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Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Since the 1968 discovery of huge oil reserves in Prudhoe Bay, Alaska's North Slope has been a site of oil exploration and production that, by the end of 2002, had produced about 14 billion barrels (558 billion gallons) of crude oil. North Slope oil currently averages about 15% of total annual domestic oil production of approximately 3.3 billion barrels and 7% of the annual domestic consumption of approximately 7 billion barrels. Active exploration on the arctic coastal plain is now expanding incrementally westward into the National Petroleum Reserve-Alaska, eastward toward the Arctic National Wildlife Refuge, and south toward the foothills of the Brooks Range (see Figure 1).

Northern Alaska's environment and culture have already been significantly affected by oil infrastructure and activities. There have been many benefits to North Slope residents including more jobs and improved hospitals and schools. These economic benefits have been accompanied by environmental and social consequences, including effects of the roads, infrastructure and activities of oil exploration and production on the terrain, plants, animals and peoples of the North Slope and the adjacent marine environment.

Although a large body of research has assessed actual and potential effects of oil and gas activities and infrastructure, no integrated, comprehensive analysis of *cumulative* effects has previously been attempted. Cumulative effects can result from individually minor but collectively significant actions taking place over a period of time or within an area. In response to a request from Congress, the National Academies convened the Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope to assess probable cumulative effects of oil and gas activities on various receptors—that is components of the physical, biological, and human systems of the region. The committee's consensus report assesses both present and likely future cumulative effects on the North Slope and adjacent marine waters for the time period of 1965 to 2025 (in some cases to 2050).

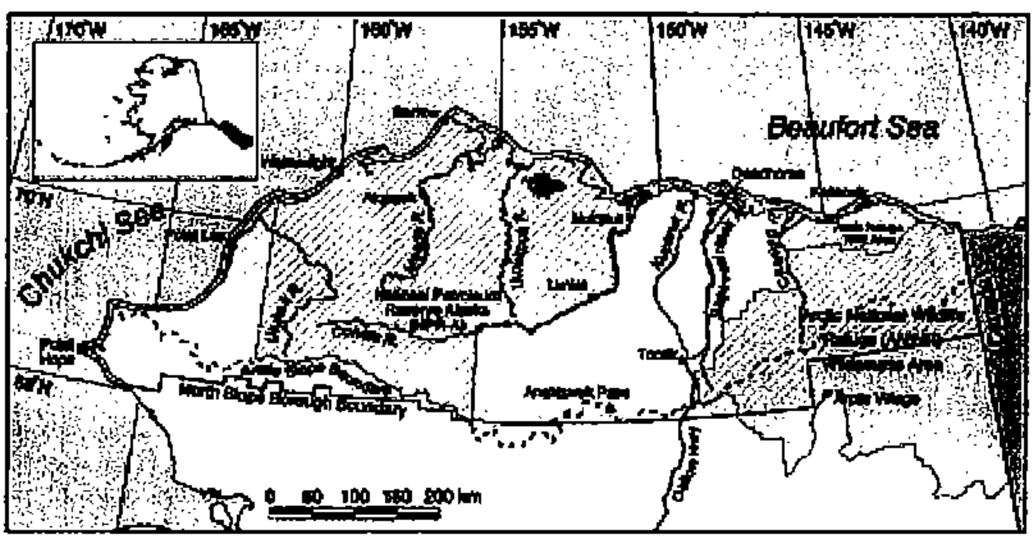

Figure 1. The North Slope (the Arctic Slope) extends from the crest of the Brooks Range to the Arctic Coast, from the Canadian border to Point Hope. Industrial activity has grown from a small operational oil field at Prudhoe Bay to an industrial complex stretching from the Alpine field near the mouth of the Colville River on the west to Badami on the east.

Accumulated Effects To Date

Unlike other U.S. oil fields, those on the North Slope are underlain by permafrost— a thick layer of earth material that stays frozen year round. The permafrost is covered by a thin active layer that thaws each summer and supports plant growth for a brief period. If permafrost thaws, the ground surface and the structures it supports will settle. To minimize disruption to the ground surface, the North Slope industrial infrastructure is specially built—pipelines are generally elevated rather than buried, and roads and industrial facilities are raised on thick gravel berms.

For a variety of reasons, nearly all of the roads, pads, pipelines and other infrastructure ever built are still in place. The environmental effects of such structures on the landscape, water systems, vegetation, and animals are manifest not only at the "footprint" itself (physical area covered by the structure) but also at distances that vary depending on the environmental component being affected. The petroleum industry continues to introduce technological innovations to reduce its footprint, for example, directional drilling and the use of ice roads and pads, drilling platforms, and new kinds of vehicles.

For some areas of concern, the committee found no evidence that effects have accumulated. For example, despite widespread concern regarding the damaging effects of frequent oil and saltwater spills on the tundra, most spills to date have been small and have had only local effects. Moreover, damaged areas have recovered before they have been disturbed again. However, a large oil spill in marine waters would likely have substantial accumulating effects on whales and other receptors because current cleanup methods can remove only a small fraction of spilled oil, especially under conditions of broken ice.

For other areas of concern, effects have accumulated, although in some cases efforts by the petroleum industry and regulatory agencies have reduced them. The committee identified the following areas in which there was evidence of effects that have accumulated.

Roads. Roads have had effects as far-reaching and complex as any physical component of the North Slope oil fields. In addition to their direct effects on the tundra, indirect effects are caused by dust, roadside flooding, thawing of permafrost, and roadside snow accumulation. Roads and activities on them also alter animal habitat and behavior and wildland values and can increase access of hunters, tourists, and others to previously inaccessible parts of the region; enhance communication among communities; and increase contacts between North Slope communities and those outside the area.

Damage to Tundra from Off-Road Travel. Surface erosion, water flow and tundra vegetation on the North Slope have been altered by extensive off-road travel. Some damage has persisted for decades. The current 3-dimensional survey method requires a high density of seismic-exploration trails. Networks of these trails now cover extensive areas and are readily visible from the air, degrading visual experiences of the North Slope. Despite technological improvements and increased care taken by operators, the potential for damage to the tundra still exists because of the large number of vehicles and camps used for exploration.

Effects on Animal Populations. Bowhead whales' fall migrations have been displaced by the noise of seismic exploration. Garbage and food provided by people working in oil fields have resulted in higher than normal densities of predators (such as brown bears, arctic foxes, ravens, and glaucous gulls) that prey on the eggs, nestlings, and fledglings of birds. As a result, the reproduction rates of some bird species such as black brant, snow geese, eiders, and probably some shorebirds in industrial areas are, at least in some years, insufficient to balance death rates. These populations may persist in the oil fields only because of immigration of individuals from source areas where birth rates exceed death rates.

The combined effects of industrial activity and infrastructure and the stress imposed by insects in some summers reduced calf production in the Central Arctic caribou herd and may have contributed to the reduction in herd size from 1992 through 1995. In contrast, the herd increased in size from 1995 to 2001, when insect activity was lower. Although accumulated effects have not prevented an increase in the overall size of the Central Arctic Herd, the spread of industrial activity into other areas caribou use for calving and insect relief, especially to the east where the coastal plain is narrower, would likely affect reproductive success, unless the degree to which it disturbs caribou can be reduced.

Interactions of Climate Change and Oil Development. Global and regional climates have changed throughout the Earth's history, but climate changes during the past several decades on the North Slope have been unusually rapid. If recent warming trends in climate continue, as many projections indicate, the effects will accumulate over the next century to alter the extent and timing of sea ice, affect the distribution and abundance of marine and terrestrial plants and animals, and affect permafrost as well as the usefulness of current oil-field technologies and how they affect the environment.

Interference with Subsistence Activities. The Inupiat Eskimo people of the North Slope have a centuries-old nutritional and cultural relationship with the bowhead whale. Most view offshore industrial activity—both observed effects and the possibility of a major oil spill—as a threat to the bowhead whale and, thereby, to their cultural survival. Because noise from exploratory drilling and marine seismic exploration have caused fall migrating bowhead whales to change their movements, subsistence hunters have been forced to travel greater distances to find whales, increasing their risk of exposure to adverse weather and the likelihood that a whale's tissues will have deteriorated before the carcass can be landed. Recent agreements concerning the timing and placement of exploration in the fall have reduced the effects on subsistence hunters.

The Gwich'in Indians of northeast Alaska and northwest Canada have a centuries-old nutritional and cultural relationship with the Porcupine Caribou Herd. Most Gwich'in oppose any oil development that would threaten the herd, especially on the calving ground, which they consider sacred, and thereby threaten their cultural survival. These threats have accumulated because repeated attempts to develop areas used by the herd have occurred and will probably continue to occur.

Social Changes in North Slope Communities. Most North Slope residents have positive views of many of the economic changes that have resulted from revenue generated by petroleum activities, such as access to better medical care, availability of gas heat for houses, improved plumbing, and higher personal incomes. At the same time, however, balancing the economic benefits of oil activities against the accompanying loss of traditional culture and other societal problems that can occur is often a dilemma for North Slope residents. Without this revenue, the North Slope Borough, the Alaska Native Claims Settlement Act, and hence the Arctic Slope Regional Corporation, would not exist or, if they did, would bear little resemblance to their current form. This discovery of oil and its development on the North Slope has resulted in major, important, and probably irreversible changes to the way of life in communities. These effects accumulate because they arise from several ongoing, interacting causes.

Cumulative Aesthetic, Cultural, and Spiritual Consequences. Many activities associated with oil development have compromised wildland and scenic values over large areas. Some Alaska Natives told the committee that they violate what they call "the spirit of the land," a value central to their relationship with the environment. These consequences have increased in proportion to the area affected by development, and they will persist as long as the landscape remains altered.

Future Accumulation of Effects

The committee assessed possible future accumulation of effects, assuming conditions favorable to continued expansion of oil and gas activities using technology and regulatory oversight at least as good as those currently used.

Response of North Slope Cultures to Declining Revenues. For North Slope residents, the current way of life of North Slope communities made possible by oil and gas activities will be more difficult to maintain when these activities cease as oil is depleted because other sources of funds appear to be modest. Eventual adjustments to reduced financial resources are unavoidable. Their nature and extent will be shaped by adaptations North Slope communities have made to the accumulated effects of the cash economy.

Legacy of Abandoned Infrastructure and Unrestored Landscapes. The network of roads, pads and pipelines, and infrastructure that support production will likely remain in place for many years to come. The oil industry and regulatory agencies have made dramatic progress in reducing the effects of new gravel fill by reducing the size of the gravel footprint required for many types of facilities and substituting ice for gravel for certain types of roads and pads. However, much less attention has been directed to restoring already disturbed sites. To date, only about 1% of the habitat on the North Slope affected by gravel fill has been rehabilitated.

With the exception of well-plugging and abandonment procedures, state, federal, and local agencies have largely deferred decisions regarding the nature and extent of restoration that will be required. Because the obligation to restore sites is unclear, and the costs of dismantlement, removal, and restoration are likely to be very high, the committee judges it unlikely that most disturbed habitats on the North Slope will be restored. Because natural recovery in the Arctic is slow, the effects caused by abandoned and unrestored infrastructure are likely to persist for centuries and could accumulate further as new structures are added.

Expansion of Activities into New Areas. Expansion of oil and gas exploration is spreading into hillier terrain and into coastal plain areas with soils, vegetation and aquatic environments that differ substantially from current areas of activity. To assess effects in these environments, they should be characterized through description of topography, permafrost conditions, sand, gravel, and water availability, hydrological conditions, and a description of the biotic communities present. In addition, future exploratory activity will probably be carried out in a warming climate, with milder winter temperatures and shorter periods of freezing conditions.

> [illegible] the National Petroleum Reserve-Alaska, and the Arctic National Wildlife Refuge

Filling Knowledge Gaps

As industrial activities proceed, it is vital to continue collecting and analyzing information on the North Slope's physical, biological, and human environments to help decision makers in developing and implementing effective natural resources management. Advantage should be taken of opportunities to learn from these activities (adaptive management).

Decisions about where, when, and under what conditions and requirements industrial activities are permitted on the North Slope are made by many different federal, state, regional, and municipal government agencies. To date, decisions have generally been made without a comprehensive slope-wide plan and regulatory strategy that identify the scope, intensity, direction and consequences of industrial activities judged acceptable. A comprehensive framework and plan should be developed for the North Slope so that actions can be evaluated with respect to their compatibility with overall goals, the likely effects of individual activities on all receptors that might be affected by them, and the likelihood that the activities will result in long-term or difficult-to-reverse undesirable effects. Knowledge gaps should be addressed through the following:

- Ecosystem-level research in addition to local ecological studies.
- Studies to understand the types of effects that exist at varying distances beyond the footprint of industrial structures.
- Studies of air pollution that provide a quantitative baseline of spatial and temporal trends in air quality over long periods across the North Slope.
- Studies of effects of seismic exploration and other off-road use on the tundra.
- Research on habitat requirements of caribou, their reproductive physiology and movements, and how natural and anthropogenic disturbance affects them.
- Studies of the effects of noise on the migratory and acoustic behavior of bowhead whales and on their feeding habits in the Alaskan portion of the Beaufort Sea.
- Studies of effects of taking water from lakes on the North Slope for ice roads, pads, and other purposes.
- Studies of methods to reduce effects of oil spills including non-mechanical methods of cleaning up oil spilled in the sea, especially in broken ice.
- Research on the specific benefits and threats that North Slope residents perceive.
- Studies of effects of oil and gas activities on human health including studies of increased use of alcohol and drugs, increased obesity, and other societal ills.

This summary was prepared by the National Research Council based on the committee's report. For more information: Contact the National Research Council's Board on Environmental Studies and Toxicology at 202-334-3060. *Cumulative Environmental Environmental Effects of Oil and Gas on the North Slope* is available from the National Academies Press, Fifth Street, NW, Washington, DC 20001; 800-624-6242 or 202-334-3313 (in the Washington area); http://www.nap.edu.

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Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Committee on the Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Board on Environmental Studies and Toxicology

Polar Research Board

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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Preface

Since production began on Alaska's North Slope in the early 1970s, about 14 billion barrels of oil have been extracted from underground deposits and sent to markets elsewhere. As much as 20 billion additional barrels of oil might be extracted from the area. In addition, the region has huge reserves of natural gas and coal. Therefore, if market conditions remain favorable, exploration and extraction are likely to continue on the North Slope and to expand into areas that have until now been uninfluenced by industrial activity.

The residents of Alaska and throughout the United States have benefited from oil and gas production on the North Slope, but, as with all industrial developments, these activities have brought with them social and environmental costs. Although research has been carried out on the North Slope during the past several decades to understand the effects of oil and gas exploration, development, and production, an integrated, comprehensive assessment of those effects has not been attempted. Understanding the nature, extent, and causes of both the benefits and costs is an essential component of effective, long-term decision-making about resource management on the North Slope.

To rectify this gap in knowledge, the United States Congress asked the National Research Council to review information about oil and gas activities on Alaska's North Slope and to assess their known and probable future cumulative effects on the physical, biological, and human environment. The NRC established a committee whose 18 members had expertise in a wide range of disciplines, including geology, hydrology, physics of permafrost, biology, sociology, anthropology, and economics. In making its assessments, the committee relied on its collective expertise, extensive literature review, information gathered during public meetings held in various places in Alaska, and written materials supplied by many individuals and organizations.

The task undertaken by the committee was difficult. The area of concern—from the crest of the Brooks Range to the Arctic Ocean and from the Canadian border on the east to the Chukchi Sea on the west—is about the size of Minnesota. It includes the continental shelf and coastal waters, flat coastal tundra, undulating foothills, rivers, lakes, and mountain slopes. Industrial activity has affected primarily the area between the Canning River and the eastern part of the National Petroleum Reserve-Alaska, but more of the North Slope could be influenced by future developments. During the several decades over which industrial activities expanded on the North Slope, technological advances dramatically changed how the industry operated and how it influenced the North Slope environment. There is every reason to believe that technical innovations will continue in the future, adding to the difficulty of making projections of future cumulative effects. In addition, the climate of the North Slope has warmed considerably during the past several decades, and the rate of warming is likely to accelerate in the future. Climate change is likely to influence nearly all aspects of industrial activity in the area and the effect of those activities on the environment.

Because of the complexity of its task, the committee met eight times. Members visited the North Slope during both winter and summer conditions. Its sessions sometimes lasted as long as a week, during which there were extensive in-depth discussions of the available data and their interpretation. Considerable work was carried out between meetings by both committee members and NRC staff. Despite the highly varied professional backgrounds, knowledge, and perceptions of the committee members, candor, mutual respect, and collegiality dominated the committee's proceedings. This spirit of cooperation made this consensus report possible.

The committee was ably assisted by staff of the Board on Environmental Studies and Toxicology (BEST) and the Polar Research Board (PRB), the two NRC boards under whose auspices the study was carried out. The efforts and experience of David Policansky (BEST) and Chris Elfring (PRB) assisted the committee in numerous ways and helped keep us on track. James Reisa (BEST) provided his usual thoughtful advice. Logistical, informational, and other invaluable support was provided by BEST staff members, especially Leah Probst, Jessica Brock, Dominic Brose, Margaret Walsh, and Suzanne van Drunick. Walter Gove provided much useful information to the committee, as did the many people who made presentations to the committee and helped us on our visits (please see Appendix B for list of participants in our meetings).

