm of indole butyric acid and in a fungicide. The distal (top) ends of the cuttings were coated with a colored paraffin layer to reduce water losses and to identify (by color) the source location of the cuttings. Cuttings were then placed in pots of compressed peat (Jiffy 7) which had been soaked in fertilizer solution until they had swelled to about 5 cm in height.

Groups of cuttings were held in plastic trays which were placed on tiers of shelves inside a modified warehouse. The temperature in the warehouse was kept at 21° to 23°C and the relative humidity was maintained close to 80%. Cuttings were sprayed regularly with water until a mist system was installed to keep the cuttings moist as well as to maintain a high humidity.

Additional lighting was installed in early June in order to increase illumination. At that time some cuttings had already been in the warehouse for three weeks. Rooting success appeared to be very high and some roots extended beyond the outer edge of the Jiffy pots. One source estimated that between 80-90% of the cuttings in the program rooted (Zasada et al. 1977).

Some problems were already apparent in early June 1977. Many of the willow leaves, especially on the lower shelves which were shielded from the overhead lighting, were severely chlorotic. Cuttings frequently had root growth along the entire length of the stem, presumably due at least in part to the high humidity. Also, there was evidence of fungus growth on some of the stems. Fungal spores may have originated in the peat pots, but high humidity accelerated fungal growth.

Following root initiation, cuttings were to be hardened off by gradually increasing the photoperiod and by lowering temperatures in the warehouse at least two weeks prior to planting. Planting was originally scheduled to be accomplished from late June to 31 July, but it was not completed until early August. Augers were to be used to make holes in the gravel for planting the cuttings on the 2-m centers. However, hand augers were not feasible for many of the gravelly or bouldery sites. Instead handpicks were used for planting. The cuttings in the peat pots were placed in the holes and then were covered over with the mineral soil to the maximum extent possible. Planting crews had a difficult time digging holes in some of the highly compacted gravel and tills.

At one site (MS 111-1A) cuttings were buried only 2 to 3 cm, at most, based upon an average total length of 20 cm. Many cuttings had the Jiffy pot exposed above the ground. A survey of 200 cuttings revealed that 46% had 15 cm or more of stem above ground, 46% had 10 to 15 cm above ground, while only 8% had less than 10 cm above ground. Preliminary studies had already indicated that success of cuttings is lessened by increased length above the ground surface (Zasada et al. 1977). Furthermore, the more shallowly placed cuttings were in a drier soil environment.

In early August 1977, a survey of six sites was made in order to assess the survival rate of the cuttings prior to winter. At that time a few cuttings were still being planted but the stock remaining at Dietrich Camp was very limited and in noticeably poor condition. The average survival rate, based upon unwilted leaves present at the 6 sites, was 2.5%.

A resurvey of the same sites in mid-August 1978 showed that less than 1% of the cuttings had successfully overwintered. Other studies with unrooted feltleaf willow cuttings have had very high success rates (88 to 96%) after three years in the Arctic (Younkin 1976).

As a followup to the 1977 willow problem, Alyeska initiated two additional programs in 1978 using unrooted cuttings. Whips were collected, as in 1977, during the early spring prior to snowmelt and were stored in freezers until ready to be planted. The whips were cut into 20- to 25-cm lengths and some of them were planted as unrooted cuttings by Alyeska field crews in a few selected material sites near Pump Stations 3 and 4. The remaining cuttings were used in a research program conducted by the University of Alaska for Alyeska. Success rates in mid-August 1978 were much greater for the unrooted cuttings in 1977. For example, based upon the author's field observations, the cuttings used by Alyeska for their limited 1978 program had a 67% survival rate in mid-August 1978. Most of the cuttings appeared to be vigorous and healthy.

CRREL restoration experiments

Two CRREL experimental restoration sites were established in northern Alaska along the Haul Road (MS 117-1,2 and MS 127-2.1B; Fig. 108.). The first objective of establishing these sites was to compare existing vegetation techniques (such as Alyeska's) with experimental techniques for promoting long-term tundra recovery. Questions to be examined included the rate of revegetation associated with each technique and the effect upon the re-establishment of native species of vegetation. A second objective was to provide sites for related research such as methods for increasing seed set from undisturbed tundra, an investigation which is being conducted by F.S. Chapin, III, University of Alaska.

Although the experimental design varied somewhat according to the two sites, variables tested at each site included 1) fertilization, 2) willow and birch shrub cuttings (*Salix pulchra* and *Betula nana*), 3) Alyeska's North Slope grass seed mix, 4) seeding for bluejoint reedgrass (*Calamagrostis canadensis*), a native grass, 5) tundra and tussock sodding (mainly *Eriophorum vaginatum*), and 6) combinations of treatments such as fertilization and seed, sod-seed-fertilizer, and seed-fertilizer-cuttings.

The Sagwon site (MS 127-2.1B) was cleared by bulldozer in late August 1976. Shrub cuttings and sodding were transplanted at that time. The Toolik site (MS 117-1,2) was cleared in early June 1977 in order to determine the significance of a shallow disturbance which removed only the upper active layer. The remaining test plots at both sites were established in early July 1977 except for additional shrub cuttings at the Toolik site which were planted in early August 1977.

The sites were observed in August 1977 and August 1978 (Fig. 114 and 115). Depth of thaw measurements, survival percentage, percentage cover, and maximum height data are given in Table 36. Although the data are still preliminary (since only 1.5 growing seasons have been evaluated), for most treatments the following tentative conclusions can be made.

Willow cuttings (*Salix pulchra*) and tussock sodding (*Eriophorum vaginatum*) offer feasible materials for re-establishing native vegetation in the Arctic. Survival is highest when planting is accomplished late in August as compared to early July. Birch (*Betula nana*) cuttings have low survival rates. As of August 1978 there was little

Figure 114. Experimental restoration site (MS 117-1, 2). Note growth of cottongrass tussocks (sod) and reseeded plots in foreground (13 August 1978).

*Figure 115. Willow (*Salix pulchra*) cuttings at Sagwon (MS 127-2. 1B) restoration site (August 1976).*

vegetative cover provided by the native species which are re-establishing on the sites. Bluejoint seed alone provided a greater cover than the Alyeska grass seed mix after one and one-half growing seasons.

The size of organic chips or sod is important since size appears to have a direct bearing on the viability of the vegetative propagules in the organic matter. In conjunction with the fuel gas line observations discussed previously, studies were conducted on frozen sod randomly collected in winter 1976-76 in order to estimate the potential success of resodding with several types of chips. The thawed sod was placed in a labora-

Table 36. Observations at CRREL restoration sites.

a. Depth of thaw (cm)

	Sagwon (MS 127-2.1B)		*Toolik (MS 117-1,2)*	
Year	*Control*	*Bladed*	*Control*	*Bladed*
1977	38.4	43.5	42.0	36.4
1978	38.9	61.0	42.4	56.8

b. Survival of shrub cuttings (%) (August 1978)

Treatment	*Willow*	*Birch*	*Willow*	*Birch*
Late August 1976	100	37		
Late August 1977			95	45
Early July 1977	75	15	88	20
Early July 1977 plus Alyeska fertilizer	88	0	72	20
Early July 1977 plus Alyeska seed & fertilizer	77	0	65	20

c. Growth of sod to 1978 (%)

Treatment	*Good**	*Fair**	*Good*	*Fair*
Late August 1976	91	9		
Early July 1977—sod alone	60	40	80	20
Sod & Alyeska fertilizer			85	15
Sod & Alyeska seed & fertilizer	75	25	70	25

d. Vascular plant cover (%) (August 1978)

Treatment			
Control	<5	<5	<5
Alyeska fertilizer	<5	<5	<5
Alyeska sod & fertilizer	40	40	35
Bluejoint & complete NPK fertilizer	40	40	55

Note: Many undisturbed cottongrass tussocks in these areas had 50 to 70% cover of standing dead.
*Good = > 30% live vegetation cover; Fair = 10 to 20% live vegetation cover.

tory chamber at approximately 24°C under fluorescent lighting and watered daily. Growth was presumably faster and better under the higher temperatures and more optimal moisture conditions of the laboratory. Desiccation could be a much more severe problem under field conditions, especially with the sustained and frequently high winds that are encountered. Vegetative growth from the larger sod chips (up to 46-cm-diameter) averaged 10 to 15% live vegetation cover after three weeks, although it did vary according to the size of the chip and species composition. Larger chips generally had greater growth. *Carex* and *Eriophorum vaginatum* showed rapid growth while mosses, lichens, *Cassiope tetragona,* and *Arctostaphylos rubra* recovered more slowly. The smaller sod chips produced by the Barber Greene trenchers were more prone to desiccation and hence vegetative cover was sparser. The highly pulverized Roc-Saw spoil had minimal regrowth and vegetation cover was less than 1%. Canadian researchers have experimented with the use of tundra sod and have reported similar results.*

* W. Younkin, R.H. Hardy and Associates, personal communication.

Conclusions

1. Revegetation along the trans-Alaska pipeline was based primarily upon currently accepted practices of mulching, fertilizing, and seeding with adapted agronomic grass species. Over 90% of disturbed areas (excluding camps) had been initially seeded by August 1978.

2. Attempts to use native grass species in the seed mix were limited. Seed increase programs for native seed did not produce enough seed in the short time allowed. However, research by Alyeska and others has increased the likelihood of native seed production in the future.

3. Alyeska's revegetation program generally improved from 1975 through 1978 in terms of seedbed preparation, scheduling, and availability of supplies and equipment. In large part this was due to a lessening of pipeline construction activity so that environmental matters were given more emphasis (Zemansky 1976). But experience gained by Alyeska personnel also contributed to improvements in the program.

4. Some problems were irremediable, such as those involving the loss of topsoil and organics which were buried or otherwise lost during initial clearing operations.

5. Temporary erosion control was a recurring problem along the pipeline. This problem could have been reduced, along with other environmental problems, by an improved quality assurance program (Carson and Milke 1976, Zemansky 1976, Morehouse et al. 1978, Mechanics Research, Inc. 1977b).

6. Native species are only slowly reinvading revegetated area. Exotic weed species have been observed at a number of revegetated sites, although it is not known how long they will persist.

7. Native animals (moose, caribou, dall sheep, etc.) have heavily grazed some revegetated areas.

8. Many revegetated areas have 80 to 90% grass cover from the seed mix. The long-term persistence of these (exotic) species and their effect upon re-establishment of native vegetation cannot be evaluated at this time.

9. The visual impact engineering (VIE) program using transplants of native trees and shrubs has initially been very successful.

10. The willow cutting (*Salix alaxensis*) program to replace lost wildlife browse was not successful during 1977. However, the revised 1978 program using unrooted cuttings is providing promising results.

11. Preliminary results for CRREL restoration studies demonstrate that willow cuttings (*Salix pulchra*) and tussock sodding (*Eriophorum vaginatum*) are feasible means of re-establishing upland arctic vegetation. Studies are continuing to determine long-term effects of experimental restoration methods in comparison to existing revegetation techniques.

Revegetation recommendations

The Haul Road has provided a large natural experimental laboratory for evaluating revegetation techniques and environmental safeguards. The following recommendations are based upon observations made by L. Johnson during 1975–1978 (Johnson 1980).

1. Material sites should be properly planned and selected to minimize aesthetic impact as well as preventing costly restoration measures (e.g. Sukakpak Mountain).

2. Saving of organics and topsoil should be emphasized at the start of the project. In particularly poor growing sites (e.g. coarse material sites in the Arctic), reuse of fine-grained disposal material for seed beds should be considered.

3. Adequate lead time for production of native seeds should be provided. Native species (seeds or transplants) offer advantages and are preferable whenever possible.

4. Research should continue on alternative methods for using native species since there is no single method which is best for all sites and situations.

5. Environmental surveillance agencies should have adequate authority to enforce regulations at the outset of construction projects. Otherwise equipment and personnel will be unavailable for revegetation and other environmental measures until construction activity slows. Similarly, environmental quality assurance programs should have adequate authority to support stipulations. Proper programs will reduce impact as well as facilitate restoration of disturbed sites (see also Mechanics Research Inc. 1977b).

GENERAL RECOMMENDATIONS

By J. Brown and R.L. Berg

1. Comprehensive environmental and engineering investigations commenced on this road within a year after its completion. In order to take advantage of this continuity of observations, it is recommended that these investigations continue for purposes of documenting and assessing long-term road performance and environmental responses.

2. Our investigations did not have the resources to document, from the project files, a complete construction history of the road. A detailed environmental engineering documentation of the preconstruction and construction phases of this project should be prepared.

3. As the road becomes older and more maintenance is required, the effectiveness of the design, construction techniques, and remedial methods should be reassessed. If cost data for maintenance are available, appropriate cost analysis should be conducted.

4. Although our investigations did not involve the design of drainage for fish passage, improved criteria now exist from knowledge gained in this construction project. Efforts should be made to include these recent criteria into design and placement practices for culverts and bridges in arctic and subarctic areas.

5. Knowledge gained from revegetation and restoration along the road and pipelines should be consolidated into new erosion control and rehabilitation guidelines and put into practice.

6. Experience on the performance of ice-rich and thaw unstable slopes along the Haul Road should be incorporated into recommendations on terrain evaluation and road design.

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APPENDIX A: GENERAL ENVIRONMENTAL GUIDELINES APPLICABLE TO SUBARCTIC AND ARCTIC ROAD CONSTRUCTION*

This appendix is a summary of existing and proposed environmental guidelines which are applicable to construction of transportation facilities in the Arctic and Subarctic. They are based on published reports, stipulations (see *Literature Cited*) and our own experiences. The guidelines are divided into the following sections: 1) minimization of impact during construction, 2) fish and wildlife considerations, 3) drainage and erosion criteria, 4) cuts in ice-rich soils, 5) roadway embankments and 6) revegetation and restoration. Although some of these are also applicable to other regions of the country and are not specific to permafrost conditions, repetition is considered worthwhile for purposes of emphasis.

Minimization of impact during construction

Minimizing the impact of road construction in arctic and subarctic environments is a major element in the project design, construction, restoration, and maintenance of the facility. Proper and effective engineering and surveillance measures should be be used to protect the environment during all phases of road work.

All working areas, platforms, pads, roads, stockpile areas, camps and other facilities, and any surface or subsurface modifications should be planned, constructed and maintained in a manner that will minimize degradation or alteration of the environment. Primary emphasis should be on doing the least clearing of vegetation and disturbance of surface materials; i.e. one should disturb only the area that is absolutely needed for the road construction. The environmental impacts occurring during construction should be rehabilitated by the responsible parties.

*Prepared from published and unpublished sources by D. Roach, R.L. Berg, J. Brown, and L.A. Johnson.

Proximity of construction activities to any officially designated park, wildlife refuge, natural area or recreation area should be specified.

When off-road activities are required, work should be conducted on frozen surfaces by use of snow or ice pads. Compaction of snow should be accomplished so that it does not have a detrimental effect on the vegetative cover or its ability to maintain the thermal regime of the subsoil in an unaltered condition. The use of vehicles and equipment that exert low ground bearing pressures is necessary when activities are not conducted on workpads or thaw-stable materials. Operators should be specifically trained to minimize surface disturbances by avoiding tight turns, rapid acceleration, and by using the proper route selection. Mobile ground equipment should not be operated in shallow lakes, rivers, or streams.

Excavated material should be removed and not be placed on the ground surface when its presence may affect either the thermal regime of the ground or the drainage of surface water.

Gravel or other stable material or a combination of gravel and an artificial insulating material should be used on temporary access roads to provide a stable wearing surface and to minimize thermal degradation of the permafrost.

If there are problems related to conformance with the stipulations or specifications during any period in construction, monitoring personnel should have the power to temporarily stop construction activities.

Fish and wildlife considerations

The protection of fish and wildlife, and their habitat, from road-related activities is a prime concern. Free passage and movement of terrestrial and aquatic organisms should be maintained.

Artificial structures or stream channel

changes that would cause blockage to fish or create velocity barriers to their movement should be provided with a fish passage structure or facility. Diversion structures should be plugged and stabilized, and pump intakes should be screened so as to prevent harm to, or trapping of, fish.

Material sites adjacent to or in lakes, rivers, streams, or wetlands may require construction of levees, berms or other suitable means to protect fish and fish passages and to prevent siltation of streams or lakes. During construction, caution should be taken to avoid creating any new lakes or marshes (other than those used for borrow areas), draining existing lakes or marshes, significantly diverting drainage (surface and subsurface), permanently altering stream hydraulics, or disturbing significant areas of river and stream beds. Temporary erosion and sediment control structures should be used to the maximum extent possible during thaw season construction to minimize impact on water quality.