Many people made our task possible by providing information, hospitality, and logistic support. We thank the governments and people of Arctic Village, Barrow, Kaktovik, and Nuiqsut for their kindness, as well as members of the North Slope Borough. We thank representatives of the oil industry for sharing information and logistic support, in particular Joseph Hegna of Phillips Petroleum and Bill Streever and Steve Taylor of BP. Theodore (Ted) Rockwell, Lisa Morales, and Tracy Nadeau of EPA provided advice, encouragement, and information to the committee while serving as the sponsoring agency's technical representatives. We also thank the other state and federal agencies and members of the public who provided us with information, guidance, and assistance.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John Bailar, University of Chicago (emeritus) (review monitor) and Wilford Gardner, University of California, Berkeley (emeritus) (review coordinator). Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Important though it is to identify and assess the nature of cumulative effects and their causes, the committee recognizes that this knowledge, by itself, cannot specify public policy. Nonetheless, without such analyses, decision-makers lack a background against which to evaluate the assertions of different groups that have specific benefits to gain from policies or who are likely to bear the brunt of costs. The committee has identified the most important cumulative effects of oil and gas development on the North Slope and has attempted to show why they have happened. The committee has also concluded that some effects have been much less important than they are widely believed to be. Therefore, this report should help focus future discussions on the major cumulative effects of industrial development on the North Slope. It should also direct attention to the inevitable tradeoffs that must be balanced when choosing future management options and the rules and regulations under which they will be carried out. If this report serves that purpose, we will all consider ourselves suitably rewarded for our efforts.

Gordon H. Orians
Chair, Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

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Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope

Summary

Oil fields on land and off the coast of Alaska's North Slope, including the Prudhoe Bay field, have produced about 14 billion barrels (bbl) of crude oil through the end of 2002 (one barrel equals 42 U.S. gal or 159 L). North Slope oil has averaged about 20% of U.S. domestic production since 1977, and it currently provides about 15% of the annual domestic production of approximately 3.3 billion bbl and 7% of the annual domestic consumption of approximately 7 billion bbl. If production of the large reserves of natural gas in the region were to become economically feasible, the strategic and economic importance of the North Slope's hydrocarbon energy resources would be even greater.

Oil and gas production on the North Slope has brought positive and negative consequences—economic, social, and environmental. Environmental consequences of concern include the effects of oil-related structures and activities on the migration of fish and marine and terrestrial mammals, especially bowhead whales and caribou. Concerns have also been raised about the risk of toxic contamination of plants and animals used for food by Alaska Natives, effects of oil and gas exploration and development on tundra and marine ecosystems, and effects of oil spills on marine and coastal ecosystems. Also of concern are the effects of oil activities and structures on endangered or threatened species, migratory birds, polar bears and other mammals, and on wildland (wilderness) values. Some of the socioeconomic changes resulting from oil and gas development, including those involving employment, lifestyles, health, and other aspects of people's lives, also have been of concern.

Considerable research has been done on various actual and potential effects of oil and gas activity on the North Slope's physical, biotic, and human environments. Reviews of this research have appeared in environmental impact statements (EISs), in reports funded by the Department of the Interior and other federal and state agencies, in oil industry publications, in journals, and in National Research Council reports, among others. However, there has been little assessment of the *cumulative* effects of those activities, the elucidation of which is critical to support informed, long-term decision-making about resource management. To address this lack of information and understanding, the Congress requested that the National Academies review and assess what is known about the cumulative environmental effects of oil and gas activities on Alaska's North Slope.

THE PRESENT STUDY

In response to the request from Congress, the National Academies established the Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North

Slope, which prepared this report. The committee was directed to review information about oil and gas activities (including cleanup efforts) on the North Slope and, based on its review, to assess the known and probable cumulative impacts of such activities on the physical, biotic, and human environments of the region and its adjacent marine environment. The committee also was directed to assess likely future cumulative effects, based on its judgment of probable changes in technology and the environment, under a variety of scenarios for oil and gas production, and in combination with other probable human activities, including tourism, fishing, and mining. Although the cumulative effects of North Slope oil and gas activities—especially production—extend beyond the region, the committee's focus was confined to Alaska's North Slope and as far into the Arctic Ocean as there is evidence of environmental effects.

The committee met eight times over the course of its two-year study. In Alaska, it met in Anchorage, Fairbanks, Barrow, Nuiqsut, Arctic Village, and Kaktovik. It heard from federal and state agencies, representatives of the oil and gas industry, environmental organizations, and officials and community members of the North Slope Borough and the municipalities it visited. It toured the oil facilities at Prudhoe Bay, Endicott, and Alpine, and flew over the Arctic National Wildlife Refuge, the National Petroleum Reserve-Alaska, Kuparuk, and the Northstar production facility. It also held meetings in executive session to write the report. Appendix A lists those who participated in the meetings.

UNDERSTANDING AND ASSESSING CUMULATIVE ENVIRONMENTAL EFFECTS

The basic issue of cumulative-effects assessment is that when numerous small decisions about related environmental matters are made independently, the combined consequences of those decisions are often not considered. The result is that patterns of the environmental perturbations or their effects over large areas and long periods are not analyzed.

The committee has followed the generally accepted approach to identifying and assessing cumulative effects that evolved after passage of the National Environmental Policy Act (NEPA) of 1969. The NEPA requires federal agencies to develop EISs for many major projects. If a project—and its EIS—is considered in isolation from similar projects or separately from diverse projects in the same area, some cumulative effects are likely to be missed. In 1978, the Council on Environmental Quality promulgated regulations to implement the NEPA that are binding on all federal agencies. A cumulative effect was defined as "...the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions....Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." The practice of cumulative-effects assessment arose to address such problems.

In interpreting the broad charge of assessing cumulative effects, the committee focused on whether the effects under consideration interact or accumulate over time and space, either through repetition or in combination with other effects, and under what circumstances and to what degree they might accumulate. As an example, consider a repeated environmental insult that is localized in space and occurs so infrequently that natural processes of recovery or human efforts can eliminate its effects before another insult occurs. In this case, one would conclude that the effects of the insult do not accumulate (rather than concluding that the insult is not "a cumulative effect"). This approach also directs attention to the circumstances under which effects might accumulate.

Although the assessment of cumulative effects has a history of several decades, doing it well remains challenging and complex, because a full analysis of how and when such effects accumulate requires the synthesis of multiple individual assessments. To address this problem, the committee developed a general process to identify how effects accumulate with respect to different receptors, i.e., the organisms, communities, and environments that are affected. The key elements are: (a) specify the class of actions whose effects are to be analyzed; (b) designate the time and space scales over which the relevant actions take place; (c) identify and characterize the receptors whose responses to the actions are to be assessed; and (d) determine the magnitude of the effects on the different receptors and whether they are accumulating or interacting with other effects.

At the most general level, the class of actions considered by the committee consisted of all activities associated with oil and gas development. The spatial area was the Alaska Arctic Slope and adjacent marine waters. The temporal period was 1965 to 2025, and the receptors were the physical, biological, and human systems of the region.

Effects typically accumulate as the result of repeated activities of similar or different types. However, in some cases the effects of a single action or event can accumulate. This is especially true if the effects persist for a long time and are augmented by the effects of other activities.

Beyond simply identifying the accumulation of effects, their magnitude and their biotic and socioeconomic importance must be assessed. The committee assessed biotic and socioeconomic importance separately for each receptor. The importance of effects is perceived differently by different individuals or groups. The committee is not aware of a satisfactory way of attributing some absolute degree of importance to effects, and so it attempted to describe the basis on which it assessed the importance of the effects. For example, in assessing importance, the committee considered factors such as ecological consequences, importance attributed by North Slope residents, economic consequences for North Slope residents, irreversibility, and degree of controversy.

OVERVIEW OF THE NORTH SLOPE ENVIRONMENT

Climate

The North Slope—or Arctic Slope—of Alaska is the 230,000 km^2 (89,000 mi^2) region north of the crest of the Brooks Range, an area slightly larger than Minnesota (Figure S-1). It encompasses the drainage basins that empty into the Beaufort and Chukchi Sea. The land slopes gradually from the crest of the rugged Brooks Range northward to the Arctic Ocean. Summer temperatures on the coastal plain are usually between 5 and 15 °C (40-60 °F); they can be higher for short periods, especially inland. Winter temperatures are usually below minus 18 °C (0 °F) and sometimes below minus 40 °C (minus 40 °F). From November 18 to January 24, the sun never rises above the horizon at Barrow, but there is a little midday twilight. The sun does not set from May 10 until August 2. Annual precipitation ranges from 12 to 20 cm (5-8 in.) in coastal and foothill areas and up to 100 cm (40 in.) in the highest elevations of the Brooks Range. Extensive areas are covered by thaw lakes, ice-wedge polygons, frost boils, water tracks, bogs, and other features typical of permafrost regions. Snowfall is difficult to measure accurately, but

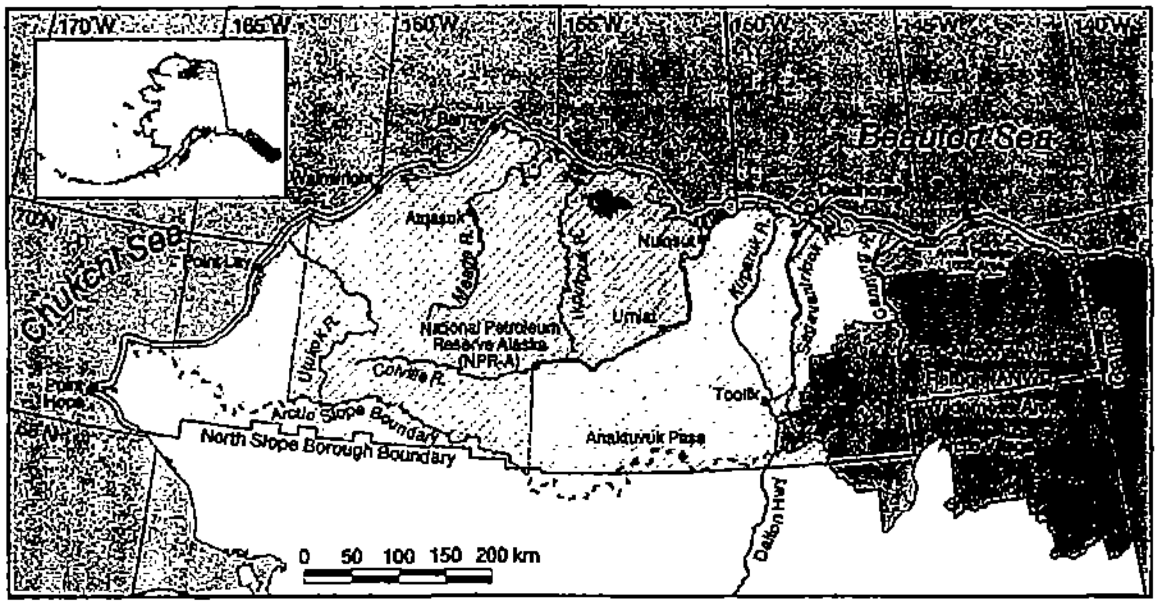


FIGURE S-1. The Alaska North Slope region. The dashed line is the southern boundary of the drainage basin. The Trans-Alaska Pipeline is close to the Dalton Highway. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

probably averages less than 50 cm (20 in.) in most coastal areas and more than 2 m (80 in.) in some mountain areas.

Permafrost

Alaska's North Slope is underlain by permafrost, earth material whose temperature stays below freezing year-round. Along the Arctic coast, the permafrost extends to depths of 200-650 m (650-2,100 ft), the deepest occurring near Prudhoe Bay. Permafrost is important primarily because its groundwater generally occurs as ice, often in massive forms. If the ice melts, the ground surface can become unstable and can subside substantially. Thus permafrost poses special problems for the development of industrial infrastructure and the preservation of natural systems.

Permafrost is separated from the ground surface by an active layer that thaws each summer to depths ranging from 20 cm (8 in.) to more than 2 m. The active layer sustains tundra plants, which in turn sustain animals and control processes of surface erosion and water flow.

Changes in surface conditions, such as disruption of the insulating organic mat or impoundment of surface water, can cause the surface to settle and create thermokarst—a disruption of the tundra's surface associated with warming and thawing of permafrost. This process is difficult to reverse and has ecological effects as well as effects on structures. To maintain permafrost, activities on the tundra must be controlled carefully, and buildings, roads, and other structures must be designed to avoid thawing their own foundations. Special conditions exist offshore where development takes place on deep permafrost warmed by the sea to temperatures close to melting. Engineering designs for the infrastructure might eventually have to be reconsidered if North Slope climates warm as predicted in the twenty-first century.

Geomorphology

The North Slope is divided into three major regions: the arctic coastal plain, the arctic foothills, and the Brooks Range. To date, all oil production has occurred on the coastal plain, but there is increasing exploration in the foothills. The only directly influenced area in the Brooks Range is the corridor for the Trans-Alaska Pipeline, which crosses those mountains at Atigun Pass.

Surface Water

The Arctic coastal plain is generally flat, with large thaw lakes (formed when the tundra surface thaws in summer) and extensive wetlands that are important habitat for waterfowl and shorebirds. Lakes and ponds are among its most striking landforms. Most lakes in the developed oil-field region between the Sagavanirktok and Colville rivers are shallow, typically less than 6 ft (1.8 m) deep. Lakes are deeper to the west and south, with mean maximum depths of more than 30 ft (9 m) in lakes south of Teshekpuk Lake, the largest lake on the coastal plain (816 km^2 or 315 mi^2). Lakes on the coastal plain are typically ice-covered from early to mid-October until early July. During winter, flow ceases in the region's many rivers, and ice develops to a thickness of about 1.8 m (6 ft). Spring break-up begins in the Brooks Range and foothills, which warm more rapidly than does the coastal plain. During this time, the lower reaches of rivers are frozen, and the tundra is still snow-covered. Thus, there is substantial ice-jamming and over-bank flooding.

Terrestrial Biota

The Arctic Coastal Plain has the largest expanse of arctic fens (mineral-rich, sedge-covered wetlands) and thaw lakes in the world, and the foothills comprise the largest expanse of tussock tundra (tundra dominated by the cottongrass *Eriophorum vaginatum*) in the world.

The most important consumers of living and dead plant tissues in terrestrial arctic tundra are mammals, birds, arthropods, and nematodes. The mammals include caribou, moose, muskoxen, grizzly bears, foxes, and wolves. Most bird species that breed in Alaska north of the Brooks Range nest in tundra habitats, associated wetlands, or adjacent marine lagoons. The dominant groups, both in the number of species and in their abundance, are waterfowl—ducks, geese, and swans—and shorebirds. Loons and some other species are of concern because their populations are generally declining elsewhere in and outside Alaska.

No cold-blooded terrestrial vertebrates can survive the arctic cold; birds and mammals are the only terrestrial vertebrates. The most abundant and important terrestrial invertebrates are insects. In fresh water, most fish species spend their lives in rivers and lakes, although some migrate between fresh water and coastal marine waters.

Marine Ecology

The nearshore marine environment contains three main aquatic habitats: delta fronts (places where fresh water from river deltas meets coastal marine water), coastal lagoons, and open coast. Some areas of the coast are open and directly exposed to the wind, wave, and current action of the Arctic Ocean. Other stretches of the shore are protected by chains of barrier islands.

The sea is usually covered in ice from November through June. High rates of primary productivity are normally associated with the ice edge and areas of upwelling.

The Arctic Ocean supports a specialized biotic community, despite its low biological productivity. However, especially near the coast, there is relatively high primary productivity because of the ice edge and upwelling.

More than 100 phytoplankton species have been identified from the Beaufort Sea, mostly diatoms, dinoflagellates, and flagellates. The zooplankton is dominated by herbivorous copepods; amphipods, mysids, euphausiids, ostracods, decapods, and jellyfish also are present. Kelp communities and benthic invertebrates are important components of the marine ecosystem.

Twenty-nine species of fish are regularly found in freshwater and nearshore habitats of the North Slope. Most marine species inhabit deeper offshore waters and are rarely found in the North Slope coastal zone. Marine mammals include three truly arctic species (ringed seals, bearded seals, and polar bears), and four principally subarctic species (spotted seals, walrus, beluga whales, and bowhead whales) that move into the area seasonally from the Bering and Chukchi seas.

The Human Environment

Alaska's North Slope is one of the most extreme environments in which humans live and work. The social organization of Alaska Natives centers on group subsistence activities and on an extensive network that shares subsistence harvests. Cultural knowledge and practices of North Slope Alaska Natives have been refined over many generations in an environment where one bad decision can lead to individual deaths or even to starvation of an entire village.

Initial contact with Western culture came in the mid-nineteenth century, when the area was first visited by commercial whalers and Protestant missionaries. Steady-wage jobs were first introduced with the U.S. Navy's petroleum exploration on the North Slope in the 1940s; construction of distant early warning radar sites in the 1950s also provided some employment. But even with these sources of income, wage-earning jobs on the North Slope were scarce throughout the 1950s and 1960s, and subsistence activities were the main source of food for most families.

North Slope Human Cultures in the Oil Era

The announcement in 1968 of the discovery of oil at Prudhoe Bay—the largest oil field in North America—catalyzed changes that affected the human environment of the North Slope and increasingly moved North Slope residents into the mainstream economy. The enactment of the Alaska Native Claims Settlement Act in 1971 established the Arctic Slope Regional Corporation and the village corporations. The North Slope Borough was established in 1972. The extremely rural nature of the North Slope Borough and the isolation of its small communities influence the nature and extent of the effects of oil and gas activities.

Environmental Limitations on Human Activities

The physical environment of the North Slope shapes and limits the ways that human communities operate. Agriculture and forestry are impossible; wood for construction is locally available only as driftwood in coastal areas. Most of the travel between communities on the North Slope, or between those communities and subsistence-hunting areas, occurs by air, by snow machine in the winter when the tundra is frozen, or by water in the summer. Transportation beyond the region is almost entirely by air.

The costs of transportation and of goods that must be transported to the North Slope are considerably higher than in the rest of Alaska or the continental United States. Because North Slope residents do not have greater incomes per capita than do some of their counterparts in Alaska, and those in the United States in general, they must either have a lower standard of living or rely to a greater extent on subsistence harvest, or both.

FINDINGS

The committee's unanimous findings and recommendations are presented in two sections. This one is an evaluation of major effects and how they accumulate. The next section provides recommendations for filling knowledge gaps.

Growth of Industrial Activity

Industrial activity on the North Slope has grown from a single operational oil field at Prudhoe Bay to an industrial complex of developed oil fields and their interconnecting roads, pipelines, and power lines that stretches from the Alpine field in the west to Badami in the east (Figure S-2). A highway and pipeline cross the state from near the Arctic coast. This network has grown incrementally as new fields have been explored and brought into production. For many reasons, nearly all of the roads, pads, pipelines, and other infrastructure are still in place and are likely to remain so for some time. The environmental effects of such structures are manifest not only at the "footprint" itself (the area physically covered by the structure), but also at distances that vary depending on the environmental component affected. Effects on hydrologic processes, vegetation, and animal populations occur at distances of up to a few miles (several kilometers) from the physical footprint of a structure. Effects on wildland values—especially visual ones—extend much farther, as can the effects on marine mammals of sound caused by some offshore activities. All visual effects due to the structures and associated activities will persist as long as the structures remain, even if industrial activity ceases. They will accumulate with expanded activity.

Regulatory oversight can be critical in reducing the accumulation of undesirable effects. The committee's predictions of future effects and their accumulation assume that regulatory oversight will continue at least to the extent of the recent past.

Interactions of Climate Change and Oil Development

Global and regional climates have changed throughout the Earth's history, but climate changes during the past several decades on the North Slope have been unusually rapid. Animals and plants evolve and change their ranges in response to environmental changes. Humans have migrated in and out of the area, and their cultures—including social, economic, and legal elements of those cultures—have changed as well. Those changes complicate and confound the assessment and isolation of the effects of oil and gas activities on the North Slope. If recent trends in climate continue, as many projections indicate they will, their effects will accumulate over the next century to alter the extent and timing of sea ice, affect the distribution and abundance of marine and terrestrial plants and animals, and affect permafrost. Such changes would eventually affect existing oil-field infrastructure and would continue to affect the usefulness of many oil-field technologies and how they affect the environment. Climate change also would affect arctic ecosystems and Native Alaskan cultures as well as the way they are affected by oil and gas activities. In some cases, it is relatively easy to apportion the causes of observed changes between climate or oil and gas activities; in others, it is impossible.

Damage to Tundra from Off-Road Travel

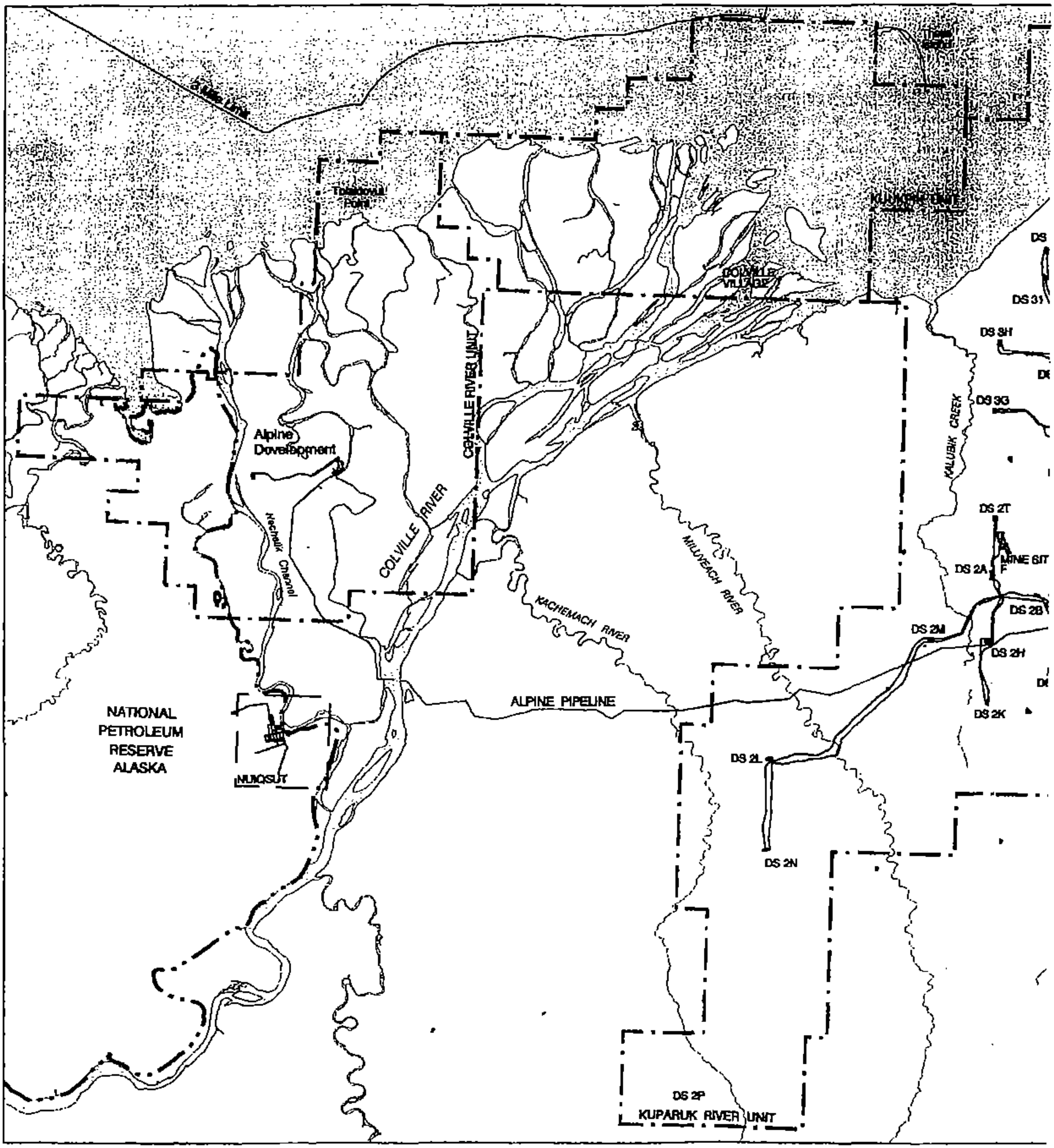
The tundra of the North Slope has been altered by extensive off-road travel. Networks of seismic-exploration trails cover extensive areas. The currently favored 3-D surveys (three-dimensional surveys that obtain geophysical data) require a higher spatial density of trails than

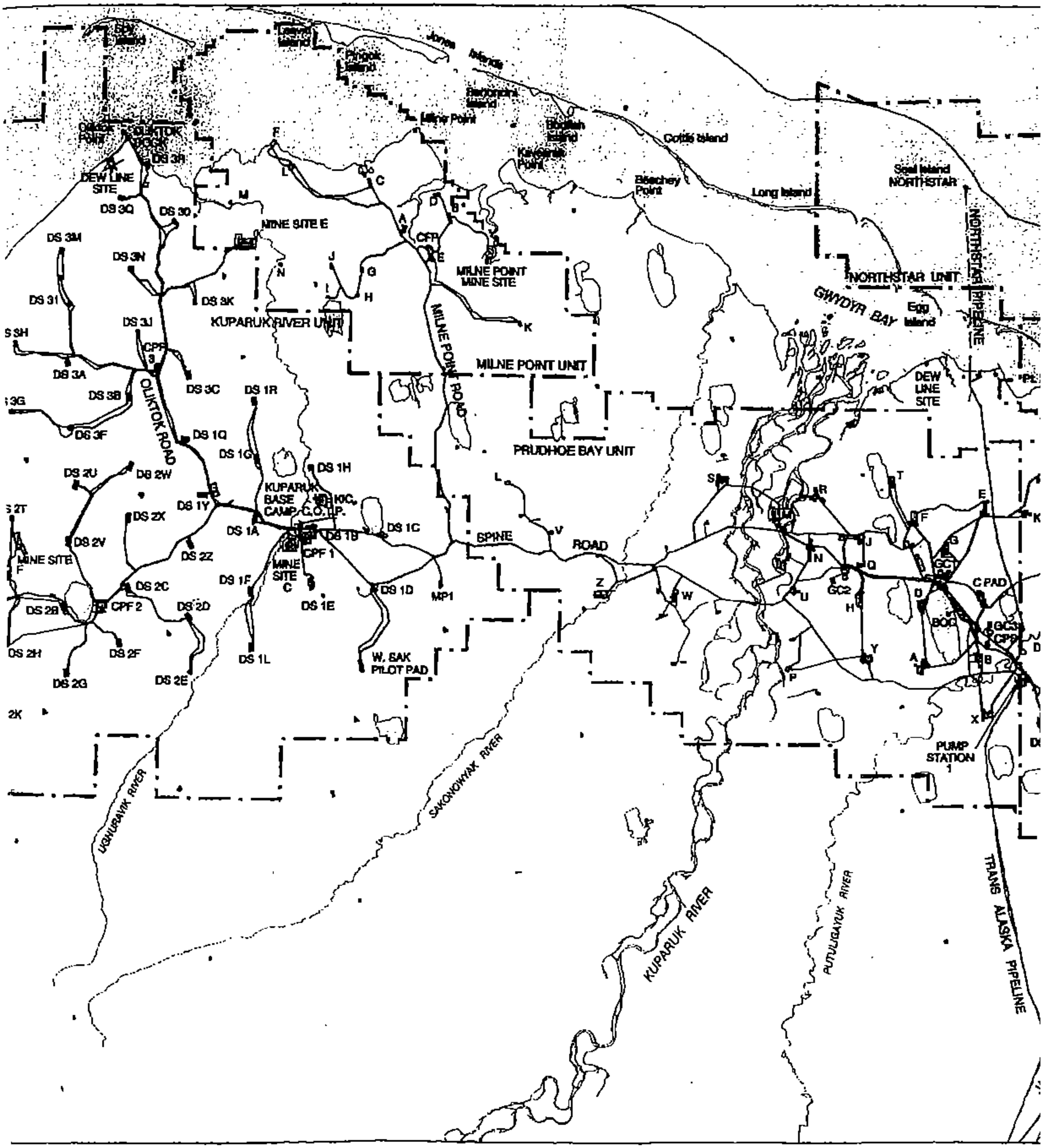
FIGURE S-2

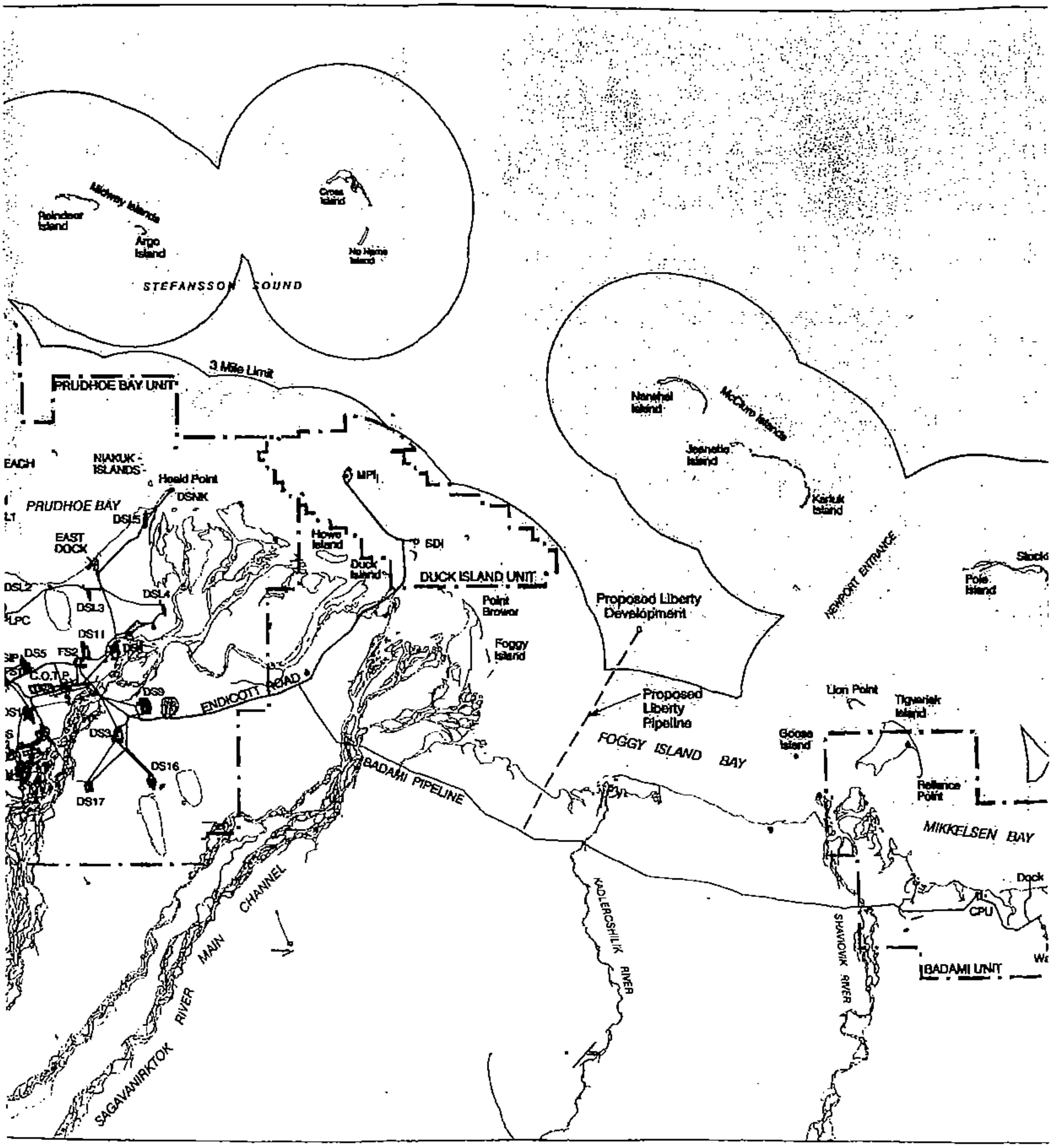
North Slope Production Facilities, Interconnecting Roads, and Pipelines

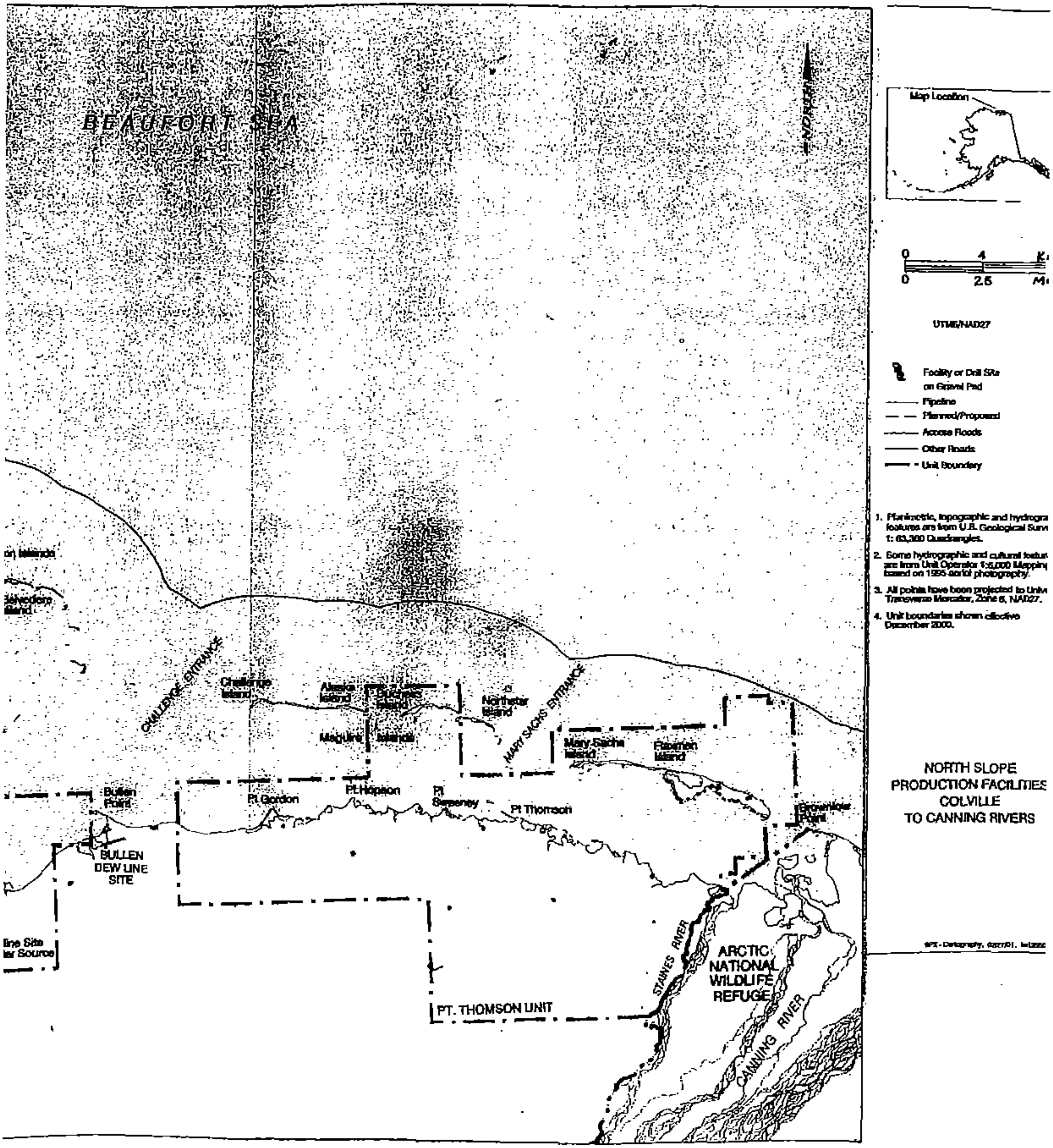
Colville to Canning Rivers

Source: BP 2001.