Construction on river and stream banks, requiring the removal of the existing vegetative cover, should provide for barriers which prevent siltation from surface runoff in denuded areas and, whenever possible, be undertaken during the winter freezeup period.

Maximum protection to fish and wildlife and their habitats should be provided through restrictions on preconstruction, construction and operational activities; these restrictions should be designed to avoid or minimize degradation of air, land and water quality. Road construction activities in key fish and wildlife areas, and in specific areas where threatened or endangered species of animals are found, may be restricted during periods of fish and wildlife breeding, nesting, spawning, lambing and calving activity, overwintering, and during major migrations of fish and wildlife.

The existing levels of suspended solids, oxygen contents, velocities, fishing activities and catches, and chemical concentrations in all streams, rivers, and lakes which may be affected by construction activities should be documented. The levels of these parameters should be monitored and acceptable limits of variation should be established prior to the beginning of construction.

Damage caused by construction, operation, maintenance or termination of a facility should be repaired. Harassment of wildlife by equipment, personnel, and aircraft should be prohibited. Overflights should be prohibited in certain areas during the breeding season and at other critical times. Feeding and hunting of bears, foxes and wolves within the construction area should be prohibited and fishing regulated.

Fish spawning beds and rearing and overwintering areas should be protected from sediment where soil material is expected to be suspended in water as a result of construction activities. Settling basins or other sediment control structures should be constructed to intercept sediment before it reaches rivers, streams, lakes, or wetlands. Alterations to critical habitat areas should be avoided.

Drainage and erosion control

The facility should be designed to withstand or accommodate the effects of the meteorologic, hydrologic and hydraulic conditions considered reasonably probable for the region (including surface and subsurface runoff, stream and flood plain erosion, meander cutoffs, lateral migration, ice jams, and icings). Culverts should be designed to be large enough to prevent clogging with debris as well as to provide adequate flow capacity. Pier spacing for bridges should preclude clogging with debris and/or ice. Culverts and bridges required at stream and river crossings should be designed to accommodate a 50-year flood in accordance with criteria established by the American Association of State Highway officials. An additional clearance of 0.6 m should be provided to permit the free passage of ice. Design flow for culverts should not exceed a 1.2 m/s for a 5-year flood. Drainage systems should not add to the erosion of the area and they should be designed to protect streams and channels.

The design of drainage structures should incorporate all available data, and the locations be field verified. Reconnaissance teams should take care to note potential problems at each site, such as icings, collection of debris, grading of eroding channels, or signs of flooding. Design should be individualized to each site and standard assumptions should be minimized.

To prevent sedimentation, provisions should be made to divert flows during the installation of cross drains. Crossing of live streams should usually be by culverts or bridges. Each application should consider the specific conditions including: hydraulic regime, debris, traffic type and volume, season of construction and stream biology. Temporary or permanent channel changes should also be considered.

Bridging should be used as an alternative to culverts where proper culvert design is uneconomical and not satisfactory for fish passage. Bridges should be located to minimize changes in stream hydraulics, while providing adequate span and clearance for free movement of debris and ice.

Well designed fords are adequate for many access roads where traffic is minimal, fish passage is noncritical, and stream bottom substrates will support the traffic.

Construction design should minimize erosion and sedimentation at stream and river crossings and those parts of the road within flood plains. Temporary access over stream banks usually should be made through use of fill ramps rather than by cutting through stream banks, and the ramp materials should be disposed of upon termination of seasonal or final use. Excavated materials should not be stockpiled in rivers, streams, floodplains, wetlands, or on ice.

Slopes cut through river banks should be designed and constructed to avoid erosion and prevent slides. To prevent erosion, riprap should be placed on the banks and on the bottoms of all river, stream, and floodplain crossings as required. Riprap should be of sufficient size to remain in place at peak river or stream velocities. Banks of rivers and streams should not be cut down. Stream and river crossings should be approximately perpendicular to stream flow. When flowing streams are to be bridged in winter with ice bridges, high banks that would require deep cutting for the approach should be avoided.

On gravel-surfaced facilities, culverts should be long enough so that inlets and outlets are not clogged by gravel during maintenance operations. Equipment operators and maintenance supervisors should be trained to prevent this problem and to correct it should it occur.

Control and prevention of culvert icing

Special drainage problems related to icings of culverts must be considered and several techniques are available for avoiding, controlling, or preventing them (Lobacz and Eff 1978). Although sound in principle, the methods are often applied without adequate understanding of the icing problems encountered, leading to unsuccessful or poor results.

The techniques for dealing with icings fall into two categories: avoidance, and control and prevention.

Methods of avoidance and control of icings deal with the effects of the icings at the location being protected, so that the type of icing (river, stream, ground, or spring) is of little significance. Methods are the following:

1. Changing the location of facilities to areas where icings do not occur can often be accomplished.

2. Raising the grade will deter or postpone icing formations (this is costly, however, and depends on availability of ample fill).

3. Providing more and larger drainage facilities can reduce susceptibility to icing problems. Openings as much as two or three times as large as those required by conventional hydraulic design criteria will accommodate sizeable icing volumes without encroaching on design flows. Culverts with large vertical dimensions, or small bridges in lieu of culverts, are advantageous.

4. Constructing dams, dikes or barriers, known also as ice fences, can limit the horizontal extent of icings. Permanent barriers of earth, logs or lumber may be built between the source of the icing and the area to be protected. Temporary barriers may be erected of snow embankments, movable wooden fending, corrugated metal, burlap, plastic sheeting, or expedient lumber construction.

5. Providing culvert closures can prevent a culvert from being filled with snow and ice, which requires a laborious spring clearing operation. Closures are placed over the culvert ends in the fall; these can consist of rocks to permit minor flows prior to freezeup.

6. Staggering or stacking culverts involves placement of two (or more) culverts, one at the base of the fill, the other(s) higher up the embankment. When the lower culvert becomes blocked by an icing accumulation, the higher ones carry initial spring runoff over the icing. As the spring thaw progresses, the lower one becomes cleared, eventually carrying the entire flow. The ponding area available for icing accumulations must be large enough to store an entire winter's ice without having the icing reach the upper culverts or the elevation of the area being protected.

7. Applying heat at places where icings occur is a common technique, the objective being not to prevent icings but to establish and maintain thawed channels through them to minimize their growth and to pass spring runoff. Steam is used to thaw culvert openings and to thaw channels into icings for collecting icing feed water or early spring runoff. Fuel oil heaters, known as firepots, are in common usage although they are

in decreasing favor due to their energy inefficiency, high maintenance requirements and the difficulty in preventing theft of fuel. Use of insulated heating cables to heat culverts is a recent adaptation successfully used where electrical power is available or, in important locations, where small generating stations would prove feasible. Portable generators have also been used. Electrical heating requires much less attention by maintenance personnel than steam thawing.

8. Breaking and removing accumulated ice is another common technique, whether by manual or mechanical equipment, but should be practiced only as an expedient or emergency measure. Culvert ends are frequently damaged by the equipment.

9. Blasting has a twofold objective: 1) physical removal of ice and 2) fracturing ice to provide paths for water flow deep in the icing. This flow can enlarge openings and still remain protected from the atmosphere and refreezing.

10. Using deicing chemicals such as sodium or calcium chloride can prevent refreezing of a drainage facility, once it has been freed of ice by other means. Objections are the detrimental effects on fish and wildlife, vegetation, and other downstream water uses, and corrosive effects on metal pipe.

Methods of icing prevention include the following:

1. Straightening and deepening a channel can prevent icings, although frequent maintenance is usually required to counteract the stream's tendency to resume natural configuration by erosion and deposition. Rock-filled gabions have been used to create a deep, narrow channel for low winter discharges. Such deepened channels permit formation of ice cover to normal thickness while providing adequate space beneath for flow. Deepening at riffles, rapids, or drop structures is especially important as icings are most apt to form in these shallow areas.

2. Insulating critical sections may prevent icings of the stream where high heat losses cause excessive thickening of the normal ice cover. These sections may be located under a bridge or at riffles or rapids. Insulating covers, while beneficial for reducing heat losses from the stream, must be removed each spring. They may also be washed downstream to become obstructions if high water occurs prior to their removal.

3. Using frost belts, also known as permafrost belts, induces the icing to form away from the bridge or culvert entrance being protected. A frost belt is essentially a ditch or cleared strip of land upstream or upslope from the icing problem area. Removing organic soil and vegetative cover and keeping the area cleared of snow during the first half of the winter enables deep seasonal frost to act as a dam. In applying this technique to a drainage channel, a belt is formed by periodically cutting transversely into the ice to cause the bottom of the ice cover to lower and merge with the bed.

4. Providing surface drainage with a network of ditches can drain the soil surface in the region of icing development. Ideally these ditches should be narrow and deep so as to drain the soil to an appreciable depth and to expose only a small surface area to heat loss to the atmosphere. In some cases, these drainage ditches are covered and insulated to maintain flow in winter.

5. Providing subsurface drainage in seasonal frost areas is more suitable than surface drainage because of its better resistance to freezing and ability to intercept more ground-water. Subsurface drainage systems can use any of numerous types of perforated, slotted or open-jointed pipe materials. Improved resistance to freezing can be obtained by placing an insulation layer above the usual granular backfill surrounding the subdrain but beneath the final native soil backfill. In any case, water collected must be conveyed to an outlet away from the area being protected even if it forms an icing at that point.

6. Insulating the ground can prevent ground icings in areas where deep seasonal frost penetration forms a dam, blocking groundwater flow. Insulating material may be snow, soil, brush or peat. It is essential that the insulation of the ground extend under the area being protected to assure that groundwater flow is maintained past it. Otherwise, seasonal frost penetration under a snow-free airfield pavement would act as a frost dam and cause an icing to form upslope from the area.

Erosion control

Erosion control specialists, researchers, and highway maintenance personnel should endeavor to recognize potential erosion problems and should take action to prevent, monitor and correct these problems. Quality control and frequent inspection of drainage and erosion sediment control structures and proceedures during construction is critically important. Erosion and sediment control practices, as determined by the needs of specific sites, should include revegetation, mulching, and placement of mat binders, solid binders, and rock or gravel blankets. Designs should provide for the construction of facilities that will avoid or minimize erosion, minimize disturbance to the thermal regime, and lessen the possibility of forming new drainage channels. Terracing should be used on long slopes to reduce water velocity and to provide favorable sites for vegetative growth. Proper design of culverts and erosion control devices can reduce sedimentation of water courses.

Drainage, erosion and sediment control around temporary facilities is as important as drainage and erosion control for permanent facilities. Use of temporary measures during construction (e.g. settling ponds, diversion channels, dikes, etc.) should be included in construction requirements.

Areas subject to mudflows, landslides, avalanches, rock falls, and other types of natural mass movements should be avoided. If avoidance is not practicable, the road design, based upon detailed field investigations and analysis, should provide measures to prevent the occurrence of mass movement and protect the road against the effects of mass movements.

Temporary and permanent drainage and erosion control measures should be incorporated into design and construction activities so as to avoid alteration of the existing hydrological regime and to minimize erosion. Ditches should be temporarily stabilized with ditch checks or netting until vegetation or other permanent lining is established. Collection of actual preconstruction sediment data is recommended in critical areas.

Installation of sediment collection devices, monitoring through use of aerial photographs, and slope erosion transect surveys are recommended to yield detailed information on erosion. Appropriate data from field studies and theoretical calculations should be used to establish the combinations of water velocity and depth that yield maximum values for the anticipated scour of bridge crossings and pipeline crossings. Design should minimize scour. Work schedules and local climatological events should be considered to ensure that adequate protection is provided. Construction activities downslope from late-melting snow beds should be avoided at that time, and if not feasible, sediment basins should be constructed downslope.

Materials used in embankment construction are subjected to extremely harsh environmental conditions and frequently break into smaller sizes due to freeze-thaw cycles and other weathering processes. Durable materials should be used when possible, and means to minimize sedimentation caused by breakage of less durable materials should be included.

Natural erosion control features such as vegetated buffer strips should be utilized, and if available on the project, materials such as brush and logs, etc., should be used for temporary erosion control.

Special attention should be given to the immediate control of runoff waters. Techniques such as diversion ditches or berms above cut and fill slopes are recommended to divert flows away from exposed, unprotected construction areas. Stable drainage courses for surface and subsurface drainage should be provided on the downslope side of the road along the road right-of-way. Where marginally stable slopes cannot be avoided, special design measures and precautions should be taken to prevent failure.

In high-ice content soils, drainage systems which concentrate sheet flows into channelized flows must be specifically designed to avoid thermal erosion downslope.

Cuts in ice-rich soils

Guidelines for making cuts through ice-rich soils include cutting nearly vertical backslopes and providing a wide ditch at the base of the cut. A wide ditch facilitates the deposition of some overlying material during the stabilization process, and the removal of this material, if necessary, while enhancing drainage and stabilization of the slope. If necessary, siltation basins should be constructed to prevent contamination of nearby streams, rivers, lakes or ponds.

Trees and shrubs should be cleared from the top of an ice-rich slope for a distance about equal to one and one-half times the height of the cut. Stumps should be cut as close to the soil surface as possible; i.e. stumps should be less than 0.3 m high. Nailing a coarse wire mesh to the stumps will provide additional tensile strength to the organic mat and reduce the amount of tearing, especially on higher backslopes. The mesh may hinder or entrap animals or birds, however. As thawing and subsidence occur during the stabilization process, it might be necessary to remove additional trees from the top of the slope. This cutting, as well as the initial cutting, should be accomplished with hand tools. Heavy construction equipment should not be used outside the lateral limits of the excavation area.

Ice-rich soils frequently continue beyond the depth of the cut and thawing frequently results in considerable settlement. Granular material should be added to the roadway surface to maintain reasonable longitudinal and transverse grades. If available, fine-grained material should be added to the depressions in the ditches. Fine-grained soils are desirable in these areas because they generally retain more moisture than the coarse-grained materials and allow vegetation to be reestablished more rapidly.

Roadway embankments

Since the wearing surface of the roadway will generally be gravel rather than an asphalt concrete or portland cement concrete pavement, frequent regrading of the surface will be necessary to maintain the required longitudinal and lateral slopes and grades. A surface course of material with a maximum size of 4 cm can be regraded much more readily than coarser material. The surface course material should also be composed of aggregate which is resistant to degradation due to abrasion, freeze-thaw cycles, and wetting and drying cycles.

When regrading the road, equipment operators must not leave berms of material on the shoulders. These berms inhibit lateral drainage and may cause severe sideslope erosion where the berms are breached. Berms are frequently found beneath guardrails placed on high fills which occur in saddles where culverts are also located. Materials from the breached berms and eroded sideslopes may be transported directly into water courses in these areas.

Due to the lack of topsoil in arctic and subarctic areas, roadway shoulders and sideslopes are not generally reseeded. To minimize erosion problems, the surface materials in these areas should be similar to those used on the wearing surface, i.e. resistant to degradation by freeze-thaw cycles and wetting and drying cycles.

The thermal resistance of the roadway embankment should be designed to minimize permafrost degradation of thaw-unstable soils beneath the road. This would in turn minimize future maintenance requirements for additional surface aggregate and possible reopening of revegetated borrow areas, as well as minimizing drainage problems frequently associated with thaw settlement of the embankment.

In the last few years, the Alaska DOTPF has successfully used toe berms along the roadway embankment. The berms serve two very useful functions: 1) they reduce thaw penetration at the toe and thereby considerably reduce differential settlement of side slopes and shoulders and resulting maintenance, and 2) they can be used as disposal areas for materials not suitable for incorporation into the embankment. An additional benefit may also result from the reduced thawing at the toe—i.e. damage of drainage structures beneath the embankment will be reduced due to less settlement.

Revegetation and restoration

Steps should be taken as soon as practical to encourage native reinvasion of disturbed areas. Seeding, planting, and fertilization of erodible disturbed areas should be conducted as soon as practicable and should be repeated until revegetation is successful. Nonerodible areas may be left unseeded if native reinvasion is judged to be adequately rapid, but should be rehabilitated, fertilized and scarified to provide a favorable seed bed. All other restoration should be completed as soon as possible following the completion of the project.