Alpine Development
COLVILLE RIVER UNIT
COLVILLE RIVER
COLVILLE VILLAGE
KALUBIK CREEK
MILUVEACH RIVER
KACHEMACH RIVER
ALPINE PIPELINE
NATIONAL PETROLEUM RESERVE ALASKA
NUIQSUT
DS 3G
DS 2T
DS 2A
DS 2B
DS 2M
DS 2H
DS 2K
DS 2L
DS 2N
DS 2P
KUPARUK RIVER UNIT


KUPARUK RIVER UNIT
MILNE POINT UNIT
PRUDHOE BAY UNIT
NORTHSTAR UNIT
MILNE POINT ROAD
OLIKTOK ROAD
SPINE ROAD
GWYDYR BAY
TRANS ALASKA PIPELINE
NORTHSTAR PIPELINE
KUPARUK RIVER
SAKONOWYAK RIVER
UGNURAVIK RIVER
PUTULIGAYUK RIVER
PUMP STATION 1
Jones Islands
Milne Point
Cottle Island
Long Island
Beechey Point
Seal Island NORTHSTAR
Egg Island
DEW LINE SITE
KUPARUK BASE CAMP
MINE SITE E
MILNE POINT MINE SITE
W. SAK PILOT PAD
CPF 1
CPF 2
CPF 3
DS 1A
DS 1B
DS 1C
DS 1D
DS 1E
DS 1F
DS 1G
DS 1H
DS 1L
DS 1Q
DS 1R
DS 1Y
DS 2B
DS 2C
DS 2D
DS 2E
DS 2F
DS 2G
DS 2H
DS 2U
DS 2V
DS 2W
DS 2X
DS 2Z
DS 3A
DS 3B
DS 3C
DS 3F
DS 3J
DS 3K
DS 3M
DS 3N
DS 3O
DS 3Q
DS 3R
MP1
C PAD
BOC
GC2
Milne Point


Midway Islands
Reindeer Island
Argo Island
Cross Island
No Name Island
STEFANSSON SOUND
3 Mile Limit
PRUDHOE BAY UNIT
NIAKUK ISLANDS
Heald Point
DSNK
PRUDHOE BAY
DSL5
EAST DOCK
MPI
Howe Island
Duck Island
SDI
DUCK ISLAND UNIT
DSL2
DSL3
DSL4
LPC
DS11
DS5
FS2
C.O.T.P.
DS9
ENDICOTT ROAD
DS3
DS16
DS17
Point Brower
Foggy Island
Proposed Liberty Development
Proposed Liberty Pipeline
FOGGY ISLAND BAY
BADAMI PIPELINE
SAGAVANIRKTOK RIVER MAIN CHANNEL
KADLEROSHILIK RIVER
Narwhal Island
McClure Islands
Jeanette Island
Karluk Island
NEWPORT ENTRANCE
Pole Island
Lion Point
Tigvariak Island
Goose Island
Reliance Point
MIKKELSEN BAY
Dock
CPU
SHAVIOVIK RIVER
BADAMI UNIT



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earlier methods. Some effects of seismic exploration accumulate because areas have been resurveyed before the tundra recovered from the effects of previous surveys. Seismic exploration has adversely affected vegetation and caused erosion, especially along stream banks. In addition, because seismic trails are readily visible from the air, they have degraded visual experiences on the North Slope over a large area. How long damages caused by seismic surveys and other off-road travel will persist is not known, but some effects are known to have persisted for several decades.

There have been substantial improvements in technologies, especially of exploration, and the operators have been taking increased care. The technology used for obtaining seismic data continues to improve, but there is still potential damage to the tundra because of the large camps, the number of vehicles used, and the higher spatial density of 3-D trails. The new technology has reduced but not totally eliminated damage to the tundra.

Roads

Roads have had effects as far-reaching and complex as any physical component of the North Slope oil fields. In addition to their direct effects on the tundra, indirect effects are caused by dust, roadside flooding, thermokarst, and roadside snow accumulation. Roads also alter animal habitat and behavior and can increase access of hunters, tourists, and others to much of the region; enhance communication among communities; and increase contacts between North Slope communities and those outside the area.

Effects on Animal Populations.

Animals have been affected by industrial activities on the North Slope. Bowhead whales have been displaced in their fall migration by the noise of seismic exploration. The full extent of that displacement is not yet known. Some denning polar bears have been disturbed. The ready availability of new sources of food from people in the oil fields has resulted in increases in predator densities. Because brown bears, arctic foxes, ravens, and glaucous gulls prey on eggs, nestlings, and fledglings of many bird species, the reproductive success of some of those species in the developed parts of the oil fields has been reduced. Efforts to reduce the amount of supplemental food available to predators have been only partly successful, because some predators have become expert at defeating anti-predator devices, and it is difficult to persuade people to stop feeding them.

The high predation rates have reduced the reproductive success of some bird species in industrial areas to the extent that, at least in some years, reproduction is insufficient to balance mortality. Those populations—called *sink* populations—might persist in oil fields only because of immigration. Sink populations have not been unambiguously detected because census data (counts) alone do not reveal them. However, several species of birds apparently have been affected in this way.

As a result of conflicts with industrial activity during calving and an interaction of disturbance with the stress of summer insect harassment, reproductive success of Central Arctic Herd female caribou in contact with oil development from 1988 through 2001 was lower than for undisturbed females, contributing to an overall reduction in herd productivity. The decrease in herd size between 1992 and 1995 may reflect the additive effects of surface development and relatively high insect activity, in contrast to an increase in the herd's size from 1995 through 2000, when insect activity was generally low. Although the accumulated effects of industrial development to date have not resulted in large or long-term declines in the overall size of the Central Arctic Herd, the spread of industrial activity into other areas that caribou use for calving and insect relief, especially to the east where the coastal plain is narrower than elsewhere, would likely result in reductions in reproductive success, unless the degree to which it disturbs caribou could be reduced. Without specific information on the exact nature of future activity and its precise distribution, it is not possible to predict to what degree the migrations and population sizes of caribou would be affected.

Oil Spills

Major oil spills have not occurred on the North Slope or adjacent oceans through operation of the oil fields. There have been three major spills from the North Slope segment of the Trans-Alaska Pipeline. Many small spills have occurred in the oil fields, but they have not been frequent or large enough for their effects to have accumulated. The effects of a large oil spill at sea, especially in broken ice, would likely be substantial and accumulate. No current cleanup methods remove more than a small fraction of oil spilled in marine waters, especially in the presence of broken ice.

Expansion of Activities into New Areas

Seismic exploration is expanding westward into the National Petroleum Reserve-Alaska and southward into the foothills of the Brooks Range. Current technology and regulations governing seismic-exploration permits and other off-road travel have reduced but not eliminated damage to the tundra. The nature and condition of permafrost in the foothills is poorly characterized, and the hilly topography increases the likelihood that vehicles will damage vegetation, especially on knolls and riverbanks, causing increased erosion, exposing bare soil, and creating thermokarst. In addition, future exploration will be carried out in a climate that is likely to continue to warm, with milder winter temperatures and shorter periods of freezing. It is hard to predict the consequences of vehicular traffic in winter on tundra under these altered conditions.

Legacy of Abandoned Infrastructure and Unrestored Landscapes

The oil industry and regulatory agencies have made dramatic progress in reducing the effects of new gravel fill by reducing the size of the gravel footprint required for many types of facilities and by substituting ice for gravel in some roads and pads. Much less attention has been directed to restoring already disturbed sites. To date, only about 40 ha (100 acres), or about 1% of the habitat on the North Slope affected by gravel fill, has been restored. With the exception of well-plugging and abandonment procedures, state, federal, and local agencies have largely deferred decisions about the nature and extent of restoration that will be required. The lack of clear state or federal performance criteria, standards, and monitoring methods governing the extent and timing of restoration has hampered progress in restoring disturbed sites. In addition, if a site has potential for future use, restoration could make that future use more expensive or perhaps impossible, thus influencing decisions to defer restoration. Potential liability for contaminated sites also constitutes a barrier to re-use of gravel.

Because the obligation to restore abandoned sites is unclear, and restoration is likely to be expensive, the committee judges it unlikely that most disturbed habitat on the North Slope will be restored unless current constraints change dramatically. Because natural recovery in the Arctic is slow, the effects caused by abandoned and unrestored structures are likely to persist for centuries. They could accumulate further as new structures are added in the region.

Socioeconomic Changes in North Slope Communities

The North Slope Borough, the Alaska Native Claims Settlement Act, and hence the Arctic Slope Regional Corporation were created as a result of the discovery and development of North Slope oil. Without it, they would not exist or, if they did, would bear little resemblance to their current form. Oil development—and the revenue stream it created—has resulted in major, important, and probably irreversible changes to the way of life in North Slope communities. The changes include improvements in schools, health care, housing, and other community services as well as increased rates of alcoholism, diabetes and circulatory disease. There have been large changes in culture, diet, and the economic system. Many North Slope residents view many of these changes as positive. However, social and cultural shifts of this magnitude inevitably bear costs in social and individual pathology. These effects accumulate because they arise from several causes, and they interact. As adaptation occurs, the communities and the people who make them up interact in new and different ways with the causes of social change. The largest changes have occurred since the discovery of oil at Prudhoe Bay in 1968.

Interference with Subsistence Activities

Offshore exploration and development and the announcement of offshore sales have resulted in perceived risks to Inupiaq culture that are widespread and intense and are accumulating effects. The Inupiat of the North Slope have a centuries-old nutritional and cultural relationship with the bowhead whale. Most view offshore industrial activity—both its observed effects and the possibility of a major oil spill—as a threat to the bowheads and, thereby, to their cultural survival. Fall-migrating bowhead whales avoid areas where the noise from exploratory drilling and marine seismic exploration exceeds 117-135 dB. The distances over which the migratory pathways of the whales are altered are not yet known, but the deflections have forced subsistence hunters to travel farther from home to hunt whales. This increases their risk of exposure to adverse weather and the likelihood that whale tissue will deteriorate before a carcass can be landed and processed. Recent agreements to limit or move some exploration activities in the fall, which are renegotiated annually, have reduced the effects on hunters. The Inupiat view the possibility of a major oil spill as a potential catastrophe by the Inupiat, even though no such spill has occurred there. Those threats accumulate because they interact and they are repeated with each new lease sale.

Proposals to explore and develop oil resources in the Arctic National Wildlife Refuge have resulted in widespread, intense perceived risks to Gwich'in culture that themselves are accumulating effects. The Gwich'in Indians of northeast Alaska and northwest Canada have a centuries-old nutritional and cultural relationship with the Porcupine Caribou Herd. Most Gwich'in oppose any oil development that would threaten the herd, especially on its calving ground, and, thereby, threaten their cultural survival. This threat accumulates, because repeated attempts to develop areas used by the herd have occurred and probably will continue to occur.

Aesthetic, Cultural, and Spiritual Consequences

Many activities associated with oil development have changed the North Slope landscape in ways that have had accumulating aesthetic, cultural, and spiritual consequences. They have reduced opportunities for solitude and have compromised wildland (wilderness) and scenic values over large areas. They also violate what some Alaska Natives call the "spirit of the land," which they describe as central to their relationship with the land. Those consequences have increased in proportion to the area affected by development, and they will persist as long as the landscape remains altered. They will accumulate further if the area affected by development increases.

Response of North Slope Cultures to Declining Revenues

The current, altered way of life of North Slope communities will be impossible to maintain unless enough money continues to come into those communities from outside sources after oil and gas activities cease. But likely continuing sources of funds appear to be modest. Painful adjustments to reduced financial resources can and probably will be postponed for as long as oil and gas are being extracted, but eventual adjustment is unavoidable. The nature and extent of adjustment will be determined by the adaptations North Slope societies have made to the cash economy made possible by oil and gas and other activities.

FILLING KNOWLEDGE GAPS

A great deal of time and effort had been invested in studying North Slope environments and assessing the effects of oil and gas activities there. Some of the research recommendations that follow are for new investigations, but many of them represent a sharpening of the focus and the emphasis of current research efforts.

To the degree possible, information on the effects of industrial development on the North Slope (including information on the physical, biotic, and human environments) should be gathered concurrent with oil and gas activities so as to take advantage of opportunities for learning, and to promote better management (i.e., adaptive management).

Need for Comprehensive Planning

Decisions about where, when, and under what conditions industrial activities are permitted on the North Slope are made by many federal, state, municipal, and other agencies. Communication among them has usually been weak and sporadic. Decisions generally have been made on a case-by-case basis, without a comprehensive plan and regulatory strategy that identifies the scope, intensity, direction, and consequences of industrial activities judged appropriate and desirable. The anticipated high costs to dismantle and remove infrastructure and to rehabilitate and restore the North Slope environment raise concerns about the availability of funds for restoration when production ends. For these and other reasons, comprehensive planning is needed. All comprehensive plans are necessarily provisional and will need to be revised as new information becomes available. Nonetheless, a comprehensive framework and plan should be developed for the North Slope so that decisions can be evaluated with respect to their compatibility with overall goals, the likely effects of individual activities on all receptors that might be affected by them, and the likelihood that the activities will result in undesirable effects that are long-lasting or difficult to reverse. The plan should include all phases of oil and gas activity, from lease sales, to dismantlement and removal of infrastructure, to environmental rehabilitation and restoration. The plan also should identify areas for research.

Ecosystem Research

Most ecological studies in the Prudhoe Bay region have been local; ecosystem-level research has largely been lacking. Although ecological communities within an oil field are likely to differ from similar unaffected communities elsewhere, the extent and nature of the differences are largely unknown. To assess those differences, researchers should be given access to protected areas inside and outside the industrial complex. Particular research attention should focus on the ecological processes most likely to be altered by industrial activities.

Offshore Oil Spills

Although no large oil spills have occurred in marine waters off the North Slope, their potential is such a major concern that the committee recommends research into mitigating their effects. Such research would help refine assessments of the accumulation of effects of a major spill in that environment. This committee did not attempt to reach consensus on whether, when, and how experimental oil spills might be used in a research program. Other research seems to be warranted, however, including on possible ways of deflecting bowhead whales and perhaps other marine mammals from spill-affected areas, and on the effectiveness and environmental liabilities and advantages of nonmechanical methods of cleaning up oil spilled in the sea (dispersants, in-situ burning), especially in broken ice.

Zones of Influence

The effects of industrial activities are not limited to the footprint of a structure or to its immediate vicinity; a variety of influences can extend some distance from the actual footprint. They range from the effects of gravel roads and pads on animals, which can extend for several miles from the footprint, to the influence of industrial structures on wilderness values, which can extend much farther. The full accumulation of effects of oil and gas activities to date, as well as future accumulation, cannot be assessed without better quantitative information about the ways in which various kinds of effects extend for various distances.

Human Communities

The communities of the North Slope have not been adequately involved in most research in the region. As a result, some important information concerning accumulated effects is missing or sparse. To improve the assessment of effects and their accumulation, research on the North Slope should be a cooperative endeavor with local communities. Traditional and local knowledge includes rich and detailed information about many aspects of the environment. Balancing economic benefits of oil and gas activities against loss of traditional culture often is a dilemma for North Slope residents. Research should be conducted to better characterize the specific benefits and threats that North Slope residents perceive are posed to their way of life and health by oil and gas activities. The studies should attempt to separate the effects of oil and gas activities from other causes of socioeconomic change. Research should seek to establish how oil and gas activities have affected the behavior of communities and individuals. Research should be done to identify the direct and indirect monetary rewards and costs—including non-use values such as existence and bequest values—associated with petroleum development on the North Slope.

Human-Health Effects

Human-health effects of oil and gas activities have not been well documented. Although some problems on the North Slope—increased use of alcohol and drugs, increased obesity, and other societal ills—are evident, it is not possible to say with the limited data available to what degree they are the direct result of oil and gas activities. Other concerns are widespread among Native residents of the North Slope. The degree to which increased financial resources related to oil have balanced adverse effects by improving the quality and accessibility of local medical care is unknown. These questions are in great need of additional reliable information.

Air Contamination and its Effects

Air pollution is a concern to many North Slope residents. Little research has been done to quantify the effects of air pollution on the North Slope or to determine how local and regional air masses interact. Air-pollution monitoring has been limited to priority pollutants from 1986 through 2002 at a few sites. Not enough information is available to provide a quantitative baseline of spatial and temporal trends in air quality over long periods across the North Slope. Given local concerns about air quality and the perception that poor air quality is affecting the public health, research and monitoring should be implemented to distinguish between locally derived emissions and long-range transport of air contaminants to determine how they interact, and to monitor potential human exposure to them.

Off-Road Traffic and the Tundra

Networks of seismic trails and trails of other off-road vehicles, ice roads, and ice pads cover large areas of the tundra. They cause concern because of the damage they do to vegetation and because of their visibility from the air. Continuing advances in the technology of seismic-data acquisition might reduce its effects by reducing the weight, tracks, or number of vehicles used, but the degree to which this will happen is not known because the effects of the new technologies have not yet been extensively studied.

Studies are needed to assess the long-term visibility of seismic trails from the air. Research also is needed to determine the amount of snow cover and the frost penetration required to adequately protect the tundra from the effects of seismic exploration and the use of Rolligons (low tire-pressure off-road vehicles) and other off-road vehicles. New areas where oil and gas exploration are likely to occur differ substantially from current areas. Characterization of those environments should include descriptions of topography; permafrost conditions; sand, gravel, and water availability; hydrological conditions; and biotic communities.

Caribou and Bowhead Whales

A better understanding is needed of the seasonal habitat requirements of caribou, natural environmental constraints that affect their reproductive physiology and movements, their vulnerability to natural disturbance, and how anthropogenic disturbance affects them at various time of the year in the Arctic.

Studies are needed to determine the qualitative relationship between the noise generated by offshore operations and the migratory and acoustic behavior of bowhead whales. The studies should include analysis of the effects of multiple noise sources. Better information is also needed about the degree to which bowheads feed in the Alaskan portion of the Beaufort Sea.

Consequences of Water Withdrawals

Water for ice roads and pads and for other purposes is taken from lakes on the North Slope. Water depth has a great influence on the distribution of fish in coastal-plain lakes because lakes shallower than 1.8 m (6 ft) freeze to the bottom in winter. Because most lakes in the existing development area, between the Colville and Sagavanirktok rivers, are shallower than 1.8 m, few fish are present and effects have been minimal. As development spreads into regions with deeper lakes, such as the Colville delta and the eastern portion of the National Petroleum Reserve-Alaska, there is a greater chance that fish populations will be affected.

The current regulatory criterion, which allows 15% of the minimum winter water volume to be removed from fish-bearing lakes, should be studied to determine its ability to prevent loss of fish and invertebrates. A study of the effects of withdrawing water from lakes that do not contain fish should also be conducted to assess the degree to which current water use affects the biota associated with those bodies of water.

Dealing with Uncertainty

Actions undertaken to identify and reduce the undesirable effects of interactions among perturbations and receptors should greatly improve the quality and quantity of data for future decision-making. However, for several reasons it is unreasonable to expect that sufficient data will ever be available to meet all needs for information. Some animal species, such as marine mammals and fishes, are intrinsically difficult to study. Detecting even fairly large changes in their population densities and other demographic characteristics could be impossible no matter how much money is allocated for research. Also, adequate experimental controls could be impossible to establish.

Whenever a statistical test is performed to assess an environmental effect, the magnitude of the effect that could have gone undetected should be explicitly stated. Those uncertainties should be communicated clearly to decision makers.

THE ESSENTIAL TRADE-OFF

The effects of North Slope industrial development on the physical and biotic environments and on the human societies that live there have accumulated, despite considerable efforts by the petroleum industry and regulatory agencies to minimize them. To the best of its ability, and given the time, data, and resources available, the committee has identified those effects. It has also attempted to assess how effects are likely to accumulate with future expansion of industrial activities into new areas. Continued expansion is certain to exacerbate some existing effects and to generate new ones—possibly calling for regulatory revisions. Whether the benefits derived from oil and gas activities justify acceptance of the inevitable accumulated undesirable effects that have accompanied and will accompany them is an issue for society as a whole to debate and judge. However, if wise decisions are to be made, the nature and extent of undesirable effects likely to accompany future activities must be fully acknowledged and incorporated into regulatory strategies and decision-making. We hope this report will assist in the process.

1

Introduction

In 1968, large oil reserves were discovered along the coast of Alaska's North Slope. The oil field in Prudhoe Bay (Figure 1-1) is now the largest in North America. It is estimated that approximately 23 billion bbl (966 billion gal or 3.7 trillion liters [L]) of oil originally was in the ground. Production began in 1977. Since that initial discovery, other large fields have augmented the production from Prudhoe Bay. By the end of 2002, about 14 billion bbl (588 billion gal, 2.2 trillion L) of crude oil had been produced. North Slope oil has averaged about 20% of U.S. domestic production since 1977, and it currently provides about 15% of the annual domestic production of approximately 3.3 billion bbl and 7% of the annual domestic consumption of approximately 7 billion bbl. Reliable estimates of technically recoverable reserves for the North Slope and its adjacent offshore areas are not currently available. There also are huge reserves of coal and natural gas in the region, and if production of those resources were to become economically feasible, the strategic and economic importance of the hydrocarbon energy resources of the region would be even greater.

The term North Slope refers to the area from the crest of the Brooks Range to the Arctic Coast, from the Canadian border to Point Hope. Although the area is more correctly called the *Arctic Slope*, the Committee on Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities has elected to follow convention and use *North Slope* in this report.

The benefits brought by oil and gas production on the North Slope have come with environmental concerns and consequences. One of the earliest major environmental impact statements (EISs) was a 6-volume effort (DOI 1972) that examined the effects of the Trans-Alaska Pipeline. As production on the North Slope increased, many other studies and EISs have been produced, and knowledge of the effects of oil and gas exploration and development has increased substantially. Environmental concerns about exploration and development on the North Slope have focused on many subjects, including but not limited to the following:

- the effects of structures on the migration of fish and large mammals, especially caribou
- the effects on the tundra of off-road travel
- the effects on bowhead whales and other marine mammals of seismic exploration and industrial noise
- the risk of toxic contamination of fish, wildlife, and plants used for food by Alaska Natives
- the effects of roads (both gravel and ice)
- the effects of oil spills on terrestrial, marine, and coastal ecosystems and on the humans that depend on them

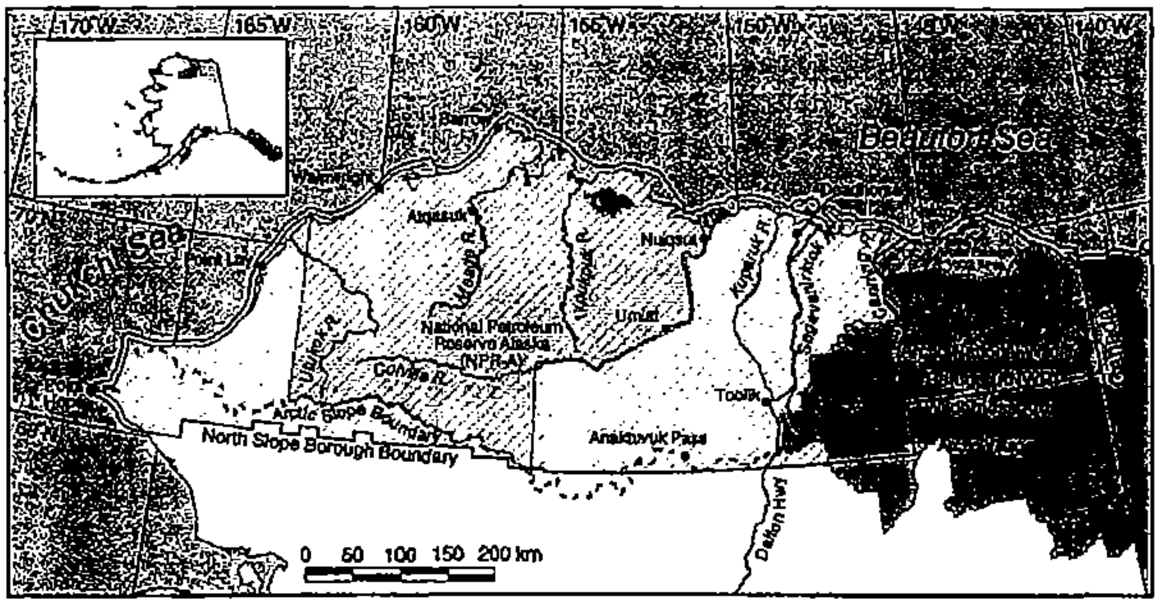

FIGURE 1-1. The Alaska North Slope region. The dashed line is the southern boundary of the drainage basin. The Trans-Alaska Pipeline is close to the Dalton Highway. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

- the effects on a variety of ecosystems of transportation of material, supplies, and people
- the extent to which effects are reversible
- whether remediation is possible and will actually be undertaken

Concerns have also focused on social consequences, such as the effects of new roads and access to formerly isolated communities; the socioeconomic effects of jobs related to oil and gas development; the effects on subsistence practices, either as a result of the introduction of a wage economy or because of environmental change; and loss of wildland and wilderness values.

There is an extensive research literature on the actual and potential effects of oil and gas activity on the North Slope's physical, biotic, and human environments (e.g., BP 1991; Engelhardt 1985a; Kruse et al. 1982; Loughlin et al. 1994; MMS 1990, 1991, 1992; Truett and Johnson 2000; Walker et al. 1986a, 1987a,b). Much of this work has been sponsored by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) of the National Oceanic and Atmospheric Administration and the Department of the Interior, and by OCSEAP's successor, the Environmental Studies Program of the Department of the Interior. Additional research has been funded by the U.S. Army, the National Science Foundation, the Geological Survey the Fish and Wildlife Service of the Department of the Interior, and the Department of Energy. Many studies have been performed and funded by the oil industry and university researchers have contributed a large amount of information about the region. Despite the considerable research since the 1960s to assess the effects of oil and gas exploration, development, and production, no integrated, comprehensive analysis of cumulative impacts has been attempted. Understanding the cumulative effects of oil and gas development at a variety of locations over time is critical to informed, long-term decision-making about resource management.

THE PRESENT STUDY

In 1999, the U.S. Congress asked the National Research Council for assistance in addressing this gap in understanding (U.S. Congress: Conf. Rept 106-379 [H.R. 2684] Fiscal Year 2000 Appropriations for the Environmental Protection Agency). In response, the Council established the Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope and charged it with providing a comprehensive analysis, including conclusions and recommendations (Box 1-1).

Although the cumulative effects of North Slope oil and gas activities—especially production—extend beyond the region, the committee's focus was confined to Alaska's North Slope and as far into the Arctic Ocean as there is evidence of environmental effects. As a result, the committee did not consider releases of compounds that could affect global atmospheric chemistry or the contribution of the burning of North Slope oil to global climate warming. The contribution of North Slope oil and gas activities to the accumulation of such atmospheric effects is small on a global basis. Climate change is considered as it interacts with the effects of oil and gas activities on the North Slope.

The committee's 18 members, who are experts in a wide range of disciplines (see Appendix K), met 8 times over the course of the study. The committee relied on its members' expertise, on an extensive review of the literature, and on information gathered from public meetings held throughout the state. Meetings and site visits were held in Alpine, Anchorage, the Arctic National Wildlife Refuge, Arctic Village, Endicott, Fairbanks, Kaktovik on Barter Island, and the Prudhoe Bay oil field. Appendix A lists those who made presentations and otherwise assisted the committee.

Box 1-1 Statement of Task

The Committee on Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope was charged to review information about oil and gas activities (including exploration, development, and production) on Alaska's North Slope and assess the known and probable cumulative effects on the physical, biological, and human environments of Alaska's North Slope (including the adjacent marine environment) of oil and gas activities there from the early 1900s to the present, including cleanup efforts. The committee was asked to provide an assessment of potential future cumulative effects, based on its judgment of likely changes in technology and the environment, on a variety of scenarios of oil and gas production volumes, and in combination with other probable human activities, including tourism, fishing, and mining. As part of its report, the committee was charged to describe and document its methodology for assessing cumulative effects and identify gaps in knowledge and make recommendations for future research needed to fill those gaps. Although cumulative effects of oil and gas activities occur beyond the North Slope (e.g., related to transportation and ultimate combustion), the committee was asked to confine its focus to the North Slope (i.e., north of the crest of the Brooks Range) and as far into the Arctic Ocean as there is evidence of environmental effects.

UNDERSTANDING AND ASSESSING CUMULATIVE ENVIRONMENTAL EFFECTS

The ecologist W.E. Odum wrote (1982) that when numerous small decisions about related environmental issues are made independently, the combined consequences of those decisions are not considered. As a result, the patterns of the environmental perturbations or their effects over large areas and long periods are not analyzed. This is the basic issue of cumulative effects assessment. The general approach to identifying and assessing cumulative effects evolved after passage of the National Environmental Policy Act (NEPA) of 1969, and the committee has followed that approach.

Although the NEPA requires EISs for many major projects, if those projects are considered separately from similar projects or in isolation from different kinds of projects in the same area, some of their effects—their cumulative effects—are likely to be missed. In 1978, the Council on Environmental Quality promulgated regulations implementing the NEPA that are binding on all federal agencies (40 CFR Parts 1500-15081 [1978]). A cumulative effect was defined as "the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions. . . . Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time." For example, an EIS might conclude that the environmental effects of a single power plant on an estuary might be small and, hence, judged to be acceptable. But the effects of a dozen plants on the estuary are likely to be substantial, and perhaps of a different nature than the effects of a single plant—in other words, they are likely to accumulate. Even a series of EISs might not identify or predict that accumulation to produce those more serious or different effects that result from the interaction of multiple activities. Cumulative impact assessment (CIA) arose to address such considerations.

In interpreting the broad charge of assessing cumulative effects, the committee focused on whether the effects under consideration interact or accumulate over time and space, either through repetition or combined with other effects, and under what circumstances and to what degree they might accumulate. As an example, consider a repeated environmental insult that is localized in space and occurs so infrequently that natural processes of recovery or human efforts can eliminate its effects before another insult occurs. In this case, one would conclude that the effects of the insult do not accumulate (rather than concluding that the insult is not "a cumulative effect"). This approach also directs attention to the circumstances under which effects might accumulate.

The accumulation of effects can result from a variety of processes (NRC 1986). The most important ones are:

- *Time crowding*—frequent and repeated effects on a single environmental medium. This would be the case, for example, if repeated oil spills occurred on an area of tundra before that area had recovered from previous spills. Time crowding also can result if there are long delays before the effects of an action are fully manifest. An increase in the melting of permafrost might not become apparent until decades after the actions that caused it were initiated.
- *Space crowding*—high density of effects on a single environmental medium, such as a concentration of drilling pads in a small region so that the areas affected by individual pads overlap. Space crowding can result even from actions that occur at great distances from one another. For example, air pollution from temperate latitudes can interact with local sources of contamination to increase atmospheric haze on the North Slope.
- *Compounding effects*—synergistic effects attributable to multiple sources on a single environmental medium, such as the combined effects of gaseous and liquid emissions from multiple sources on a single area, or nonlinear effects, or interaction of natural and anthropogenic effects, such as the *Exxon Valdez* oil spill and El Niño events.
- *Thresholds*—effects that become qualitatively different once some threshold of disturbance is reached, such as when eutrophication exhausts the oxygen in a lake, converting it to a different type of lake.
- *Nibbling*—progressive loss of habitat resulting from a sequence of activities, each of which has fairly innocuous consequences, but the consequences on the environment accumulate, for example by causing the extirpation of a species from the area.