Upon completion of construction work, temporary facilities and construction equipment should be removed and the area cleaned up and returned as closely as possible to its original stable condition. Practices to accomplish this may include removing embankments, grading, seeding, planting, mulching, removing temporary drainage control structures, blocking access, placement of mat binders, soil binders, rock or gravel blankets or structures, or other practices determined by the needs of specific areas.

Materials from access roads, ramps, berms, dikes, and any other earthen structures should be used in the reconstruction and restoration procedures. They should be leveled or otherwise disposed of in an approved manner. Excavated and stockpiled organic material should be mixed into the surface (upper 10 cm) of disturbed sites. This will help to reduce erosion as well as to aid subsequent plant growth. Fine-grained subsurface materials from excavations may also be reused on coarse-grained disturbed soils in areas of low precipitation. Restoration measures should include erosion control procedures in order to minimize the effects that may result from thawing produced by flowing or ponded water on permafrost terrain. Restoration should not create new lakes, drain existing lakes, divert natural drainages, disturb natural stream drainages, stream beds or stream hydraulics, or degrade water quality. During cleanup, extreme care should be taken to minimize disturbance to the natural surface layer.

Revegetation standards for native species were developed for the trans-Alaska pipeline system and should be utilized when applicable. These standards include provisions for stockpiling and replacing organic material, planting of willow and other woody cuttings, sprigging of sedges and grasses, transplanting of woody shrubs and trees, procedures for storing seed and fertilizer, watering of planted areas, and specifications for mulching during slope revegetation. Mulching, followed by dormant seeding after the first freeze or snow, may be used to take advantage of increased early spring soil moisture for germination.

Seeding should be attempted only on relatively stable portions of the newly exposed slopes. If the slope is exposed in the early spring, the lower portion of the slope should be fertilized and heavily seeded with annual and perennial grasses near the end of the first thaw season. This will establish a relatively stable zone near the base of the slope before deep thawing occurs the following summer. Following this procedure for two or three years, grasses should be established in successive stages to meet with the subsiding organic mat near the top of the cut. During the second and third summers, willow and birch seedlings could also be used, although these trees grow very rapidly from root-stock or seeds deposited by natural means.

In order to reduce the impact to the public view, a screen of native vegetation should be left in place, or if removed, established after construction is completed. Temporary access roads should be revegetated. Other disturbed sites and access roads used for maintenance should be vegetated except those portions that continue to be used such as a single pair of vehicle tracks on the access road. Vegetation, overburden and other materials removed from surface material sites should be disposed of at the termination of use of the site. Chipped vegetative debris should be spread evenly over the entire site together with other organic materials and topsoil, and these materials should be harrowed into the subsoil in order to reduce erosion and aid in revegetation. Nonerodible disturbed areas in the Subarctic should be prepared by top-dressing with available organics and fine-grained disposal materials, fertilizing, and harrowing. Native species can then reinvade the area more readily without artificial reseeding.

APPENDIX B: UNIVERSITY-BASED STUDIES ALONG THE YUKON RIVER-PRUDHOE BAY HAUL ROAD*

Investigations of weeds and weedy vegetation along the Yukon River-Prudhoe Bay Haul Road, A.W. Johnson and S. Kubanis, San Diego State University.

Vegetation mapping and response to disturbance along the Yukon River-Prudhoe Bay Haul Road, P.J. Webber, V. Komárková, D.A. Walker and E. Werbe, University of Colorado.

Botanical reconnaissance of the Yukon River-Prudhoe Bay Haul Road, D.M. Murray and B. Murray, University of Alaska.

Soil invertebrates as indicators of environmental change along the Yukon River-Prudhoe Bay Haul Road, S.F. MacLean, Jr., University of Alaska.

Distribution and properties of road dust and its potential impact on tundra along the northern portion of the Yukon River-Prudhoe Bay Haul Road, K.R. Everett, Ohio State University.

Clay mineralogy of road materials and dust along the northern section of the Yukon River-Prudhoe Bay Haul Road, R.C. Reynolds and H. van Oss, Dartmouth College.

Field survey of selected culverts along the Yukon River-Prudhoe Bay Haul Road, G.L. Guymon, University of California (Irvine).

Erosion rates in natural and revegetated sites within the Brooks Range, L.J. Onesti, Indiana University.

Chemistry of icings and related water sources in the Brooks Range, N. Krothe, Indiana University.

Revegetation of Alaskan disturbed sites by native species, F.S. Chapin, III, University of Alaska; G. Shaver, San Diego State University.

Soil-landform interactions in wet arctic and alpine tundras along a regional climatic gradient, K.R. Everett, Ohio State University.

*Supported by ARO, CRREL, DOE and FHWA funds at CRREL and ARO.

APPENDIX C: CRREL MAPS OF HAUL ROAD SHOWING LOCATIONS OF ALL STUDY SITES

Cultural Legend

- Haul Road
- Pipeline, aboveground
- Pipeline, underground
- Gas feeder line
- Trail
- Airfield
- Camp
- Pump Station
- Oil pipeline-road crossing
- AS# Alignment sheet
- 20 → Mileage
  - Road: N from Yukon
  - Pipeline: S from Prudhoe Bay
- Bridge
- Major drainage structure (culverts total over eight ft wide)

CRREL Observational and Sample Location

- ⟨1⟩● CRREL climatic station (● snow gage)
- III-2 ② CRREL cross-section; ②-Subsurface temperature installation (number of profiles at each site)
- Walker and Webber vegetation map (WW#)
- 2-326 Komarkova-Webber transects and plots
- M-59 Murray site
- K1 Kubanis weed/succession transects and plots (A.W. Johnson)
- Everett soil map strip
- Dust transects and location (DT-PB)
- *79J1 Photo-vegetation point (L. Johnson)
- *118G1 Gas line transect (L. Johnson)
- *85T1 Trail site (L. Johnson)
- 116TC Chapin trail site (with Shaver)
- F Chapin fertilizer site (with Shaver)
- ML MacLean invertebrate site
- R van Oss road, dust and soil samples (R. Reynolds)
- ▽ Q-4 Staff gage - suspended sediment sampling point (L. Onesti)

Other Agencies

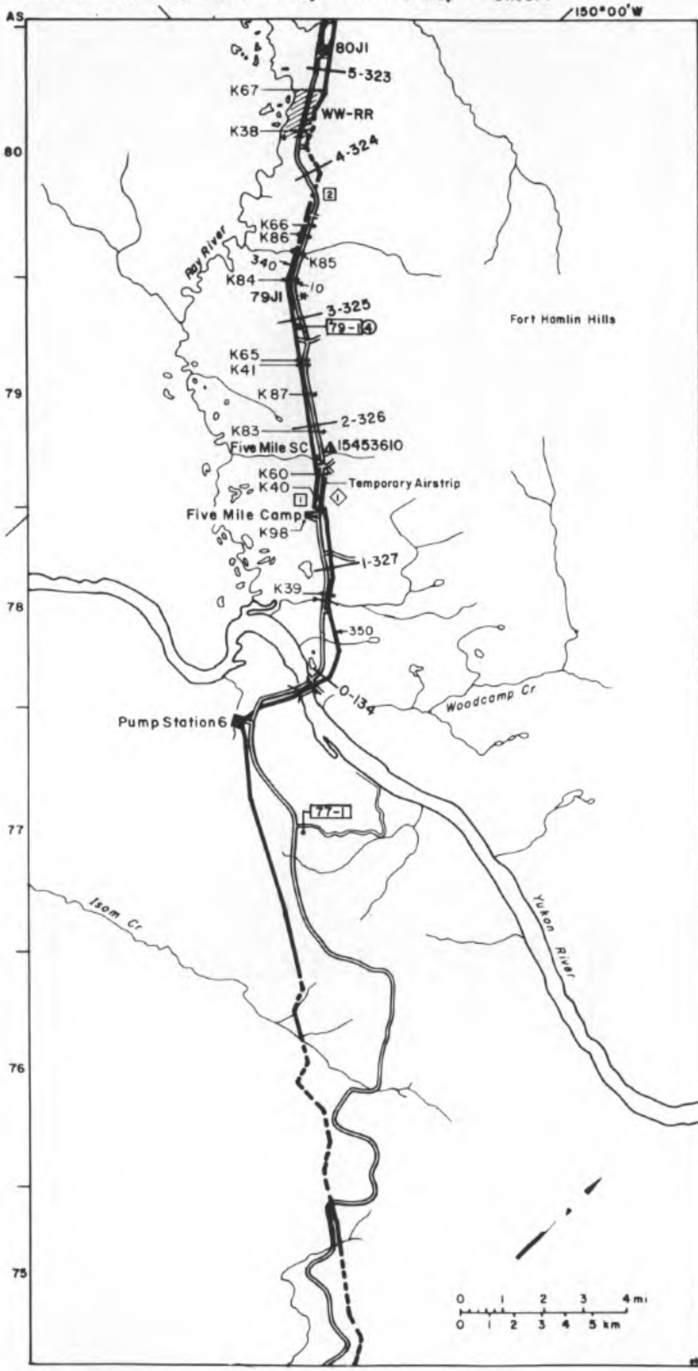
- △ (▲) USGS gaging station (crest-stage gage)
- SCS snow course (SC)
- ⊕ Shacklette (USGS) vegetation sample site

Conversion
($1.609 \times$ mi = km)

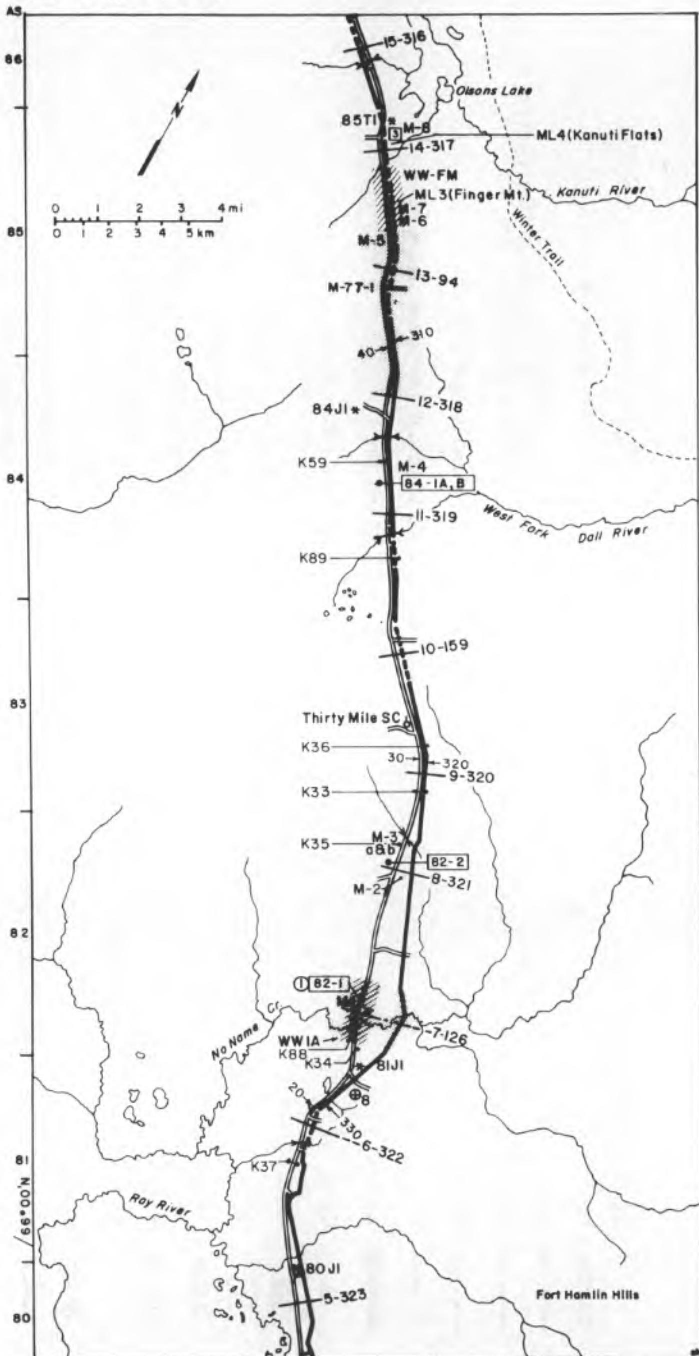
(mi)	(km)	(mi)	(km)
0	0	210	338
10	16	220	354
20	32	230	370
30	48	240	386
40	64	250	402
50	80	260	418
60	97	270	435
70	113	280	451
80	129	290	467
90	145	300	483
100	161	310	499
110	177	320	515
120	193	330	531
130	209	340	547
140	225	350	563
150	241	360	579
160	257		
170	274		
180	290		
190	306		
200	322		

Maps: Compiled by E. Huke
Edited by J. Brown

CRREL Yukon River-Prudhoe Bay Haul Road Map - Sheet 1



CRREL Map - Sheet 2



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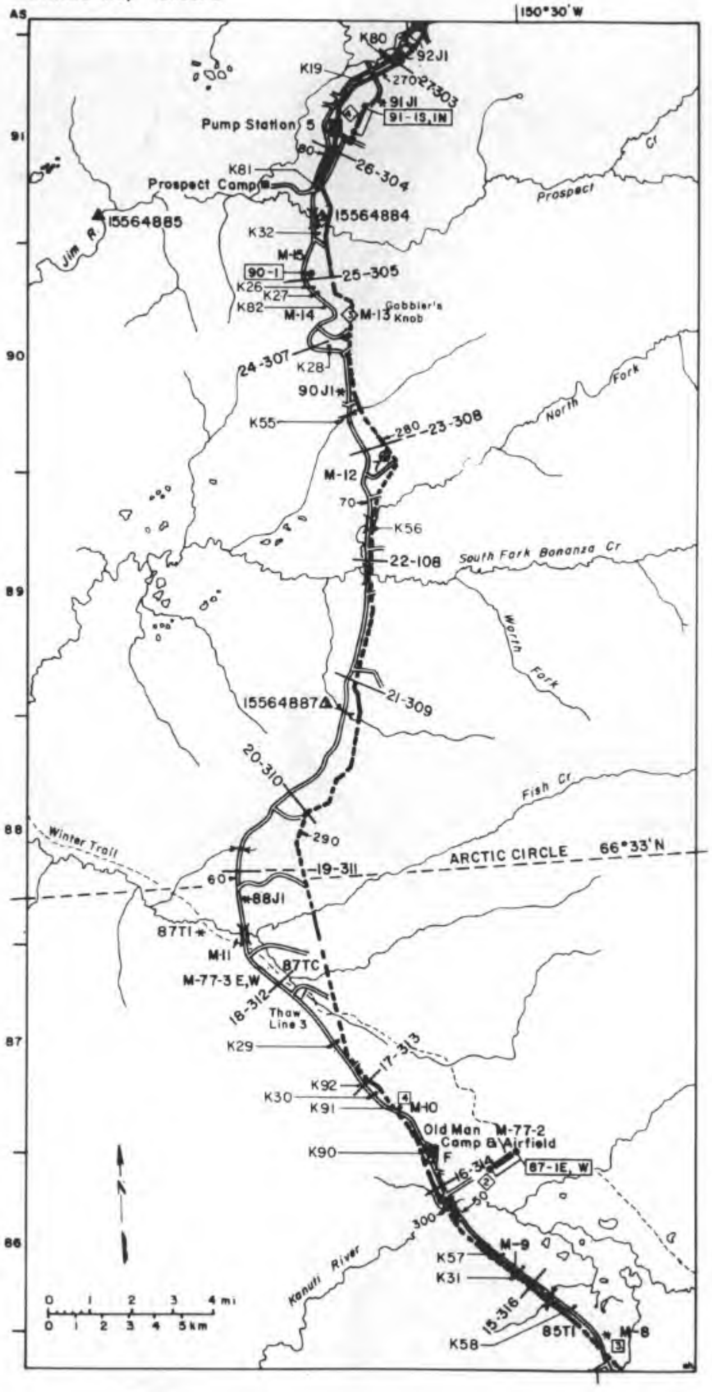