These examples illustrate why recognizing and measuring the accumulation of effects depends on the correct choice of domain—temporal, spatial—for the assessment. If the time domain chosen to analyze the effects of a power plant on an estuary is the plant's period of operation and the space domain is that covered by its exhaust plume, then the accumulation of the effects of multiple plants will be missed if a series of EISs analyzes each plant in isolation. Alternatively, if the space domain is the entire estuary, and the time domain is long enough to include the commissioning of several plants, then at least some accumulation of effects is likely to be detected. Effects typically accumulate as the result of repeated activities of similar or different types. However, in some cases the effects of a single action or event can accumulate. This is especially true if the effects persist for a long time and are added to by the effects of other activities, with the result that there is a change from what would have resulted if the single event had not occurred.

Although the assessment of cumulative effects has a history of several decades (e.g., NRC 1986), it is still a complex task. The responses of the many components of the environment (receptors) likely to be affected by an action or series of actions differ in nature and in the areas and periods over which they are manifest. An action or series of actions might have effects that accumulate on some receptors but not on others, or on a given receptor at one time of the year but not at another. Therefore, a full analysis of how and when effects accumulate requires multiple assessments.

To address this problem the committee attempted to identify the essential components of a such an assessment:

- Specify the class of actions whose effects are to be analyzed.
- Designate the appropriate time and space domain in which the relevant actions occur.
- Identify and characterize the set of receptors to be assessed.
- Determine the magnitude of effects on the receptors and whether those effects are accumulating.

These criteria cannot always be applied because of data limitations. As will become apparent later in this report, the effects of individual actions range from brief or local to widespread, long-lasting, and sometimes irreversible.

At the most general level, the class of actions considered by the committee encompasses all of those associated with oil and gas development. The spatial domain is the North Slope of Alaska and its adjacent marine waters. The temporal domain is 1965 to 2025, or in some cases 2050, and the receptors are the physical, biological, and human systems in the region.

The committee conducted analyses of specific activities (e.g., seismic exploration, road building, gravel mining), and determined their most significant effects (individual or collective) on specific receptors (e.g., tundra vegetation, species of special concern, subsistence hunting, employment).

A particularly challenging problem is to determine the area over which the effects of an activity, such as building a drilling pad, a road, or a seismic survey trail, are felt. Some analyses measure the effects of an activity by its "footprint"—the physical area covered by a drilling pad or road, for example—although the effects can extend well beyond that space. The effect of a road extends beyond the actual physical area where the gravel smothers vegetation. Large vehicles make noise that can frighten wildlife some distance from the road; they raise dust that settles downwind, affecting the timing of snow melt and thus the underlying vegetation. Roads also impede drainage. A highway can increase access and thus bring hunters to an area. All of these effects can be defined and measured.

To conduct an analysis of how effects accumulate, one must understand what would occur in the absence of a given activity. The accumulated effects are the difference between that probable history and the actual history or projected effects of the action. Such analyses are most readily accomplished if good baseline data are available or if data are available about the same kinds of receptors in similar areas that are not influenced by comparable actions. In some cases, the lack of such information prevented the committee from identifying and assessing possible effects of some activities.

In estimating the accumulation of effects it is customary to assume that the only source of environmental change is the action under study, and that the environmental setting itself has no bearing. There is a challenging complication in the Alaskan Arctic, however, because the climate is expected to warm so rapidly that the effects of current activities could be much greater on the permafrost landscape than would be the case if the climate were relatively stable.[1] The committee's prediction of the accumulation of effects over several decades has been limited by ignorance of the details of how this climate change will proceed and thus of its potential effects on North Slope ecosystems.

Even if accumulating effects are identified, their magnitude and their biological, economic, and social importance must be assessed. Discontinuities or inflection points in biotic or social relationships, a change in some important process, or the widespread perception of members of an affected community of the importance of some change are generally associated with environmentally or socially important effects. The committee assessed biotic and social importance separately for each receptor.

Although the committee was directed to evaluate the cumulative effects of oil and gas activities on the North Slope, the accumulation of physical, biotic, and human environmental effects of those activities extends beyond the region. Moreover, activities elsewhere in the world influence what happens to the North Slope environment. Although the committee followed its charge and concentrated attention on the North Slope, external effects had to be considered in situations where they combine with activities on the North Slope to influence the nature and extent of environmental effects there.

SOURCES OF KNOWLEDGE

Information about Alaska's North Slope, the functioning of its human communities and ecosystems, and the effects of industrial activities during the past century comes from many sources, including peer-reviewed literature, government reports, and industry documents. The committee made a special effort to evaluate and incorporate the traditional and local knowledge of residents of the North Slope. People have lived on the North Slope since long before industrial activity began, and because they have had intimate, sustained contact with the immediate environment, they provide a unique source of knowledge. The committee did not compare the North Slope with the Russian experience because—despite some environmental similarities—environmental laws and regulations, societal factors, and economic systems are very different from Alaska's, and because reliable information is not easy to obtain.

Despite the evident value of the traditional and local knowledge of Alaska Natives, their insights have been poorly incorporated into the overall public perception, both on and off the North Slope, about cumulative changes and their causes. The reasons for this failure are generally understood (Box 1-2, Appendix H), but the problem is still largely unresolved (but see

[1] The largest contributor to climate warming is the burning of fossil hydrocarbon fuels. Although the resultant climate change affects the North Slope—probably more than lower-latitude areas—this effect is not considered as an effect of North Slope oil and gas activities in this report because the North Slope provides only a small fraction of all the fossil hydrocarbons burned on earth. However, it is an important factor that must be considered in all analyses of this type.

Kofinas et al. (2002) and Huntington (2000) for descriptions of incorporation of traditional knowledge into research on environmental change in the Arctic).

Box 1-2 Why Answering Why is Difficult: Reconciling Alaska Native Observations of Environmental Change with Western Science

Alaska Native hunters from the Arctic region have told the committee about changes in the character of seal skins—some are thinner (almost translucent) than in the past and they no longer crimp as readily when they are shaped into soles for mukluks (boots). In other locales, Alaska Natives also have observed other changes: There are unusual sores and lesions on fish, moose, and caribou. There is a change in the taste and color of the local tea. Caribou meat tastes different. People in their villages are suffering from increased respiratory diseases. Communities ask why the changes are occurring, and local opinion often finds blame in industrial development.

There is little in the way of scientific data to shed light on such questions and anomalies, and anecdotal evidence is difficult for scientists to study or explain. Because some of the questions are about subtle changes in small areas or for short periods, and because examining those issues could require unattainable investment of research resources, some of the questions could be unanswerable. There also are few predevelopment data to use for comparison. And there might be no way to distinguish which factors contribute given effects (and in what combination), or whether the changes can be attributed to natural variability, climate change, oil and gas development, modernization, or other human or natural influence.

The seal-skin observations are difficult to study, for example, because they occur in isolated instances and it would be difficult (if not impossible) to do the sampling and measurements necessary to obtain meaningful data. Socioeconomic questions are even more perplexing: Could research help explain what proportion of significant social problems—alcohol and drug abuse, domestic violence, health problems—is attributable to oil and gas development or to other forces of cultural disruption?

No relevant data or plausible mechanisms have been identified to relate changes in seal-skins to oil and gas development. But that example is just one illustration of repeated Alaska Native concerns about changes in the environment for which explanations are sought. And local concerns at times are difficult for outsiders to understand because visitors usually lack the intimate, even spiritual, relationship Alaska Natives have with their environment.

Improving the ways science addresses the issues important to Alaska Native communities affected by development on the North Slope is a problem far bigger than this report can address. This much is clear: A better mechanism is needed to increase Alaska Native input into the research process; some way by which they can be involved in translating their observations into hypotheses that can be addressed by research, and some means to ensure that Alaska Natives become partners in the research. Appendix H describes some of these difficulties and approaches to resolving them.

Most cross-cultural collaborations have been informal and occur on a case-by-case basis. They often begin because of the interest and commitment of individual researchers who have no special training in working across cultures. There are few policy directives and only limited financial support for use of traditional and local knowledge or for researchers to engage in cross-cultural awareness and communication orientation programs. Consequently, institutional commitment to understanding and using traditional and local knowledge for stewardship and research has been subject to shifts in emphasis as governments change. Those shifts are a source of frustration and distrust for Alaska Natives who have to undertake extensive and costly efforts to educate new administrators, policy-makers, and managers each time they change.

Scientists find it difficult to assess the quality and spatial scales of relevance of much traditional knowledge, so it is difficult to determine whether the observations offered by any Alaska Native collaborator are valid. Alaska Natives, for their part, have told the committee that they are sometimes skeptical of the scientific motivations to acquire information and thus can be reluctant to cooperate or participate. Moreover, they are rarely involved in the formative stages of collaborative research, and for the most part they are not involved in the actual research efforts. In addition, many Alaska Native elders, who are potentially important sources of information, do not speak English fluently or at all, and they are not schooled in communicating with Western culture, thus diminishing the value of any information exchanges that may occur. Traditional and local knowledge can provide useful, qualitative information to scientists and an early warning system for identifying emergent biological or environmental trends and anomalies in local, regional, or ecosystem-wide geographical areas. For example, Alaska Natives in the Arctic have reported changes in migration patterns of the bowhead whale, changes in the thickness and elasticity of seal skins, and changes in the taste and color of "Eskimo tea." Many changes in wildlife are apparent only to people who interact with the animals regularly; scientists who do not eat the local diet would not know, for example, that the taste of seal meat has changed—no matter how much research has been conducted. If communication and collaboration were improved, traditional and local knowledge could provide scientists with new and timely hypotheses to pursue in their search for the causes of wildlife declines.

Traditional and local knowledge can influence many aspects of research, but better and more systematic ways to access and use this information must be developed if that value is to be realized (e.g., Huntington 2000). The process must consider, among other things, issues of communication protocols, dispute resolution, and information exchange; appropriate use of information; protocols for attribution of information sources; compensation for research collaborators; community relations; and cross-cultural communications and cultural-awareness training. The failure to seek and use traditional and local knowledge can have far-reaching consequences, including the loss of time and resources. The assessment of changes in the bowhead whale population is one instance in which traditional knowledge has been incorporated into the design and conduct of a major, long-term research effort (Albert 2001).

Bowhead Whales

Estimating population size for the Bering Sea bowhead population became a priority in the mid- to late 1970s when there was increasing concern in the International Whaling Commission (IWC) that the subsistence harvest in Alaska was unduly pressuring the stock. At the same time, there was growing interest in offshore petroleum development. All of this prompted the National Marine Fisheries Service (NMFS) of the U.S. Department of Commerce to undertake a population estimate. In 1976 and 1977 observers were placed at the seaward edge of the shore-fast ice near Point Barrow, where the passing whales came close to shore. Their data suggested a population of 600–2,000 whales (Tillman 1980). Data from 1978 and 1979 (Branham et al. 1980), which included ice-based and aerial surveys, yielded an estimate of 1,783-2,865 (mean 2,264) whales (Braham et al. 1980). The numbers were so low that the IWC initially set a 1978 harvest quota of zero whales. However, a revised quota of 12 landed or 18 struck was set after a special IWC meeting was called by the United States. This experience alarmed bowhead-dependent communities in Alaska, who believed their hunt was being unduly restricted because the whale counters were not counting the whales accurately (Albert 2001).

In the early 1980s, the responsibility for estimating bowhead population size was transferred to the people of northern Alaska. By then, a substantial difference had developed in views between the Alaska Native hunters and most scientists familiar with the bowhead issue. The "scientific wisdom" of the late 1970s was that the northward migrating bowhead whales traveled primarily in elongated open areas (leads) in the deteriorating and drifting ice, and that most of the passing whales could be counted by observers at the seaward edge of the shore-fast ice.

Alaska Native hunters cited their own observations, as well as information handed down through the generations, that bowheads passing Point Barrow move on a broad front (to about 20 km [12 mi] wide) and are not restricted to large areas of open water. They also move through areas of broken ice and heavy ice, not just through areas of open water, and they use their heads to fracture ice from below to produce small breathing holes that are easily missed by observers (Albert 1996, 2001; George et al. 1989). The Natives therefore believed that the population estimate of 2,000 animals was far too low.

Those comments were considered by scientists of the NMFS and others and a multiyear counting program was designed to assess them. The new census used both ice-based visual observations and acoustical techniques to help detect passing whales. During the spring field season of 1984 the use of passive acoustics—used to locate calling whales at distances of 16-19 km (10-12 mi)—was fully integrated into the census (Clark et al. 1985, Dronenburg et al. 1986).

To correlate the number of calls with the number of passing whales, a tracking algorithm linked a sequence of acoustic locations, visual sightings, or both to form a whale track (Ellison et al. 1987, Ko and Zeh 1988, Sonntag et al. 1986). The acoustical techniques, the associated tracking algorithm, and the related complex statistical analysis allow the visual and acoustic data to be combined (Clark et al. 1996; Clark and Ellison 1988, 1989; Sonntag et al. 1986; Zeh et al. 1990) to produce more accurate population estimates. Those estimates are submitted annually to the IWC's Scientific Committee for rigorous peer review. During the 1987 Scientific Committee meeting, that group agreed to a best estimate of 7,200 whales (2,400 standard error) (Gentlemen and Zeh 1987, IWC 1988, Zeh et al. 1988). Over the next several years, as the tracking algorithm, acoustic techniques, and statistical techniques were refined, the population size estimate became more precise and the harvest quota increased. By 1996, the IWC-accepted estimate was 8,200 whales (with a 95% confidence interval from 7,200 to 9,400) (IWC 1997, Raftery and Zeh 1998). The estimated annual rate of increase (after hunting removals) from 1978 to 1993 was 3.2% (with a 95% confidence interval of 1.4-5.1) (Raftery and Zeh 1998).

Thus, after many years of intensive study, the assertions of Alaska Native hunters were verified (Albert 2001). This prolonged and continuing effort is one significant instance in which several aspects of traditional knowledge have been confirmed by scientific study and have been used in management decisions.

REPORT ORGANIZATION

Chapters 2 and 3 set the stage by describing the human, physical, and biotic environments of Alaska's North Slope. They are not intended to be exhaustive. They present only enough information for a general overview. Chapter 4 provides the history of oil and gas activities on the North Slope. It includes brief descriptions of how oil is found, extracted, and transported, and it describes the physical infrastructure of North Slope oil fields. It ends with descriptions of recent technological advances and of how oil and gas activities can affect the environment. Chapter 5 is the committee's analysis of a plausible scenario of future industrial activity that assumes continued exploration and production. It provides the basis for the committee's predictions of how the effects of oil and gas activities might accumulate in the future.

Chapters 6-9 treat the physical environment, plants, animals, and humans, respectively, as receptors of environmental effects. Those chapters present the committee's assessments of the effects to date and the degree to which they have accumulated, and their potential to accumulate in the future. The committee also identifies some effects that appear not to have been serious or to have accumulated to date. Each chapter includes a summary of the committee's findings and research recommendations. Chapter 10 describes knowledge gaps and recommends research; Chapter 11 summarizes the committee's findings about major cumulative effects.

A series of appendixes provides additional detail on a variety of topics. They include information on committee meeting places, dates, and participants (Appendix A); abbreviations and their meanings (Appendix B); a history of factors that influence petroleum exploration and development on the North Slope (Appendix C); and a description of recent technological developments (Appendix D). Appendix E provides the analysis of oil industry data, provided mainly by BP, that was performed for the committee by Aeromap, Inc. Appendixes F and G describe spills of oil and saline water on the North Slope and some of their effects. Appendix H is a signed essay by a North Slope Native on reconciling traditional and Western scientific knowledge. Appendix I, reproduced from an EIS for leasing in the Beaufort Sea, describes the legal framework for oil and gas activities on state lands of the North Slope. Appendix J describes a method for analyzing how economic consequences of long-lasting biotic and physical effects might accumulate. Appendix K provides biographical information about the committee's members.

2

The Human Environment

The harsh climate of Alaska's North Slope shapes and limits the ways that people there live and work. The most notable factor is the extreme cold, which influences the availability of natural resources, restricts transportation and communication, and limits the ways that communities incorporate the amenities of modern western culture. Although there are areas of North America where extreme winter temperatures can be colder than those on the North Slope, the average temperatures there are too low to grow food or timber. Agriculture as a cash-producing activity, and gardens—a traditional supplemental source of food in many other rural areas—are not possible. Similarly, forestry is not possible there.

Arctic tundra is difficult terrain to traverse in summer. The flat coastal regions of the North Slope are poorly drained, so there are thousands of small shallow ponds and boggy ridges that impede transportation in summer. Most of the travel between communities on the North Slope, or between these communities and subsistence areas, is by air, by snow machine in winter when the tundra is frozen, or by water in summer. With the exception of a barge that travels to Barrow once in late summer, transportation between North Slope Native communities and areas off the North Slope is virtually entirely by air.

The NSB's eight main communities (Anaktuvuk Pass, Atqasuk, Barrow, Kaktovik, Nuiqsut, Point Hope, Point Lay, and Wainwright) are not connected to each other by road or to the rest of the state by highway. Table 2-1 provides details of past and current community populations.