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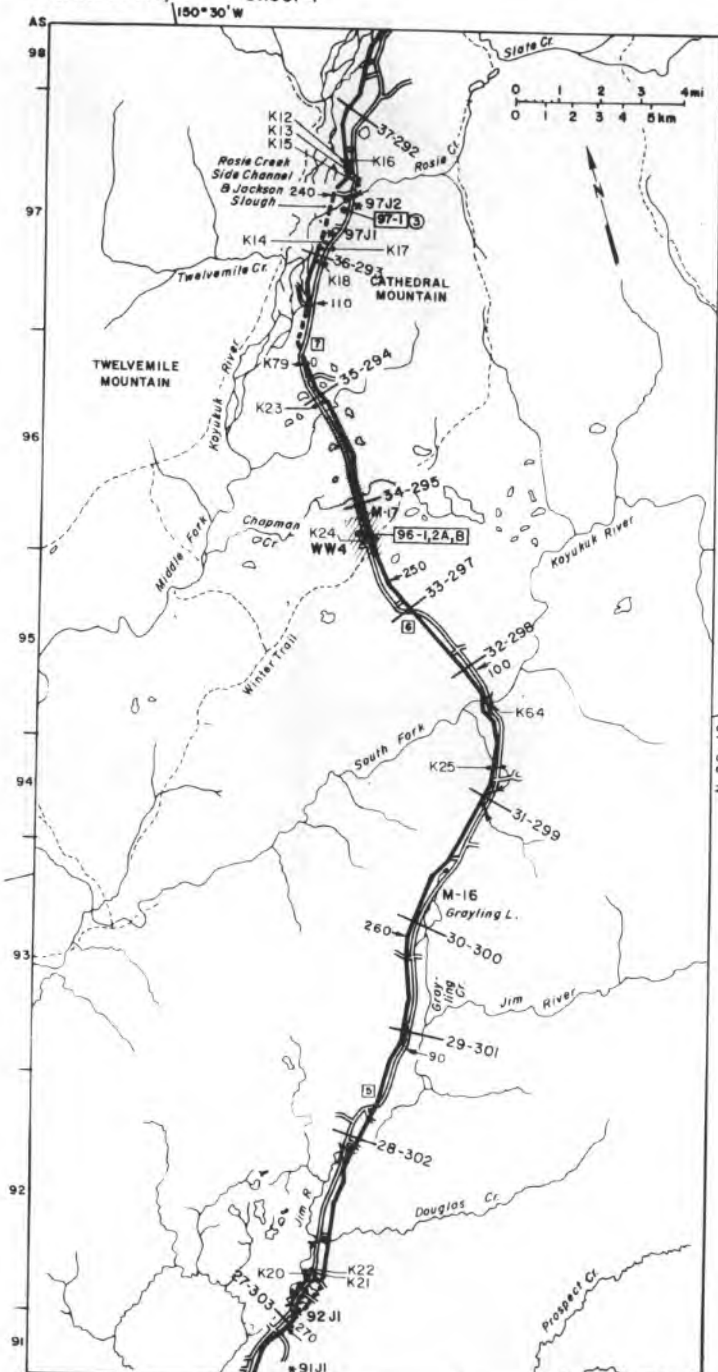

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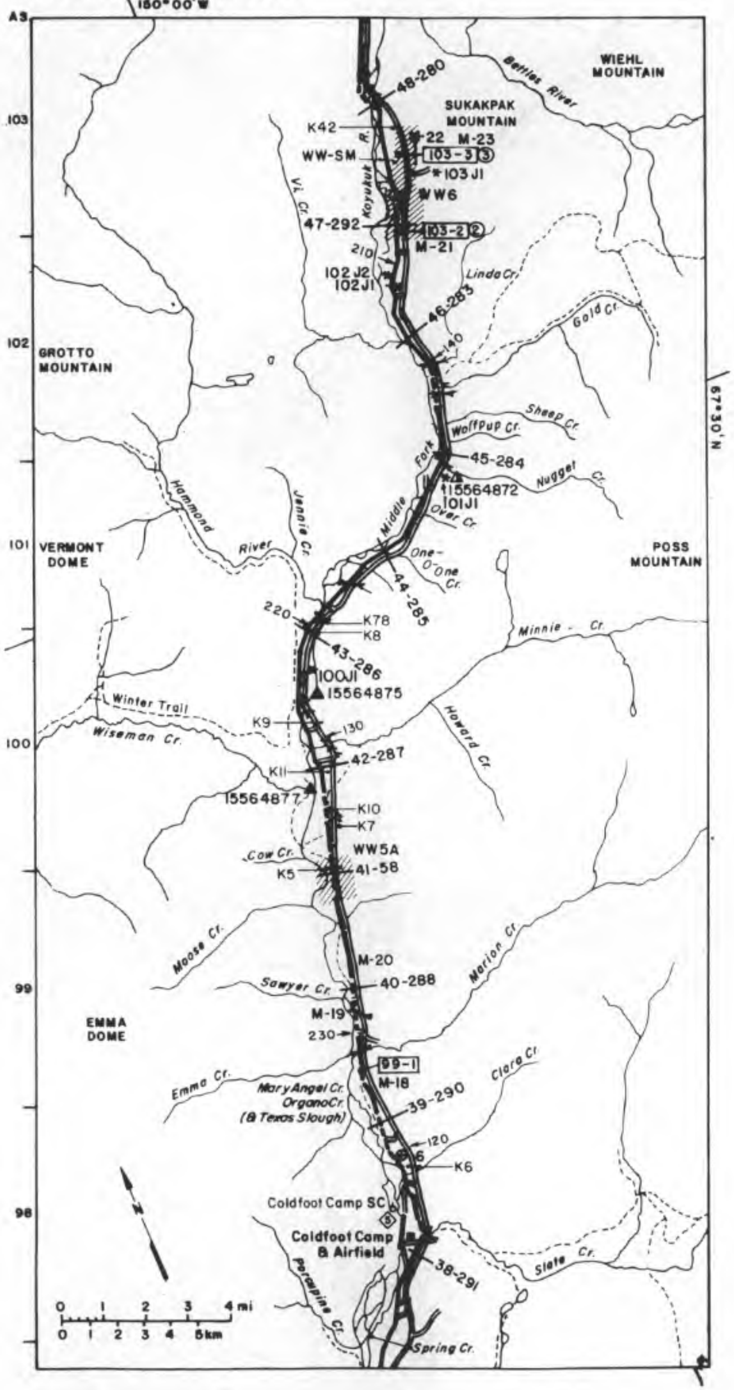

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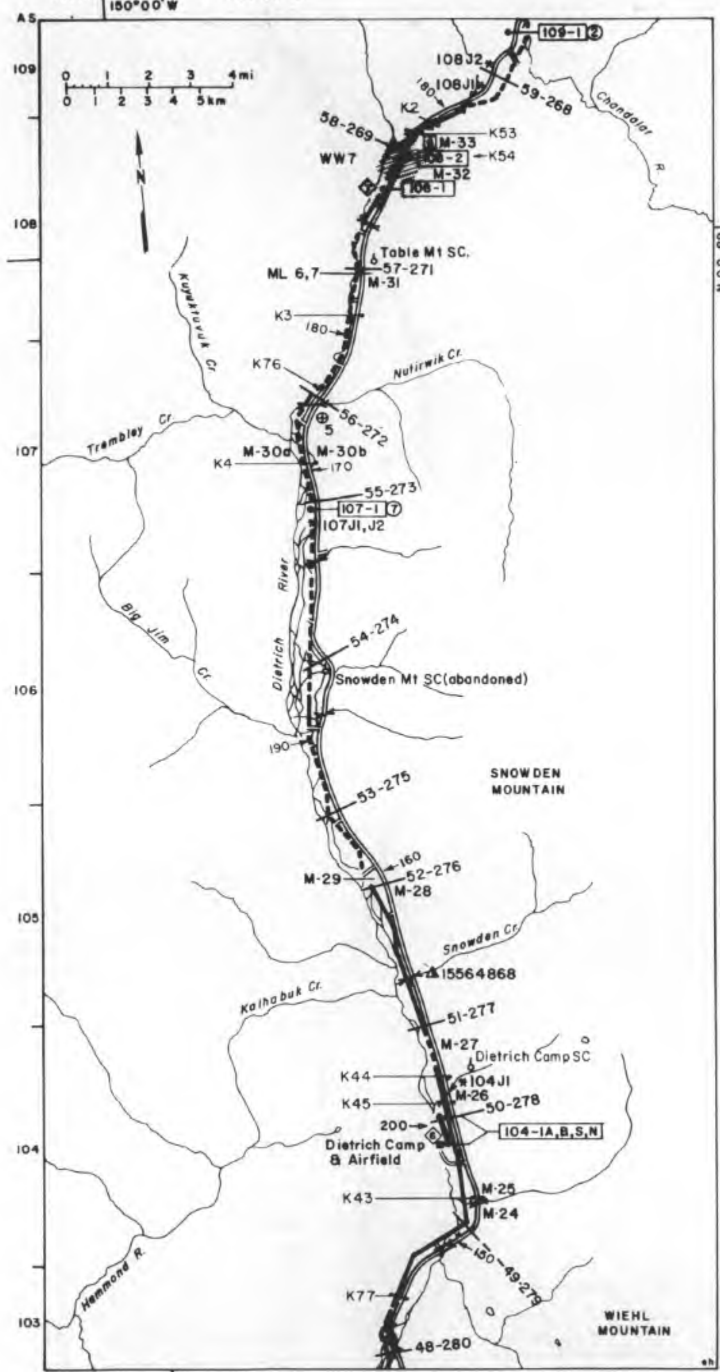

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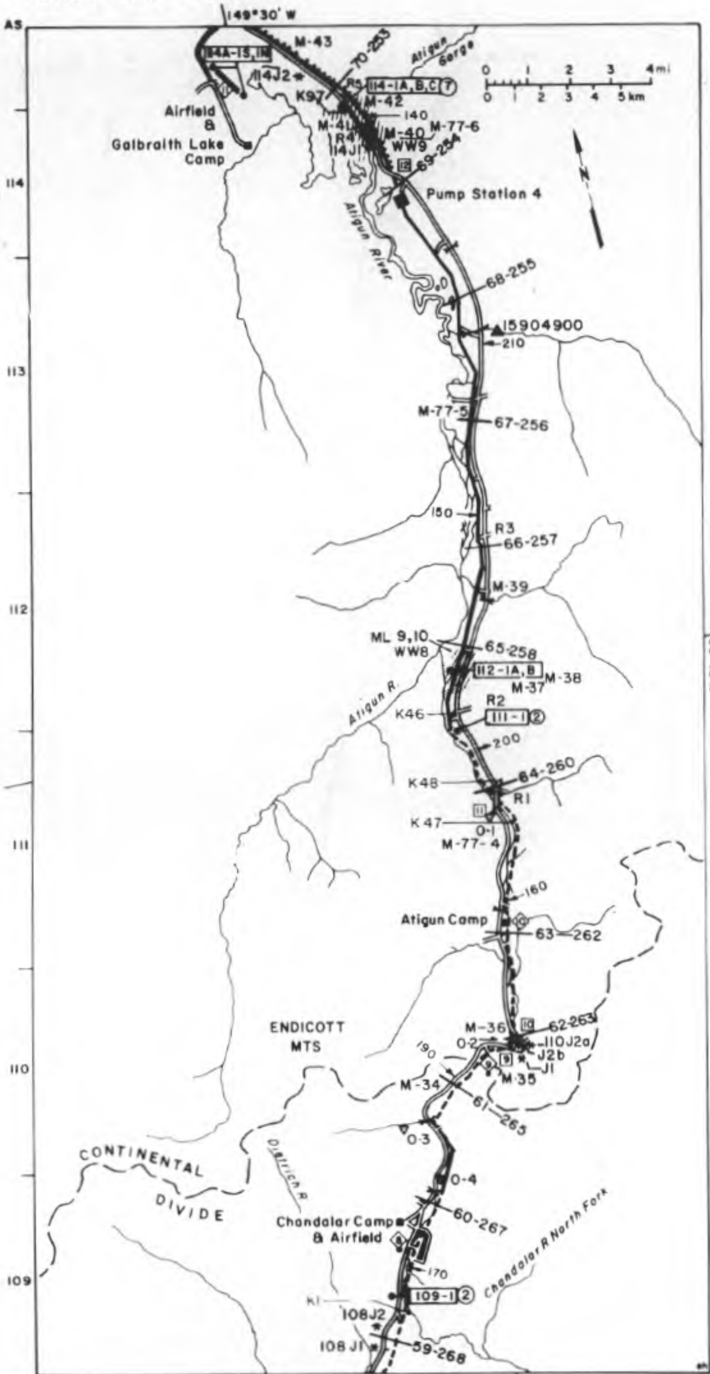

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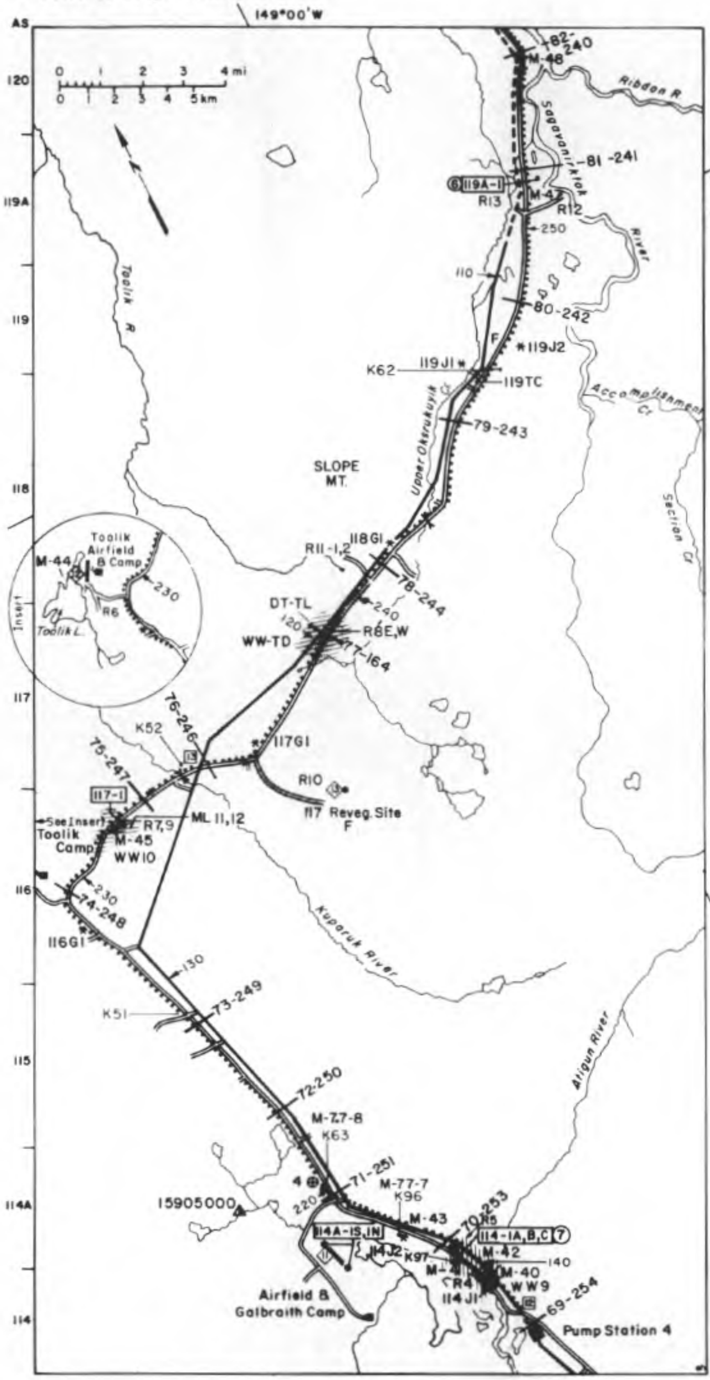

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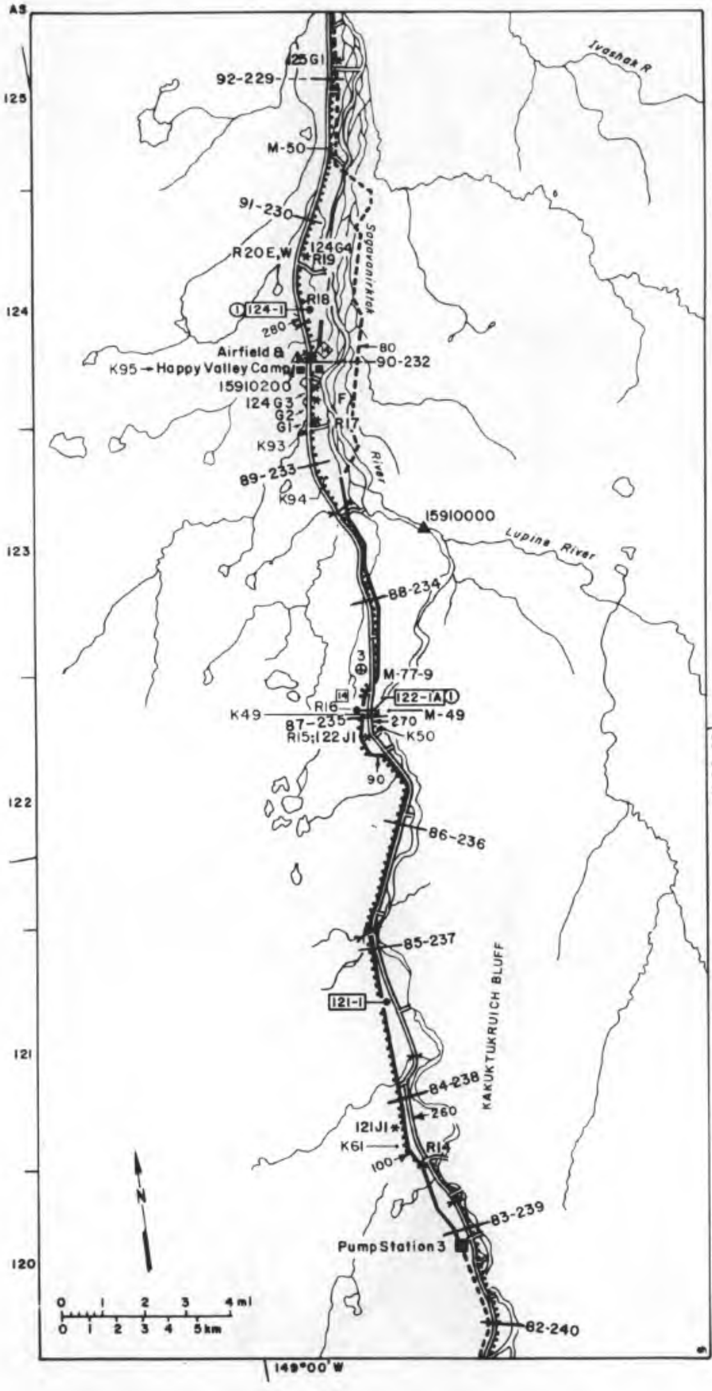

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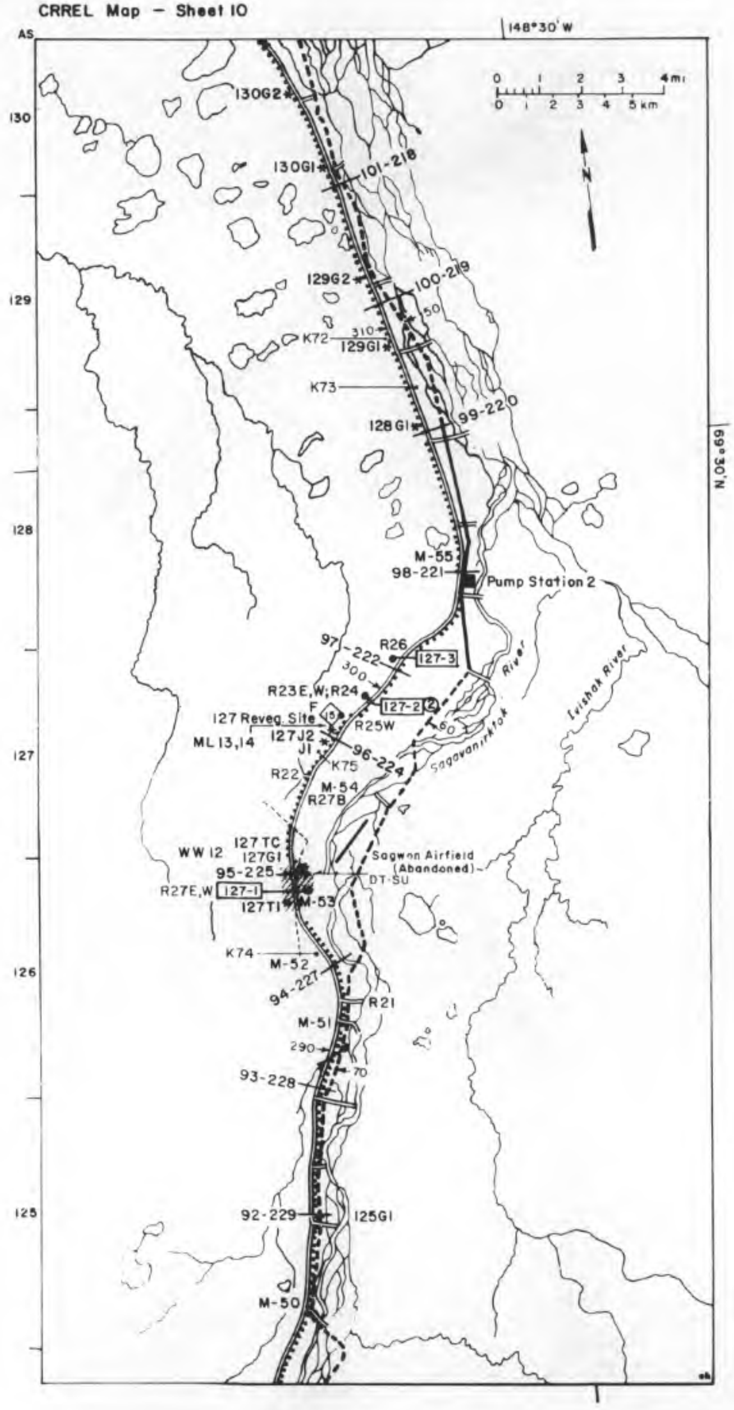

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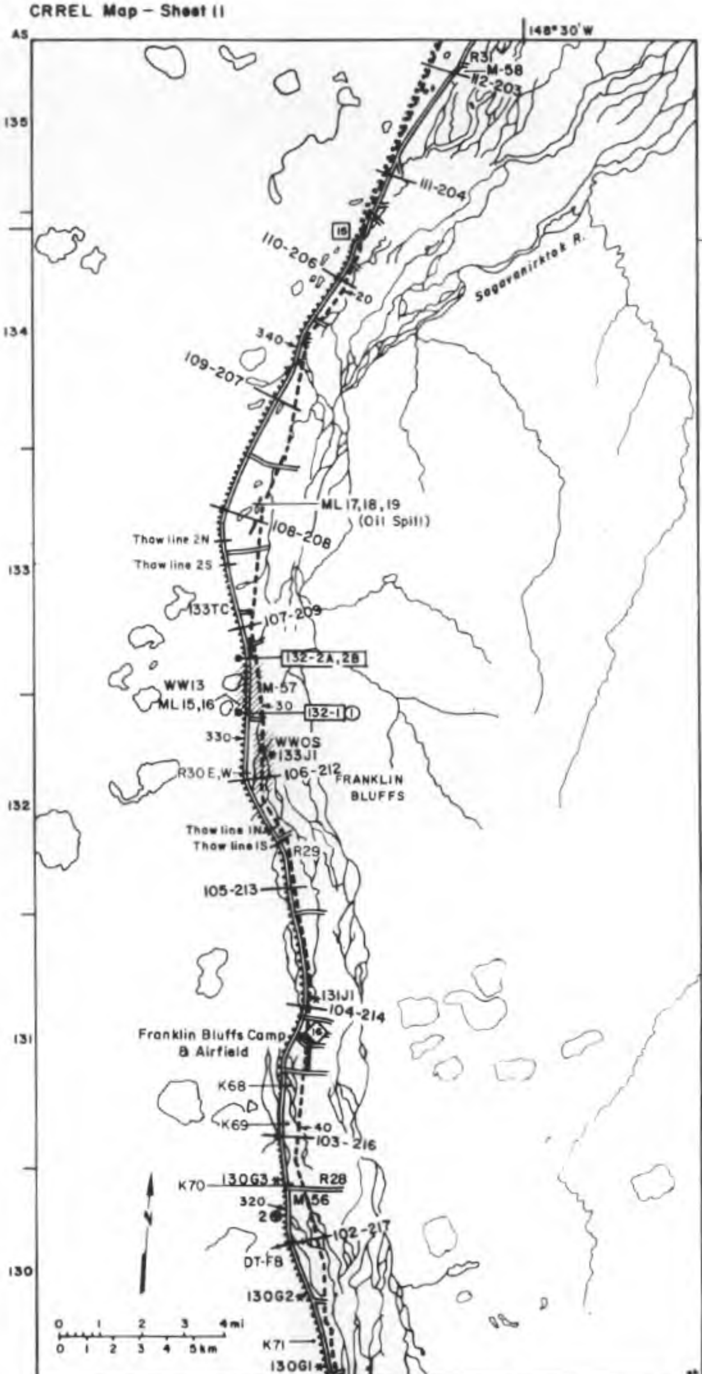

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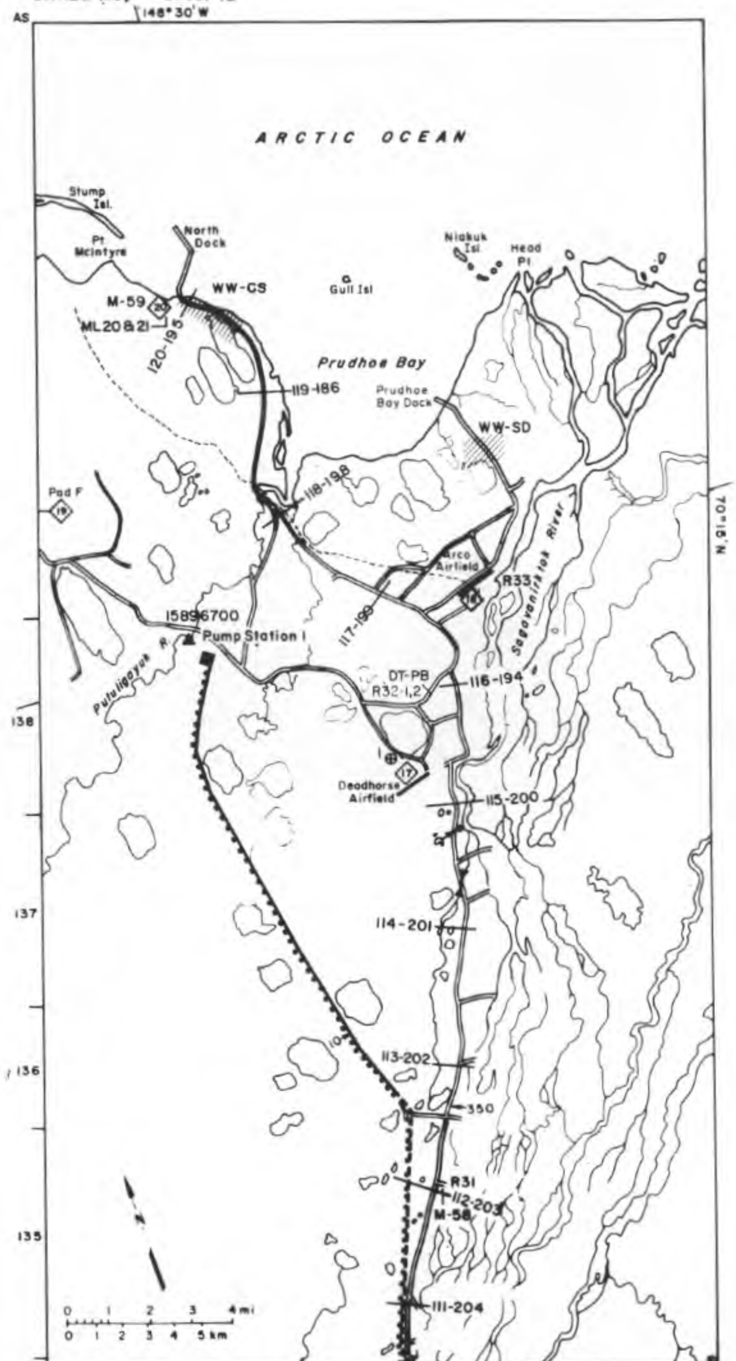
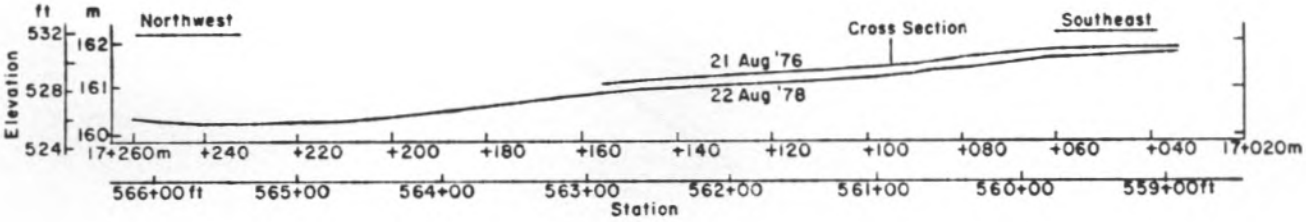


APPENDIX D: ADDITIONAL HAUL ROAD CROSS-SECTIONAL PROFILES



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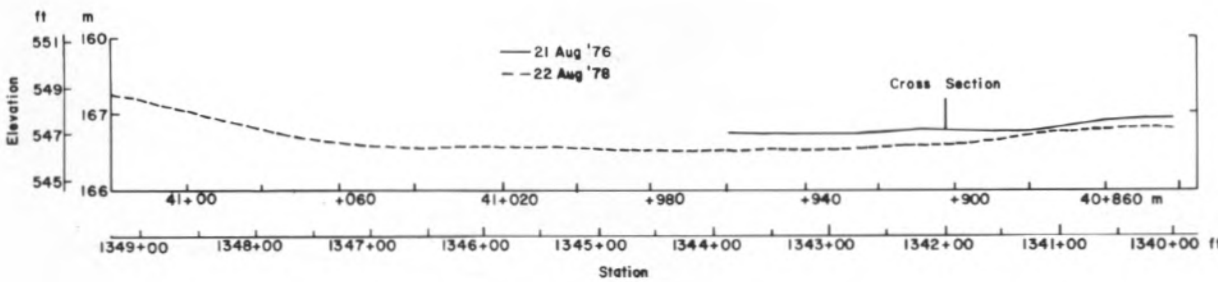

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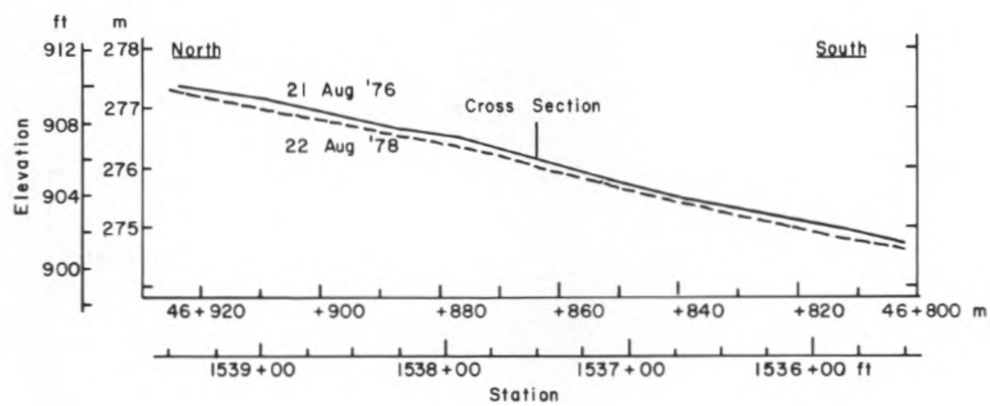