Table 2-1 North Slope Population

	Anaktuvuk Pass	Atqasuk	Barrow	Kaktovik	Nuiqsut	Point Hope	Point Lay	Wainwright	Total
1939		78	363	13	89	257	117	341	1,258
1950	66	49	951	46		264	75	227	1,678
1973	134		2,167	144	128	376	31	353	3,333
1980	203	107	2,267	165	208	464	68	405	3,887
1988	264	219	3,335	227	314	591	132	514	5,596
1990	259	216	3,469	224	354	639	139	492	5,792
1993	270	237	3,908	230	418	699	192	584	6,538
1998	314	224	4,641	256	420	805	246	649	7,555

Source: NSB 1999. Anaktuvuk Pass was settled in the late 1940s; Atqasuk and Nuiqsut were abandoned, and then resettled in the 1970s, mainly by former residents of Barrow.

Approximately 70% of NSB residents are Inupiaq Alaska Natives. The remainder of the population is made up of whites (16.8%), Asians (7.2%), other Alaska Natives (2.3%), African Americans and Hispanic people (0.8%), and a sprinkling of other ethnic groups (NSB 1999). The proportion of Inupiaq people is higher in the smaller communities (Anaktuvuk Pass, 92%; Atqasuk, 95%; Kaktovik, 85%; Nuiqsut, 90%; Point Hope, 91%; Point Lay, 92%; Wainwright, 93%) than in Barrow (53%) (NSB 1999). Arctic Village, not part of the North Slope Borough, had 152 people in 2000, of whom 92% were Alaska Native (mainly Gwich'in Indians) (U.S. Census Bureau 2000).

Isolation from major transportation routes and the area's inability to produce construction materials and agricultural products mean that the prices of goods and the cost of transporting them to the North Slope are considerably higher than in the rest of Alaska or the continental United States. In 1998, the cost of a "typical market basket" in Anchorage was $122.19; in Barrow it was $218.03 (NSB 1999) and perhaps double that amount in outlying North Slope villages. Similar proportionate increases occur for vehicles, construction materials, fuel, appliances, tools, and other consumer goods. Because North Slope residents do not have greater per capita incomes than some of their counterparts in the rest of Alaska or in the United States in general (Table 2-2), North Slope residents must accept a lower standard of living, rely to a greater extent on subsistence harvest, or both.

Table 2-2 Per Capita Income for 1999 Compared

Area or Place	Income
Anaktuvuk Pass	$15,283
Atqasuk	$14,732
Barrow	$22,902
Kaktovik	$22,031
Nuiqsut	$14,876
Point Hope	$16,641
Point Lay	$18,003
Wainwright	$16,710
North Slope Total	$20,540
Alaska	$22,660
United States	$21,587

Data from U.S. Bureau of the Census 2000

By comparison, Arctic Village, which is not part of the North Slope Borough and whose residents also rely heavily on subsistence, had a per-capita income of $10,761 in 1999 (U.S. Census Bureau 2000).

The cultural knowledge and practices of North Slope people have been refined over many generations in an environment where one bad decision can lead to an individual death or even starvation of an entire village. The archaeological record shows that there were groups of people whose primary subsistence and economic emphasis was on sea mammals and other groups who relied on caribou from inland areas. Group composition and resource emphasis changed over time, depending on climate, weather, warfare, and shifting political alliances. Although the affiliations and origins of the Inupiat are still unclear, physical anthropological and archaeological data suggest that the North Slope Inupiat have lived along the coastline from Point Hope on the west to the Canadian border on the east roughly since AD 1250 to 1300. The principal form of social organization traditionally revolved around large, extended families ranging from fewer than a dozen to more than 50 people (Burch 1976). The size of a local family was determined by the resource base and the ability of family members to exploit it. Larger families were associated with plentiful game, skilled hunters, or both. Most families lived in clusters of adjacent houses.

Initial contact with Western culture came in the mid-19th century, primarily with the arrival of commercial whalers and Protestant missionaries (Bockstoce 1978, Spencer 1959). Commercial whalers hired North Slope natives as crew members; and Natives later began to captain their own vessels. By 1915, a combination of the introduction of substitutes for baleen and the decline in the bowhead whales population that resulted from overharvesting brought an end to commercial whaling. However, by this time, the cash economy was well-integrated into North Slope culture. Two sources of income rose and fell during this period. Reindeer were introduced in the 1890s by the U.S. Bureau of Education. The reindeer population increased dramatically from the 1,250 originally imported to more than 600,000 animals by the 1930s. By the 1950s, however, overgrazing, increasing predator populations, and losses because animals joined migrating caribou herds had caused the population to decline to fewer than 25,000 (Chance 1966).

Trapping had an even more precipitous trajectory. Although North Slope Natives had traditionally supplemented their incomes by trapping, many more began to do so in the early 1920s when arctic fox pelts rose dramatically in value. In the Great Depression the value of fox pelts dropped, and this source of income dried up (Brower 1942, Sonnenfeld 1956).

Steady-wage jobs were first introduced by the U.S. Navy's early petroleum exploration on the North Slope in the 1940s. Construction of distant early warning radar sites in the 1950s also provided some employment. But throughout the 1950s and 1960s, wage-earning jobs on the North Slope were scarce, and subsistence activities supplied the majority of food for most families.

SUBSISTENCE

Subsistence activities are important to Alaska Native communities of the North Slope. For residents of coastal villages, individual and community identity is tied closely to the procurement and distribution of bowhead whales. Bowhead is the preferred meat and a unique and powerful cultural basis for sharing and community cooperation. Caribou, birds, fish, and plants also are valuable subsistence resources. In inland arctic Alaska—in Arctic Village and Anaktuvuk Pass, for example—caribou are the most important subsistence resource, with lesser use of sheep, moose, and fish. Many people maintain strong cultural and spiritual ties to the resources, so that disruption of subsistence activities affects far more than food supplies.

To understand the subsistence economies of the North Slope, it helps to examine annual subsistence cycles for a coastal and an inland northern Alaskan subsistence system. The following are generic cycles, based on a combination of village and regional data sets (Figure 2-1). For people in most North Alaskan villages, individual participation in the contemporary annual subsistence cycle is both voluntary and variable. Few individuals participate in all

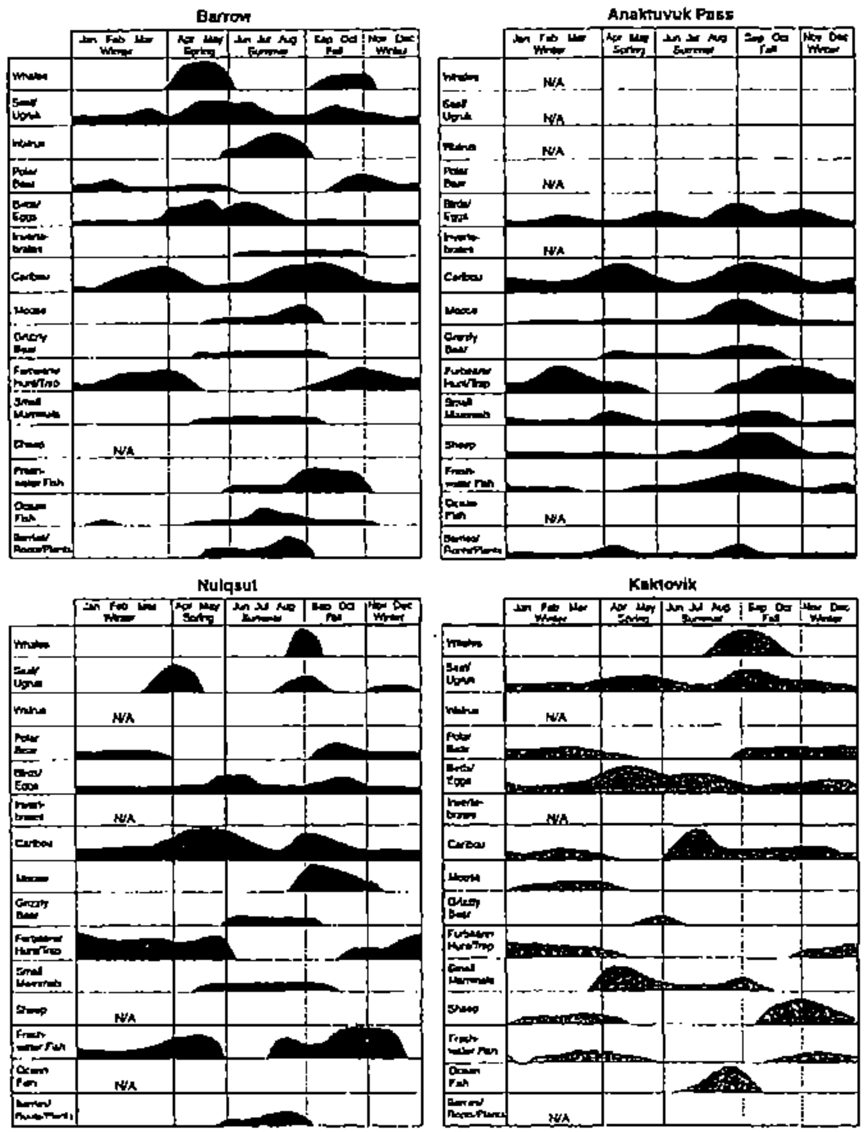

FIGURE 2-1. Seasonal subsistence cycle for four North Slope villages. Thickness of bars indicates relative importance. N/A= food source not available. Source: Galganitis et al. 2001.

activities in every season, but most participate in some. Both the system and the patterns have changed as Alaska Natives have established fixed residential bases and have incorporated new technologies into their subsistence system.

Coastal Northern Alaska

Subsistence harvest patterns for northern Alaska are well described, and qualitative information is available from history references and ethnographic sources (ADF&G 1999; Brower and Opie 1996, 1997; Hall et al. 1985; Harcharek 1995; IAI 1990a,b; Shepro and Maas 1999; S.R. Braund and Associates 1988, 1989, 1993). The following summary is adapted from the work of Galginaitis and colleagues (2001).

Coastal villages can be divided into those for which the bowhead whale is the primary resource, and those that are not geographically positioned to take advantage of spring or fall bowhead whale migrations. For the latter, ringed seal, fish, and caribou are typically the important subsistence resources.

Bowheads are the preferred meat and the most important subsistence resource of coastal villages. The bowhead provides a unique and powerful cultural basis for sharing and community cooperation, and it is the foundation of the sociocultural system (BLM/MMS 1998, Galginaitis et al. 2001). This statement is true for Barrow, Kivalina, Point Hope, Wainwright, Nuiqsut, and Kaktovik.

In pre-contact times North Slope residents expected bowhead whale hunting to provide sufficient fuel and food in four out of five winters (Mason and Gerlach 1995, Simpson 1855, in Bockstoce 1988). In 1852-1853, when few seals and whales were present in the vicinity of Barrow (Bockstoce 1988), people journeyed inland for caribou earlier in the year than usual, and they hunted birds, fished, and ate dogs (Bockstoce 1988). Barrow's subsistence varies less from year to year now than does subsistence in the smaller North Slope Borough villages, for a variety of social and economic reasons (Galginaitis et al. 2001). Quotas, level of effort, weather, ice conditions, and whale migration routes contribute to variable success in the bowhead harvest from village to village, and from year to year.

Subsistence harvest surveys were conducted in Kaktovik in 1985, 1986, and 1992. Caribou harvest surveys were completed in 1987, 1990, and 1991. The caribou harvest over this period was consistent, with a spike 1985, a year in which no bowheads were landed in Kaktovik (Galginaitis et al. 2001). Complete harvest data are available for Nuiqsut for 1985, 1993, and 1994-1995. During these years, Nuiqsut harvested only one whale. In years when the bowhead hunt is unsuccessful, fish and caribou are more important to the overall subsistence economy. In an ideal year, the annual subsistence harvest consists of roughly equal dependence on fish, caribou, moose, and marine mammals in most coastal villages.

Inland Northern Alaska

The committee considered the two inland villages of Anaktuvak Pass and Arctic Village. The subsistence patterns of the inland, predominately Inupiaq, village of Anaktuvuk Pass are not as well studied as are those of the coastal villages (Figure 2-1). Harvest data are available only for 1994-1995 (Brower and Opie 1996), although estimates are available for 1990, 1991, 1992, and 1993 (ADF&G 1999). Those and other historical records (Hall et al. 1985) show that the caribou harvest is the most important subsistence resource in all years (Binford 1978, 2002), but sheep, moose, and fish also are taken. Sharing and exchange with individuals in other communities provide Anaktuvuk Pass residents with access to a wider variety of subsistence resources than they procure directly (Galginaitis et al. 2001, Harcharek 1995, Shepro and Maas 1999). Caribou harvested near Anaktuvuk Pass most commonly come from the Western Arctic and the Teshekpuk Lake herds.

The Arctic Village Gwich'in continue to maintain strong cultural and spiritual ties to the Porcupine Caribou Herd and the Arctic Coastal Plain. The Community Profile Database generated by the Division of Subsistence, Alaska Department of Fish and Game, has no specific harvest information for the Gwich'in community. The limited studies that are available, however, indicate that there is considerable variation in the annual subsistence cycle. The emphasis is on terrestrial mammals, including caribou, moose, and sheep, and on considerable use of furbearers, hare, squirrel, and porcupine. Black and grizzly bears are harvested, but less often than moose or caribou. Ducks, geese, and ptarmigan are seasonally important, as are salmon, grayling, and whitefish. Patterson (1974) suggested that fish are almost as important in terms of quantity and calories as are terrestrial mammals. Caribou, however, are still the most important subsistence resource, integrating people across vast landscapes in northeastern Alaska and Canada.

Subsistence is more than the sum of harvest and resource procurement that has just been used to describe it. Subsistence is ideological, value-driven, and value-laden—an idiom that defines self and community. It is illustrated by specific forms of knowledge about sustainable use of land and resources. It includes a specific suite of behaviors and actions through which wild resources are procured, consumed, and distributed among relatives and neighbors across a wide network of communities.

Therefore, studies of subsistence should be integrated into broader socioeconomic research on contemporary rural life in Alaska, and subsistence activities should be studied in an integrated way that focuses on the everyday reality of life in Alaska Native communities. If this is not done, valuable traditional knowledge will be lost.

NORTH SLOPE HUMAN CULTURES IN THE OIL ERA

The discovery of oil at Prudhoe Bay catalyzed many changes that affected the human environment of the North Slope and that increasingly moved North Slope residents into the mainstream economy. The discovery of oil accelerated political processes for resolving complex issues of land tenure and rights without which investment in, and development of, the oil fields would have been impossible. Of major importance was passage of the Alaska Native Claims Settlement Act in 1971 (see Chapter 4), which established the Arctic Slope Regional Corporation and the village corporations and led to the founding of the North Slope Borough (NSB) in 1972.

The NSB largely overlaps the geographic area of Alaska's North Slope. It is larger than any municipality or county in the United States; it is in fact larger than 39 of the other states. With a land area of 230,036 km^2 (88,817 mi^2) and a human population of 7,555 in 1998, it also has a lower population density—0.033 persons per km^2 (0.085 per mi^2)—than any municipality or county in the United States. The borough's extremely rural nature and the isolation of its small communities are important to consider when assessing the effects of oil and gas activities

(NRC 1994). The population is concentrated in eight communities: Anaktuvuk Pass, Atqasuk, Barrow, Kaktovik, Nuiqsut, Point Hope, Point Lay, and Wainwright. (Deadhorse, at the northern terminus of the James Dalton Highway, is listed as a "place" by the census, but it functions mainly as a support center for the industrial complex surrounding petroleum development. In 1990, its population was 26, of whom 24 were adult males.)

Approximately 70% of NSB residents are Inupiat. The remainder of the population consists of Whites (16.8%), Asians (7.2%), other Alaska Natives (2.3%), African American and Hispanic people (0.8%), and a sprinkling of other ethnic groups (NSB 1999). There are more Inupiat in the smaller communities (Anaktuvuk Pass, 92%; Atqasuk, 95%; Kaktovik, 85%; Nuiqsut, 90%; Point Hope, 91%; Point Lay, 92%; Wainwright, 93%) than in Barrow (53%) (NSB1999). Similarly, 92.1% of Arctic Village's 2000 population of 152 consisted of Alaska Natives (Gwich'in Indians).

The NSB taxes oil and gas facilities and is responsible for education and for an array of other services including water and sewer service, electrical power, health care, housing, transportation infrastructure, and police and fire protection. The borough is the dominant economic force in North Slope communities. Among the main effects of the expansion of services and the capital improvement program were the creation of jobs in direct employment by the borough, the expansion of the educational system, construction projects for the capital improvement program, and the emergence of new businesses as a result of the growing economy. In addition, oil and gas activities have resulted in local energy production for Barrow.

The NSB government, school district, and capital improvement projects; Ilisagvik College; and city, state, and federal governments combined employ 61% of the workforce. Although they are increasingly being employed, North Slope residents are still underrepresented in the oil-field workforce, given that they are approximately 70% of the population. For companies that collected data on residency, of the 7,432 reported individuals who worked on the North Slope in 1999 and who were employed in the oil and gas sector of the economy, only 64 lived in the state's "Northern Region," which consists of Nome and the North Slope and Northwest Arctic boroughs (Alaska Department of Labor and Workforce Development 2001). Part of the explanation of the lower employment proportion is the large percentage of young people, but other factors, such as the need for specially trained, mobile professionals, also contribute. Some North Slope residents obtain oilfield jobs, and then move to Fairbanks or Anchorage. Some later return to their home village, bringing their education and income with them.