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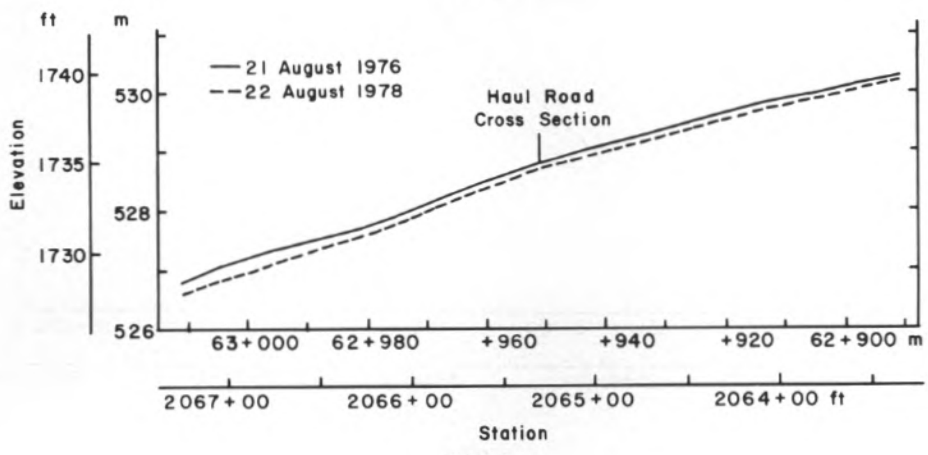

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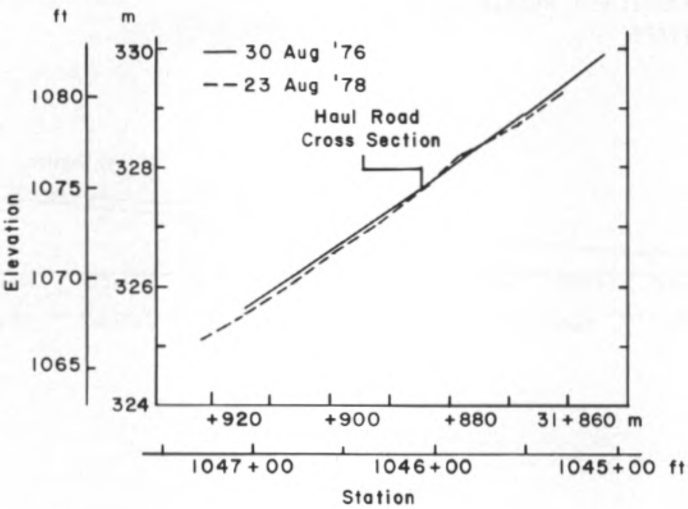
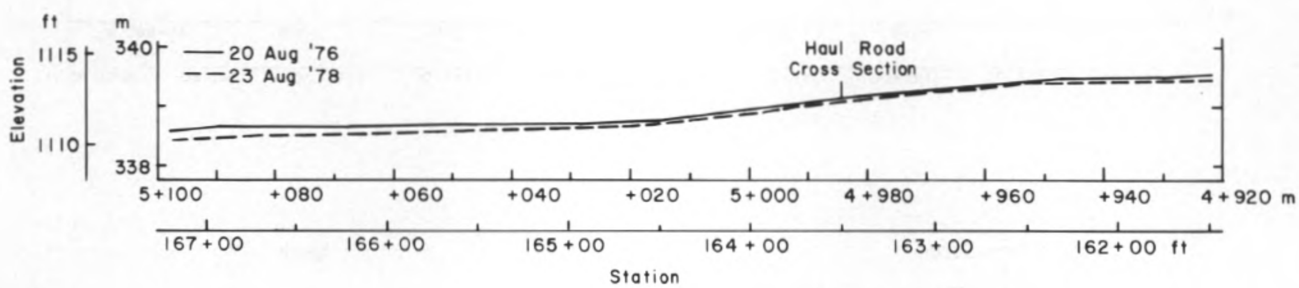
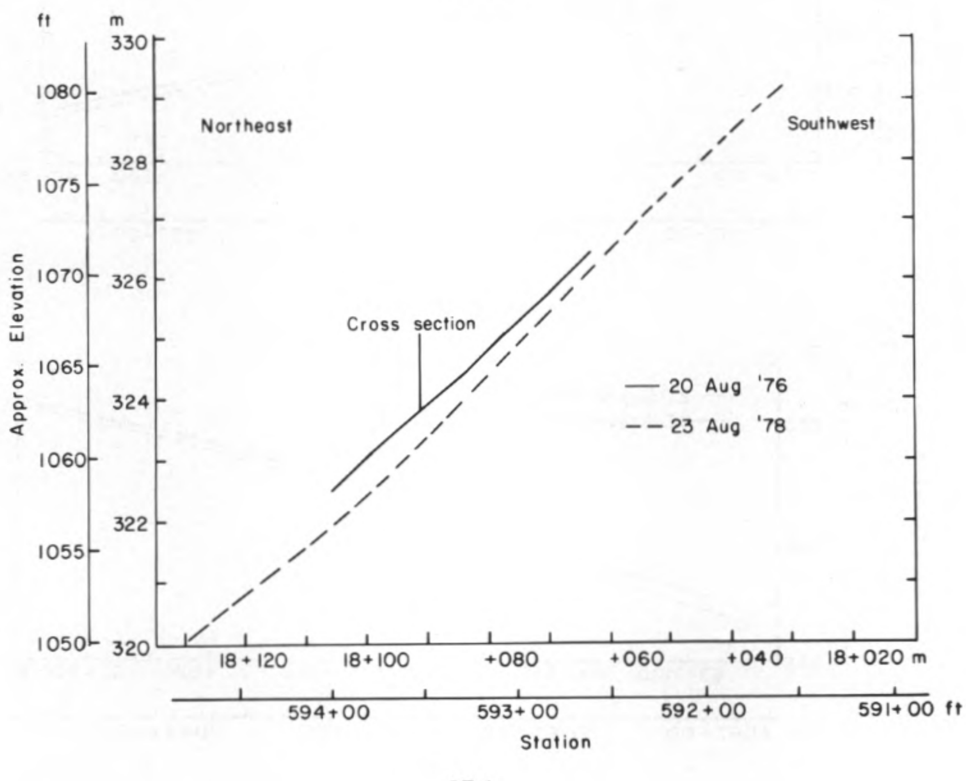

ft
m
30 Aug '76
23 Aug '78
Haul Road
Cross Section
Elevation
1080
1075
1070
1065
330
328
326
324
+920
+900
+880
31+860 m
1047+00
1046+00
1045+00 ft
Station

90-1


ft
m
20 Aug '76
23 Aug '78
Haul Road
Cross Section
Elevation
1115
1110
340
338
5+100
+080
+060
+040
+020
5+000
4+980
+960
+940
4+920 m
167+00
166+00
165+00
164+00
163+00
162+00 ft
Station

96-2A


ft
m
Northeast
Southwest
Cross section
20 Aug '76
23 Aug '78
Approx. Elevation
1080
1075
1070
1065
1060
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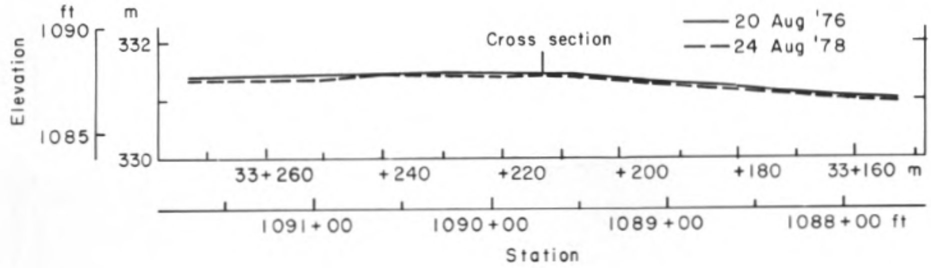
1050
330
328
326
324
322
320
18+120
18+100
+080
+060
+040
18+020 m
594+00
593+00
592+00
591+00 ft
Station

97-1



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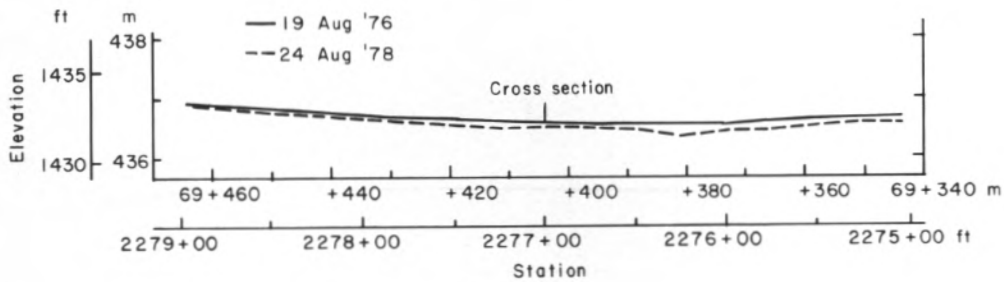

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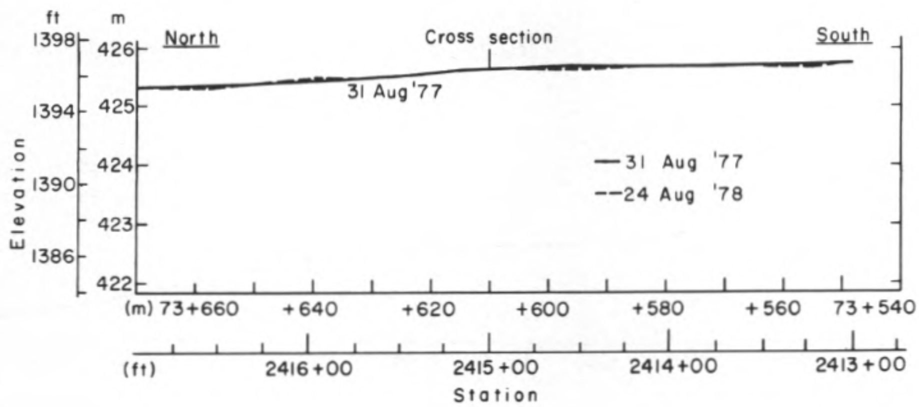

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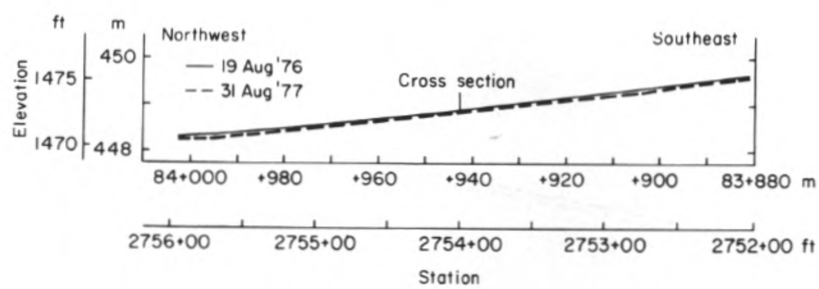

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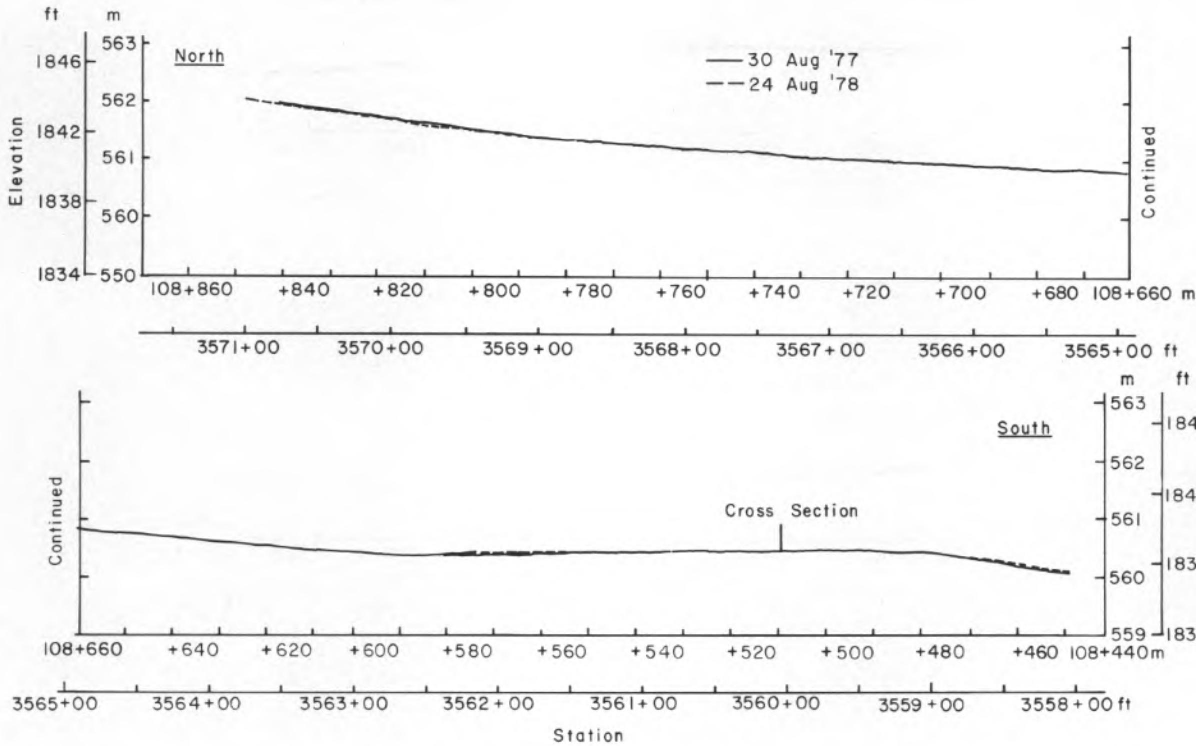

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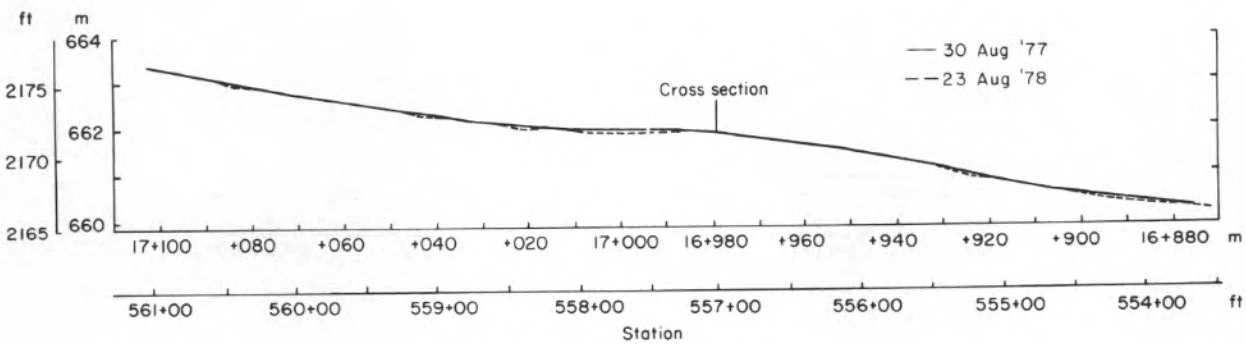

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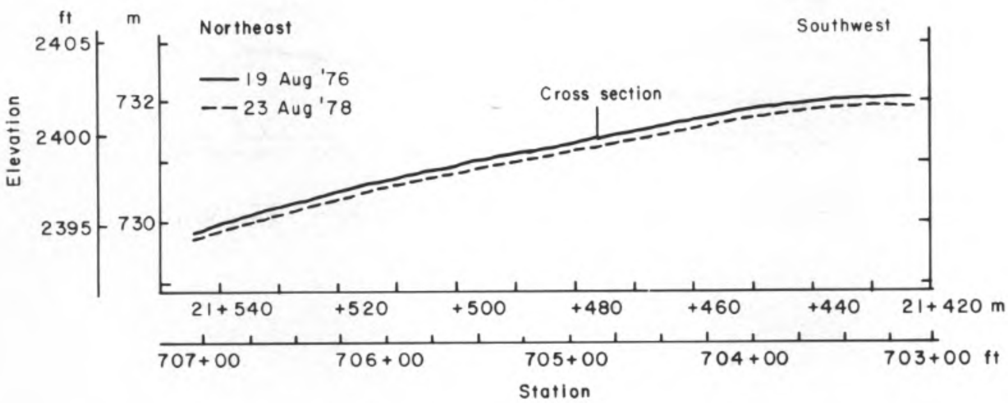

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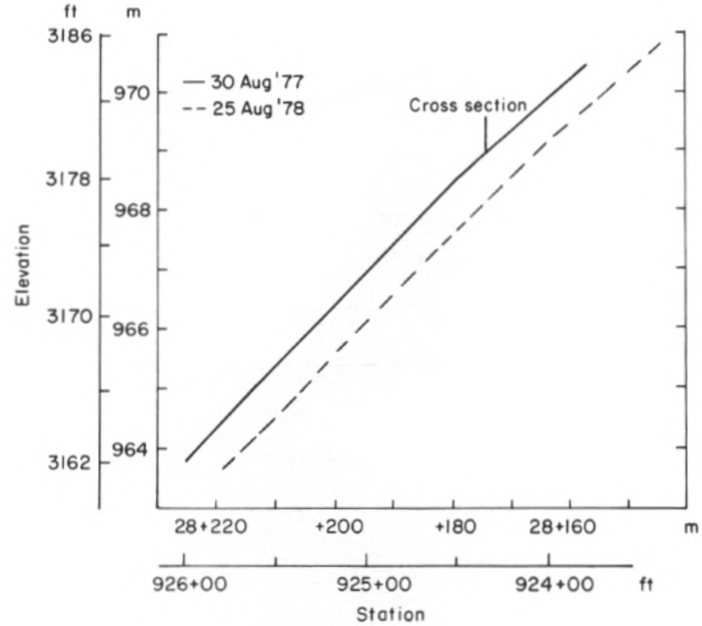

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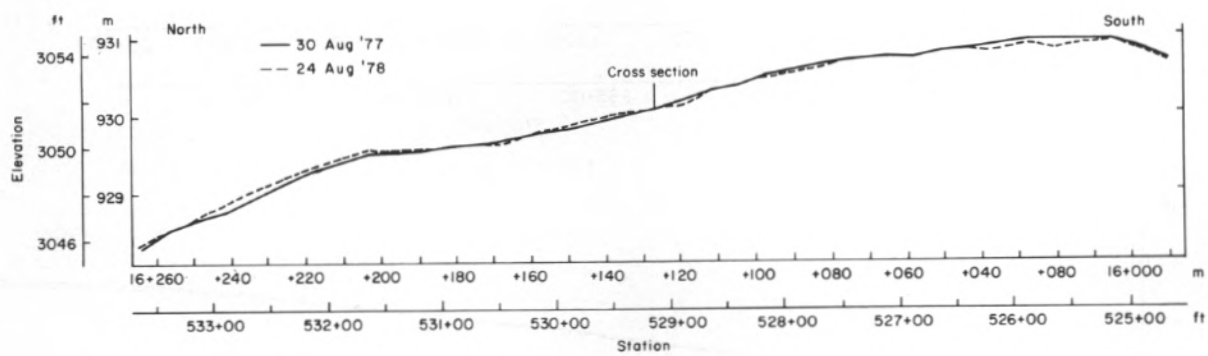

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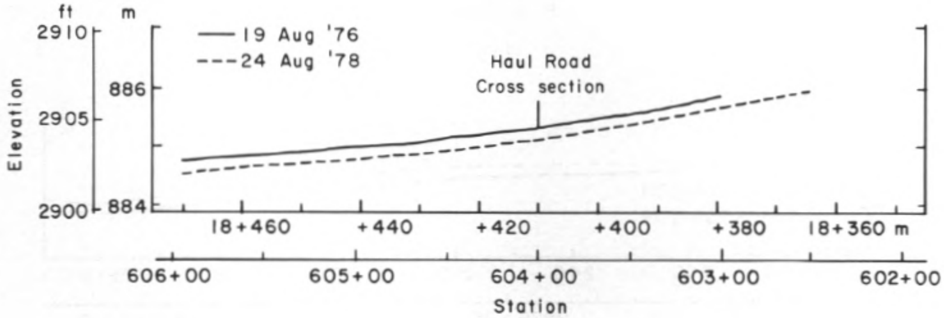

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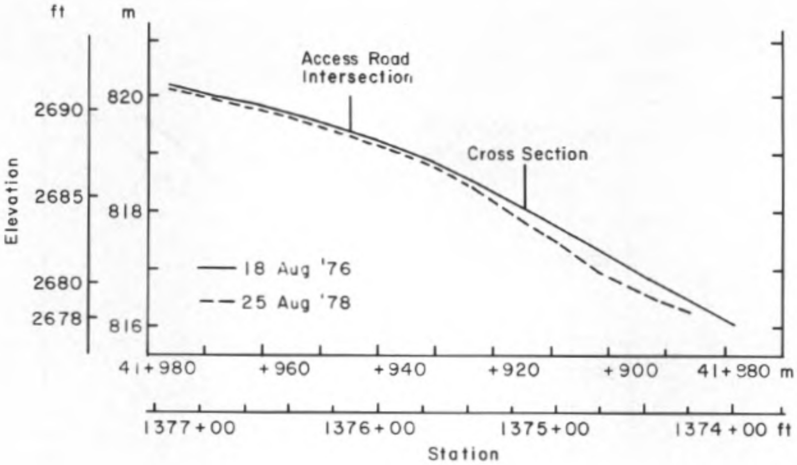

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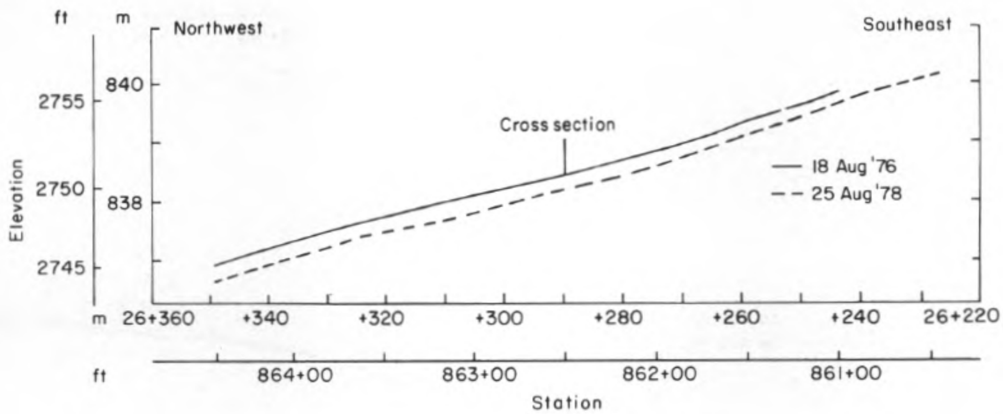

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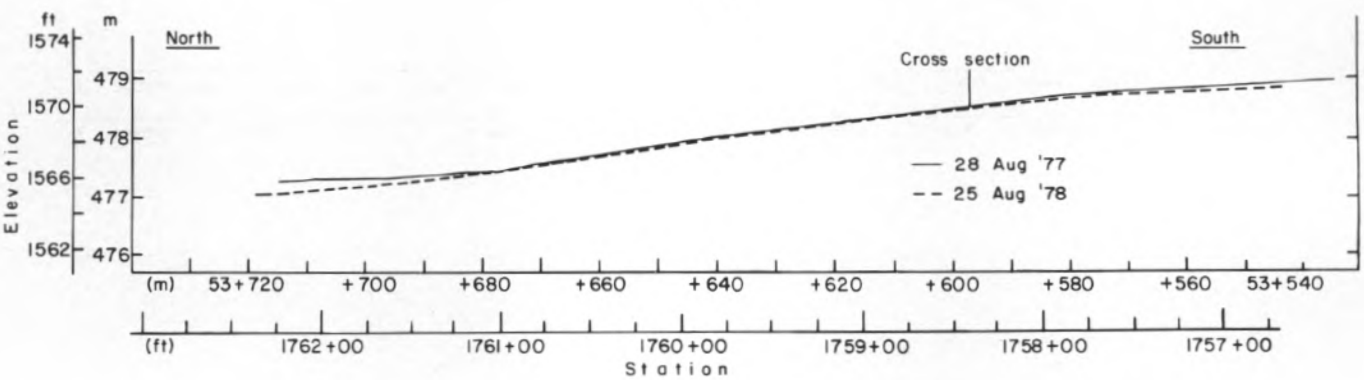
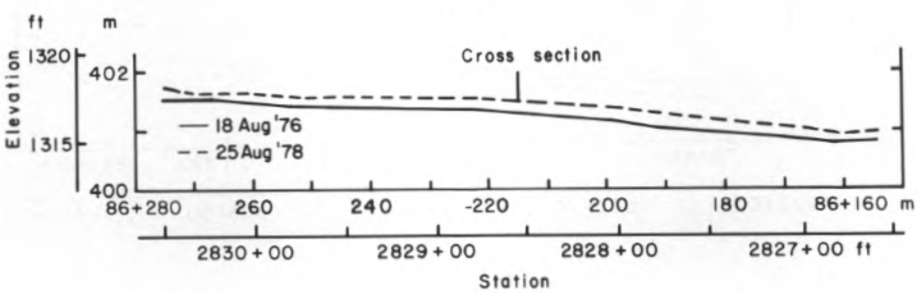
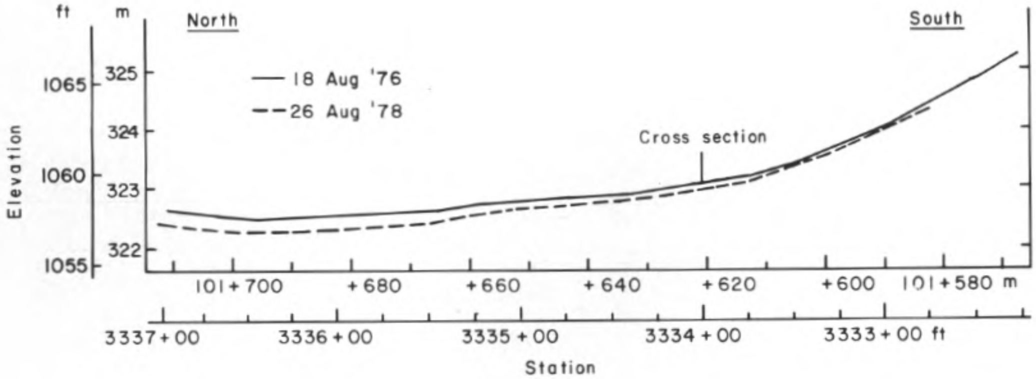


119A-1



122-1A



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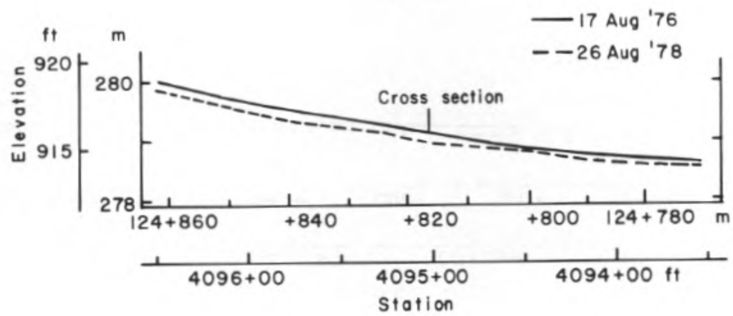
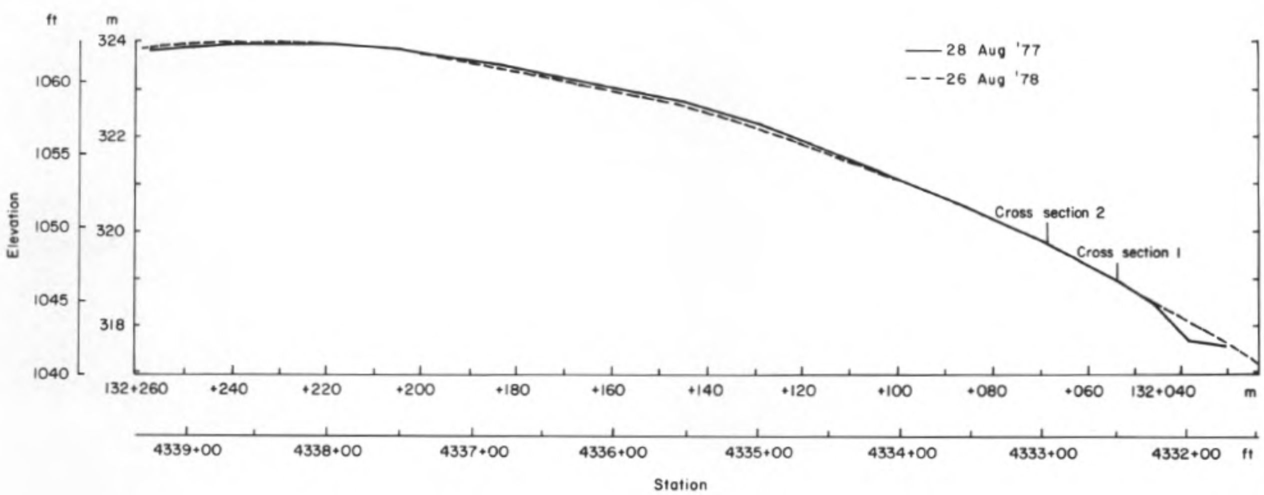
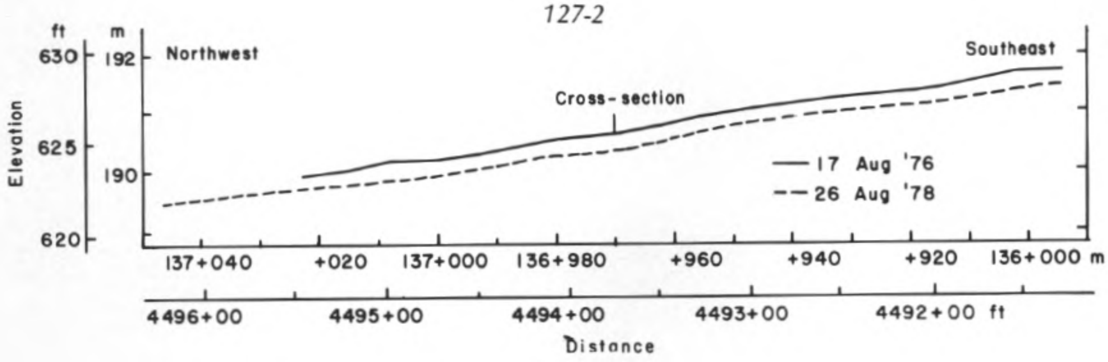


127-1



127-2



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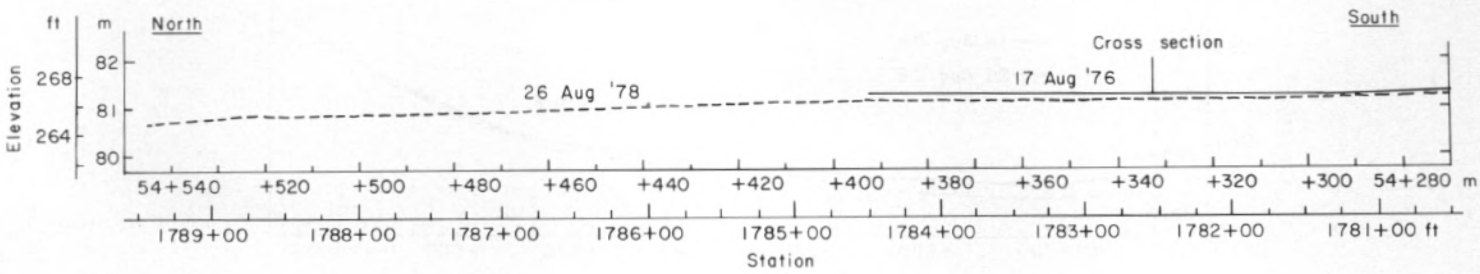
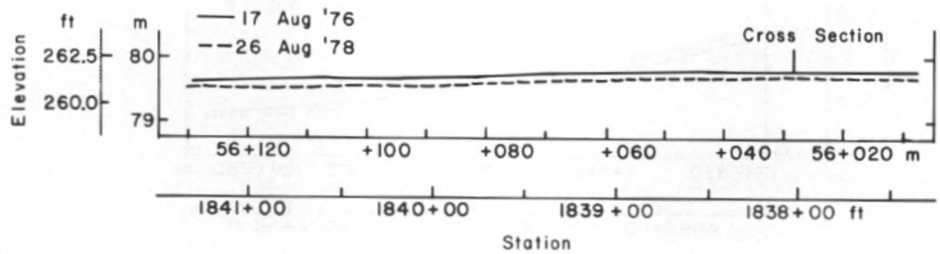

ft
m
North
South
Elevation
268
264
82
81
80
Cross section
17 Aug '76
26 Aug '78
54+540
+520
+500
+480
+460
+440
+420
+400
+380
+360
+340
+320
+300
54+280 m
1789+00
1788+00
1787+00
1786+00
1785+00
1784+00
1783+00
1782+00
1781+00 ft
Station

132-1


ft
m
Elevation
262.5
260.0
80
79
17 Aug '76
26 Aug '78
Cross Section
56+120
+100
+080
+060
+040
56+020 m
1841+00
1840+00
1839+00
1838+00 ft
Station

132-2A

APPENDIX E: CLAY MINERALOGY OF ROAD-RELATED MATERIALS*

The purpose of the present study was to determine the type of clay minerals added to the tundra from road dust. Samples were obtained from the road and adjacent material sites including bedrock exposures, adjacent tundra soils, and the dust itself.

Samples were collected by Richard Haugen (CRREL) in June 1977 and Hendrik van Oss in July 1977 during a round trip from Prudhoe Bay to the Brooks Range (Table E1). The road and material site samples were sieved in the field; materials coarser than 2 mm were discarded. The soil samples were collected at varying distances (between 100 and 300 m) on either side of the road. A few of the soil samples were taken from frost boil material; most, however, were taken from the gley horizon that existed 10 to 15 cm below the organic-rich surface layer. This mineral layer should be uncontaminated as it is overlain by tens of centimeters of dense organic matter. The gley samples are generally plastic, indicating a high clay content. They did, however, contain coarser clastic material in addition to the clay. The soil samples were sealed in plastic bags to maintain their moisture content. Three bedrock samples were also collected (no. 11b, 15, 27d), and four dust samples (no. 6b, 27e, 30d, 32c) were supplied by Dr. K.R. Everett of Ohio State University.

Laboratory analysis

The clay mineralogy determinations were made by X-ray diffraction analysis at the Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire, by Hendrik van Oss. The analysis procedure was as follows. Between 10 and 30 g of material was agitated in water overnight to release clays into suspension. If the sample was consolidated, minor grinding was done preliminary to the agitation. The suspension was washed to remove soluble salts by centrifuging at 2000 rpm for 10 minutes. This left most of the material settled at the bottom of the centrifuge cup. The remaining suspension was discarded. About 60 ml of distilled water was added to the bottom material which was then brought again into suspension by a combination of stirring followed by ultrasonic agitation. A

*Prepared by R.C. Reynolds and H.G. van Oss of Dartmouth College.

Table E1. Sample sites.

Field number	*CRREL map number*	*Location*	
Road and material site samples			
1	R-1	MS 111-1	
2	R-2*	MS 112-0	
3	R-3	MS 112-3.1	
4	R-4	Stream sediments at Atigun River Bridge	
5	R-5	CRREL 114-1ABC	
6a	R-6	Toolik Lake material site	
7	R-7*	Cross section 117-1	
8a	R-8	117 APL-3	
10	R-10	MS 117-2	
11a	R-11-1	Slope Mountain material site	
12	R-12	MS 119-4N	
13	R-13*	CRREL 119A-1	
14	R-14	MS 121-1	
16	R-16*	CRREL 122-1A	
17	R-17	MS 124-1	
18	R-18	CRREL 124-1	
21	R-21	126 APL-AMS 1A	
22	R-22*	MS 127-1.2	
24	R-24*	CRREL 127-2	
25a	R-25	MS 127-2.1B	
26	R-26*	0.4 km north of CRREL 127-3	
27a	R-27	CRREL 127-1	
28	R-28	MS 130-5 (MS 130-3)	
29	R-29*	MS 132-1	
30a	R-30	Franklin Bluff	
31	R-31*	MS 135-ABC-2	
32a	R-32-1*	Arctic Gas Road	
32b	R-32-2	Arctic Gas Road	
33	R-33	Prudhoe Bay gravel site	
Tundra soil samples			
8b	R-8W	117 APL-3	200 m west of road
8c	R-8E	117 APL-3	200 m east of road
9	R-9	117-1	100 m west of road
19	R-19	MS 124-4	100 m east of road
20a	R-20W	0.8 km north of MS 124-2	100 m west of road
20b	R-20E	0.8 km north of MS 124-4	100 m east of road
23a	R-23W	CRREL 127-2	100 m west of road
23b	R-23E	CRREL 127-2	100 m east of road
25b	R-25W	MS 127-2.1B	300 m west of road
27b	R-27E	CRREL 127-1 Sagwon Upland	200 m east of road
27c	R-27W	CRREL 127-1 Sagwon Upland	
30a	R-30W	Franklin Bluff	200 m west of road
30b	R-30E	Franklin Bluff	200 m east of road
Bedrock samples			
11b	R-11-2	Slope Mountain	
15	R-15	Happy Valley Cut	
27d	R-27B	Sagwon Upland sandstone	
Dust samples (supplied by Everett)			
6b	DT-TL	Toolik Road (117 APL-3)	
27e	DT-SU	Sagwon West	
30d	DT-FB	Franklin West	
32c	DT-PB	Prudhoe Road (Arctic Gas site)	

*Collected by R. Haugen, June 1977.

peptising agent ($Na_4P_2O_7 \cdot 10H_2O$) was then added to the suspension, which was then further ultrasonically agitated for about 20 seconds. This procedure causes the clay particle aggregates to deflocculate. The next step was to centrifuge the deflocculated suspension for 10 minutes at 450 rpm. The procedure leaves the <2-μm clay fraction in suspension. This suspension was decanted. A clay mount was prepared of the sample by centrifuging the clay fraction suspension (10 minutes, 2000 rpm) onto a porous porcelain plate. This step was generally repeated once in order to achieve a reasonable clay thickness on the plate. The clay mount was then air-dried at room temperature and further dried for several hours at about 100°C. The clay mount was then X-rayed using Ni-filtered Cu K-alpha radiation; scans were made from 30° to 2° 2θ at a speed of 2° per minute.

In order to allow determination of an expandable clay (such as montmorillonite) component, the clay mounts were then glycolated by exposing the clay mounts, upside down, to an atmosphere saturated with ethylene glycol vapor at 60°C for a minimum of 8 hours. The mounts were then X-rayed again.

To confirm the presence of chlorite, the clay mounts were placed in a 550°C oven for 1 hour. This treatment causes the 001 peak of well-crystallized chlorite to be enhanced and its other peaks to be decreased. It also converts any kaolinite to meta-kaolinite, thus removing kaolinite peaks from the diffractogram. If, however, the chlorite is poorly crystallized, all of its peaks will be destroyed by this heat treatment.

Because chlorite and kaolinite share many of the same peaks (especially the 7 Å and 3.5 Å peaks) on a diffractogram, it is very difficult to identify kaolinite with the above procedures. It is thus necessary to selectively remove the chlorite. This was accomplished by taking fresh material from 17 samples and heating then in 2N HCl at about 85°C for 4 hours. A clay mount was then made of each sample by the method described above, but it should be noted that since the HCl treatment adds salt to the suspension, it was necessary to wash the suspensions four times by centrifugation prior to introduction of the peptising agent. The HCl treatment removes all but the most Mg-rich chlorite, and leaves any kaolinite unaffected.

Results

The X-ray diffractogram peaks were assigned to clay minerals as follows: the 4.3 Å peak is quartz, the 5 and 10 Å peaks are illite, the 7 Å peak is chlorite and/or kaolinite. The 14 Å peak is assigned to chlorite, and for the glycolated clay mounts, the 17 Å peak is assigned to montmorillonite. Certain peak asymmetries (especially for the roughly 3.35 Å peak) and a peak "platform" after glycolation, in the range of 10 to 20 Å, are assigned to a mixed-layer clay with an expandable component.

The clay mineralogy of all samples (road material, tundra soil, dust, and bedrock) was virtually identical. The mineralogy was chlorite, illite, a mixed-layer expandable clay, and minor quartz. All non-soil samples contained minor amounts of calcite. The low pH and high moisture content would preclude the presence of calcite in the tundra soils. Of the 17 samples treated with 2N HCl (these included samples from all categories), 16 showed kaolinite.

Only three samples (no. 30a, 32a, 32b) showed discrete montmorillonite. These are road material samples from locations at Prudhoe Bay. Four samples (no. 10, 29, 30b, 32b) had small peaks in the 8- to 9-Å range. These peaks are tentatively assigned to a zeolite mineral. A lack of other good peaks precludes a specific identification. Two samples (no. 18, 27d) had peaks at about 11.3 Å, probably indicating a mixed layer clay. Five samples (no. 3, 23a, 23b, 25a, 30c) had peaks at 6.3 Å; this probably represents lepidocrocite [FeO(OH)]. These minor peaks were all destroyed during the 550°C treatment. Because the assigned materials all contain either H_2O or OH groups, this result is not surprising.

The 550°C treatment revealed the only apparent difference between the tundra soil and other samples. All but one of the tundra soil samples either failed to show a 14 Å peak after this treatment, or had their 14 Å peak reduced in intensity from that generated after simple air-drying. However, virtually all other samples showed the expected enhancement of the 14 Å peak. It is interesting to note that with many of the samples (of all categories), the 10 Å (illite) peak was reduced in intensity and the large peak at about 3.36 Å experienced a significant increase in intensity, following the 550°C heat treatment.

Diffractograms for the dust samples are

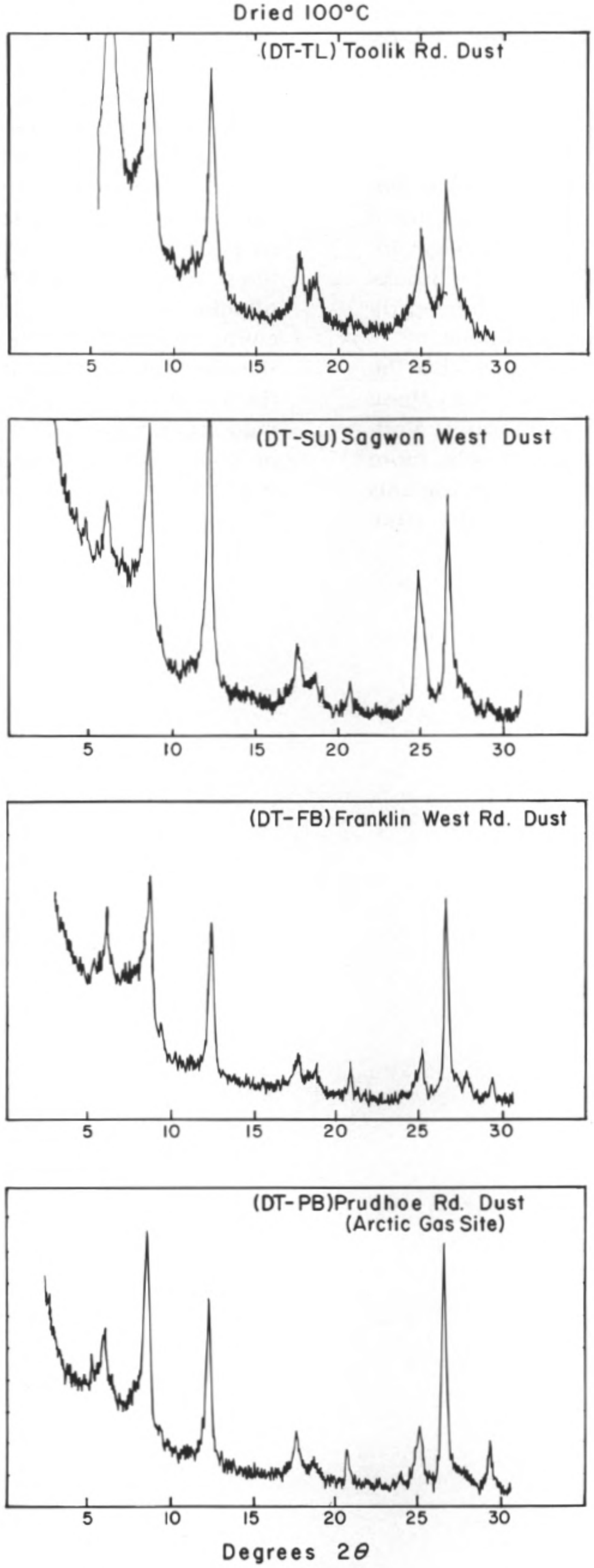


Figure E-1. X-ray diffractograms of road dust dried at 100°C.

shown in Figure E1. The complete set of diffractograms for all samples listed in Table E1 is on file at CRREL.

Interpretations and conclusions

The fact that the bedrock, road material, and material site samples all have the same clay mineralogy is not surprising. Most of the road material came from gravel deposits of the Sagavanirktok River which are derived from the Brooks Range. The alluvial fan material is derived directly from bedrock of the Brooks Range.

The tundra soil clay mineralogy is also the same as that of the other samples. Had these soils developed in place, one might expect a different mineralogy such as, for example, more montmorillonite. The tundra soil diffractograms had good sharp peaks, indicating good crystallinity. However, the failure of the chlorite 001 (14 Å) peak to be enhanced after the 550°C heat treatment indicates that the soil chlorite is less well crystallized than chlorite in the other samples. This difference is interpreted as indicating that the soils are in fact derived from transported material of Brooks Range origin, the chlorite having degraded or weathered somewhat since deposition of the soil material. Of interest also is the restriction of discrete montmorillonite to three samples, all located in the vicinity of Prudhoe Bay. These were all road samples, and the presence of montmorillonite in them is interpreted as being the result of drilling mud contamination. Drilling mud is rich in bentonite (and thus montmorillonite) and the mud had been spread to control road dust.

APPENDIX F. LIST OF REPORTS IN THE JOINT STATE/FEDERAL FISH AND WILDLIFE ADVISORY TEAM SERIES

Special Reports 1-24, listed by publication number

1. Van Ballenberghe, V. (1976). First interim report of the moose-pipeline technical evaluation study.
2. Cameron, R.D. and K.P. Whitten (1976). First interim report of the effects of the trans-Alaska pipeline on caribou movements.
3. Hemming, J. and K. Morehouse (1976). Wildlife atlas: Trans-Alaska oil pipeline, Prudhoe Bay to Valdez.
4. Francisco, K. (1976). First interim report of the commercial fish technical evaluation study.
5. Wendling, F.L. (1976). Preliminary report on gravel porosity studies along the trans-Alaska pipeline.
6. Bendock, T. (1974). First interim report of the sport fish technical evaluation study.
7. Hallberg, J. (1975). Second interim report of the sport fish technical evaluation study.
8. Cameron, R.D. and K.P. Whitten (1977). Second interim report of the effects of the trans-Alaska pipeline on caribou movements.
9. Francisco, K. (1977) Second interim report of the commercial fish technical evaluation study.
10. Van Ballenberghe, V. Second interim report on the effects of the trans-Alaska pipeline on moose movements.
11. List of designated wildlife crossings for the trans-Alaska oil pipeline, (August 1977).

11A. List of designated wildlife crossings for the trans-Alaska oil pipeline, (December 1977).

12. Kavanagh, N.L. (1977). Interagency approach to environmental surveillance: a history and evaluation of the Joint State/Federal Fish and Wildlife Advisory Team.
13. Burger, C. and L. Swenson (1977). Environmental surveillance of gravel removal on the trans-Alaska pipeline system with recommendations for future gravelmining.
14. Milke, G. (1977). Animal feeding: Problems and solutions.
15. Kavanagh, N. and A. Townsend (1977). Construction-related oil spills along trans-Alaska pipeline.
16. Gustafson, J (1977). Evaluation of low water crossings at fish streams along the trans-Alaska pipeline system.
17. Francisco, K. and W.B. Dinneford (1977). Third interim report on the commercial fish technical evaluation study: Salcha River.
18. Wendling, F.L. (1978). Final report on gravel porosity studies along the trans-Alaska pipeline.
19. Franciso, K. and W.B. Dinneford (1977). Fourth interim report of the commercial fish technical evaluation study: Tanana and Delta Rivers.
20. Dinneford, W.B. (1978). Final report of the commercial fish technical evaluation study: Tanana and Delta Rivers.
21. Dunnefort, W.B. (1978). Final report of the commercial fish technical evaluation study: Salcha River.
22. Cameron, R.D. and K.R. Whitten (1978). Third interim report of the effects of the trans-Alaska pipeline on caribou movements.
23. Van Ballenberghe, V. (1978). Final report on the effects of the trans-Alaska pipeline on moose movements.
24. Pamplin, W. Jr. (1979) Construction-related impacts of the trans-Alaska pipeline system on terrestrial wildlife habitats.

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