3

The Alaska North Slope Environment

The North Slope of Alaska includes about 230,000 km^2 (89,000 mi^2) north of the crest of the Brooks Range, an area slightly larger than Minnesota. It encompasses the drainage basins that empty into the Arctic Ocean and the Chukchi Sea, including the Kongakut River on the east and small drainages east of Point Lay in the west. The land slopes gradually from the crest of the Brooks Range northward to the Arctic Ocean. During the nine-month winter, temperatures can plunge to -50 °C (-58 °F). Annual snowfall averages less than 50 cm (20 in.), but the nearly constant winds produce drifts that are as much as 6 m (20 ft) deep. From November 18 to January 24, the sun never rises above the horizon in Barrow, the northernmost part of the North Slope, although there is a little midday twilight. Conversely, the sun does not set from May 10 until August 2. Annual precipitation ranges from 12 to 20 cm (5-8 in.) along the coast and up to 1 m (40 in.) in the highest elevations of the Brooks Range. Low temperatures reduce evaporation, and permanently frozen soil prevents vertical drainage of water. As a result, extensive areas of the North Slope are covered by thaw lakes, ice-wedge polygons, frost boils, water tracks, bogs, and other features typical of permafrost regions. The patterns created by these features are often difficult to perceive on the ground but are striking from the air. They are particularly well expressed in the Prudhoe Bay region.

To set the stage for the committee's analyses of cumulative effects, we next describe the diverse terrestrial, freshwater, and marine environments of the North Slope.

Terrestrial Environment

Geology

The North Slope is the largest coherent geological province in Alaska. Rocks exposed in the sea cliffs of the Chukchi Sea on the west can be identified in outcrops all the way to the Canadian border on the east. Long ridges of sandstone that continue for many miles in the foothills maintain their east-west orientation and define and expose a giant trough of folded sedimentary rocks, called the Colville Basin or Colville Syncline. The trough extends west to the Chukchi Shelf, where the associated folded structures turn to the northwest and are cut off by vertical faults that mark the eastern border of the Chukchi Basin (Grantz et al. 1994). To the south, that trough is bounded by the overthrust front of the Brooks Range. To the north, it is bounded by, and separated from, the Canada Basin of the Beaufort Sea by a buried ridge of older rocks, a composite structural feature commonly called the Barrow Arch. At Barrow the top of this ridge is only about 700 m (2,300 ft) deep. The arch plunges east to a depth of about 4,000 m

(13,000 ft) in the Prudhoe Bay area and then continues east until it loses its identity as a major structural feature in the Arctic National Wildlife Refuge (Bird and Magoon 1987). The arch extends west into the Chukchi Shelf, and to the north it slopes gently offshore to underlie the Beaufort Shelf. The south flank of the Barrow Arch forms the primary trap for the Prudhoe Bay oil field (Morre et al. 1994). Carbon-rich sedimentary rocks primarily of Mesozoic age are believed to be the source for the oil accumulations that have been found in nearly all of the sedimentary rock units of the Colville Basin.

Permafrost

Permafrost is earth material that stays frozen year-round. On the North Slope it extends to below surface depths of 200-650 m (650-2,000 ft), with the deepest permafrost occurring at Prudhoe Bay. It is insulated from the ground surface by an "active layer," which thaws each summer to a depth of 20 cm (8 in.) in some peats to more than 2 m (80 in.) in some well-drained inland soils. The active layer is subject to continuous natural change, but its disruption by, for example, destruction of the organic insulating mat, or impoundment of surface water, can initiate permafrost thawing and conspicuous surface changes. In extreme cases, called "thermokarst," the differential settlement and loss of strength creates thaw pits, ponds, retreating scarps, or mud flows. To maintain permafrost in its natural frozen condition and to avoid destructive surface settlement, buildings, roads, and other structures must be built on thick gravel foundations and off-site activities must be carefully controlled.

Surficial Geomorphic Features

The North Slope has three distinct regions: the Arctic Coastal Plain, the Arctic Foothills, and the Brooks Range (Gallant et al. 1995). All North Slope oil extraction has occurred on the Arctic Coastal Plain, but there has been some exploration in the foothills.

Arctic Coastal Plain

The coastal plain is generally flat with large oriented thaw lakes and extensive wetlands. The plain is about 150 km (93 mi) wide south of Barrow, and it narrows toward the east. The Prudhoe Bay oil field is within an exceptionally flat portion of the coastal plain (flat thaw lake plains) between the Sagavanirktok and Kuparuk Rivers (Walker and Acevedo 1987). Drainage systems in this portion of the coastal plain are often poorly defined, and much of the runoff occurs in sheet flows, which can shift direction depending on the volume of discharged water.

The Kuparuk oil field is in a somewhat hillier portion of the coastal plain (gently rolling thaw lake plains) (Walker and Acevedo 1987). The hilly aspect of this region is caused in part by large broad-based low hills, or "pingos," created by permafrost and generally 5-20 m (16-65 ft) tall (Walker et al. 1985). Gently rolling plains occur east of the Sagavanirktok River. Those regions have better-defined drainage networks, with more runoff channeled into streams instead of sheet flows.

The dominant geomorphic characteristics of the flat coastal plains are thaw lakes, drained lake basins, polygonal patterned ground, and pingos. Frost boils or nonsorted circles (Washburn 1980) cover large areas of the coastal plain and foothills. Those features typically measure 1-2 m (3.2-6.5 ft) in diameter and are the result of frost heave (Peterson and Krantz 1998). They are highly sensitive to off-road vehicle disturbance, such as that caused by seismic operations.

Thaw lakes are formed by thawing of the frozen ground (Britton 1967, Hopkins 1949) and have a distinct directional orientation attributed to the action of wind (Carson and Hussey 1959, Rex 1961). The lakes grow until they breach other lake basins or stream channels, at which point they empty, leaving drained lake basins (Britton 1967, Peterson and Billings 1980). Ice-wedge polygons dominate the terrain between lake basins. The micro-elevation differences associated with ice-wedge polygons are only a few centimeters (1-2 in.), but soil-moisture differences associated with those small changes in elevation influence the distribution of plants on the landscape.

Pingos are common in drained lake basins, particularly where the water had been deep enough to cause deep thaw zones in the permafrost (Mackay 1979). When lakes drain, those thawed areas are exposed to the weather, and permafrost re-forms. Water is expelled from the freezing soil and an ice core develops, which expands and deforms the soil, eventually forming a hill. Pingos are very stable because of their gravelly parent material and the cold climate.

Rivers west of the Colville meander sluggishly in valleys incised between 15-100 m (50-330 ft); rivers to the east of the Colville are fast flowing, braided, and have extensive delta systems. River systems support a diversity of plant and animal life and can serve as corridors for migrating mammals and birds.

The Beaufort Sea coastline is irregular and contains many small bays, lagoons, spits, beaches, and barrier islands. Extensive mud flats occur in the deltas of the rivers. Most of the coastline is low lying, with only small bluffs less than 3 m (10 ft) high. At Camden Bay, the land rises more steeply from the sea, and the bluffs are up to 8 m (26 ft) high.

Arctic Foothills

The Arctic Foothills is a band, roughly 50-100 km (30-60 mi) wide, of generally smoothly rounded hills between the Arctic Coastal Plain and the Brooks Range. Major drainage systems form broad valleys between the masses of hills. Numerous east-to-west linear bedrock outcrops occur within the foothills, reflecting the orientation of the underlying sedimentary deposits. Most of the hills have gentle slopes with parallel, closely spaced, shallow channels that are unique to permafrost regions (Cantlon 1961). The northern sector of the foothills is smoothly eroded. The hills are covered with late Tertiary to mid-Pleistocene-age glacial till, capped with more recent windblown glacial silt deposits. The southern sector was glaciated more recently (late Pleistocene), and it has many irregular glacial features. The basins between hills have peat deposits and a variety of wetlands (Walker and Walker 1996).

Brooks Range

The Brooks Mountain Range extends almost across the width of Alaska, centered at about 68° north latitude. It is a complexly folded sedimentary mass made up of shale, slate, sandstone, schist, conglomerates, limestone, marble, and granite (BLM 1998). It is incised by north-south river valleys on its north slopes. Maximum elevations reach only about 3,000 m (9,800 ft), but because of the mountains' northern location, they form a barrier to many plants—especially trees—that occur on the south slopes.

Freshwater Environments

Rivers and Streams

Several types of streams are found north of the Brooks Range (Craig and McCart 1975). *Mountain streams*, such as the Colville, Sagavanirktok, Ivishak, and Canning rivers, which originate in the Brooks Range, are the largest river systems that cross the Arctic Coastal Plain. Smaller mountain streams include the Shaviovik and Kavik rivers and most of the streams between the Canning River and the Mackenzie delta in Canada. *Spring streams* are spring-fed tributaries, generally less than 1.5 km (1 mi) long and a few meters wide, that feed the upper reaches of mountain streams. Short, meandering *tundra streams* drain the tundra-covered slopes of the Brooks Range foothills and the coastal plain. They are either tributary to mountain streams or flow directly into the Beaufort Sea. Larger tundra streams include the Ikpikpuk, Meade, Inaru, and Kuparuk rivers.

During winter, river flow ceases except perennial springs (Walker 1983), and ice forms to a thickness of about 1.8 m (6 ft). Smaller streams typically freeze completely; larger streams have water in discontinuous, deep pools. Stream habitat is reduced by 98% during winter (Craig 1989). More than half of the annual stream flow is discharged from Arctic Coastal Plain streams during the 2-to 3-week ice break-up each spring (Sloan 1987).

Lakes and Ponds

Lakes and ponds are among of the most striking landforms of the coastal plain, particularly when viewed from the air. Most lakes in the oil-field region between the Sagavanirtok and Colville rivers are shallow, typically less than 1.8 m (6 ft) deep (Moulton and George 2000). In the Colville delta, site of the Alpine oil-field development, the mean maximum lake depth is 4.5 m (15 ft). Lakes are deeper to the west and south, with a mean maximum depth of more than 9 m (30 ft) in lakes south of Teshekpuk Lake. Many of the lakes are oriented in a north-south direction, a striking feature of the landscape.

Lakes on the coastal plain are typically covered with ice from early in October until early in July. Maximum ice thickness typically reaches 1.8 m (6 ft) by April, but can exceed 2.4 m (8 ft) in some years (Sloan 1987). Shallow ponds become ice-free by mid-to late June, with deeper lakes retaining ice into early July. Teshekpuk Lake, the largest lake on the coastal plain (816 km^2 [315 mi^2]) retains its ice cover into late July or early August.

Because of the dry climate of the North Slope, a substantial amount of surface water evaporates during the short summer (Miller et al. 1980). Much of the snowmelt runoff in the coastal plain during break-up goes to replenish pond and lake water lost to evaporation in summer. In the Barrow area, only about half of the snowmelt becomes runoff; the rest goes into ponds (Miller et al. 1980). In contrast, 85% of the precipitation becomes runoff in the steep drainage basins of the Brooks Range.

Marine Environments

The Chukchi Sea extends from the 200 m (660 ft) isobath of the Arctic Ocean to the Bering Strait (Weingartner 1997). The Alaska Beaufort Sea extends from Point Barrow to the Canadian border (Norton and Weller 1984). The seafloor slopes gently for 50-100 km (30-60 mi) to form the Beaufort Sea shelf, which is among the narrowest of the continental shelves in the circumpolar Arctic. A series of linear shoals landward of the 20 m (66 ft) contour (Reimnitz and Kempema 1984) determines where ice ridges and hummocks form. The larger rivers that discharge into the Beaufort Sea form depositional delta shelves that can extend several kilometers from the shore. Some areas of the coast are directly exposed to the wind, wave, and current action of the open ocean. Other stretches of shore are protected by chains of barrier islands composed of sand and gravel that enclose shallow lagoons.

Ocean Processes

Surface circulation in the Beaufort Sea is dominated by the southern edge of the perpetual clockwise gyre of the Canadian Basin (Selkregg et al. 1975). Most of the year the gyre moves surface water and ice shoreward. The subsurface Beaufort Undercurrent flows in the opposite direction, to the east, over the outer continental shelf (Aagaard 1984). Currents in the shallower waters of the inner Beaufort Sea shelf are primarily wind driven and, thus, can flow either east or west. Because the principal wind direction during the summer ice-free season is from the east, nearshore flow is generally from east to west (Wilson 2001a).

East winds generate west-flowing surface currents that are deflected offshore in response to the Coriolis effect (Niedoroda and Colonell 1990). This offshore deflection of surface waters causes a depression in sea level (negative storm surge), which is partially compensated for by an onshore movement of underlying marine water. Under persistent east winds, bottom marine water can move onshore, where it is forced to the surface. This upwelling of marine water can cause some otherwise brackish and warm areas along the coast to become colder and more saline (Mangarella et al. 1982; Savoie and Wilson 1983, 1986). Under strong and persistent east winds, the negative storm surge causes nearshore water levels to drop as much as 2 m (6.5 ft).

When westerly winds prevail, the Coriolis effect deflects surface waters onshore, causing nearshore water levels to rise. That onshore transport of surface waters is balanced by offshore transport at depth, resulting in regional downwelling along the coast. Those wind-driven marine surges are the principal forces that determine sea level along the coast. Lunar tides along the North Slope are very small, averaging 20-30 cm (8-12 in.) (Norton and Weller 1984, Selkregg et al. 1975, USACE 1998).

The Chukchi Sea receives water flowing northward through the Bering Strait, driven by the half-meter drop in sea level between the Aleutian Basin of the Bering Sea and the Arctic Ocean (Overland and Roach 1987). Pacific waters are an important source of plankton and carbon in the Chukchi and Beaufort seas (Walsh et al. 1989), influencing the distribution and abundance of marine biota and seasonal migrations (Weingartener 1997). The deeper waters (100 m [330 ft]) offshore in the northern Chukchi Sea are a potentially important source of nutrient-rich waters. Waters upwelled from greater depths (250 m [800 ft]) contain nutrients and change the temperature-salinity structure of the northern Chukchi (Weingartner 1997).

Sea Ice

The Beaufort Sea is covered with ice for about 9 months each year. The Chukchi Sea is covered for 8 months of the year. The ice that first forms is weak and easily displaced by wind and waves, often forming pileups and ridges. By late winter, however, land-fast ice about 2 m (6.5 ft) thick extends from the shore to the zone of grounded ice ridges or to a depth of about 15 m (50 ft) (MMS 1987a, Selkregg et al. 1975). Nearshore waters shallower than 2 m (6.5 ft) freeze to the bottom. Seaward of the 2 m isobath, land-fast ice floats and can be displaced during winter into ridges.

The shear zone is a bank of deformed and dynamic ice that extends over waters that are 15-45 m (50-150 ft) deep (Barnes et al. 1984). Here, land-fast ice is sheared by the constantly moving mobile pack ice, resulting in an extensive pressure ridge system of massive ice buildups. Ridge buildups and the accumulation of old ice can be so extensive that large pieces of ice frequently gouge and plow the bottom.

The pack ice zone is seaward of the shear zone. It consists of first-year ice, multi-year ice floes, and ice islands. The pack ice moves from east to west in response to the Beaufort Sea gyre at rates that range from 2.2 km to 7.4 km (1.4 to 4.6 mi) per day (MMS 1987b). Retreat of sea ice begins in June and usually attains its farthest north position (approximately 72° N) by mid-September (NOCD 1986). High rates of biological primary productivity are normally associated with the ice edge (Niebauer 1991) and with areas of upwelling.

By mid-July, the Beaufort Sea is usually ice-free from the shore to the edge of the pack ice, which by late summer retreats from 10 km to 100 km (6 to 60 mi) off shore. River runoff, coupled with the melting of coastal ice, creates brackish (low to moderate salinity) conditions in nearshore areas, particularly near the mouths of rivers. The relatively warm water discharged by rivers and insolation elevate nearshore water temperatures. As summer progresses, this nearshore coastal band of warm, brackish water begins to cool as it mixes with the large sink of cold, arctic marine water. By late summer it is gone, and nearshore waters remain cold and saline until they freeze again in September or October (Wilson 2001a).

Biota

Plants and Vegetation

Arctic vegetation patterns and dynamics are strongly influenced by topography, climate, and soils (Walker et al. 2001a,b; 2002). For the purposes of this report, we divide the vegetation of the North Slope into six general categories (Table 3-1, Figure 3-1). Vegetation patterns in the Brooks Range are complex, but the dominant vegetation on well-drained, wind-blown slopes is generally dry tundra dominated by arctic avens (*Dryas*) (Unit 1). The Arctic Foothills are dominated by moist tussock tundra (Unit 4) with tussock cottongrass, abundant shrubs, and mosses. The Arctic Coastal Plain's wetlands are an intricate mosaic of wet, moist, and aquatic vegetation types. Wet tundra (Unit 6) is dominated by sedges, and mosses. Moderately drained (moist) areas on the coastal plain have either moist nonacidic tundra (Unit 2) with sedges, mosses, and low-growing and creeping (prostrate) shrubs or, on sandy substrates, a dwarf form of moist acidic tussock tundra (Unit 3).

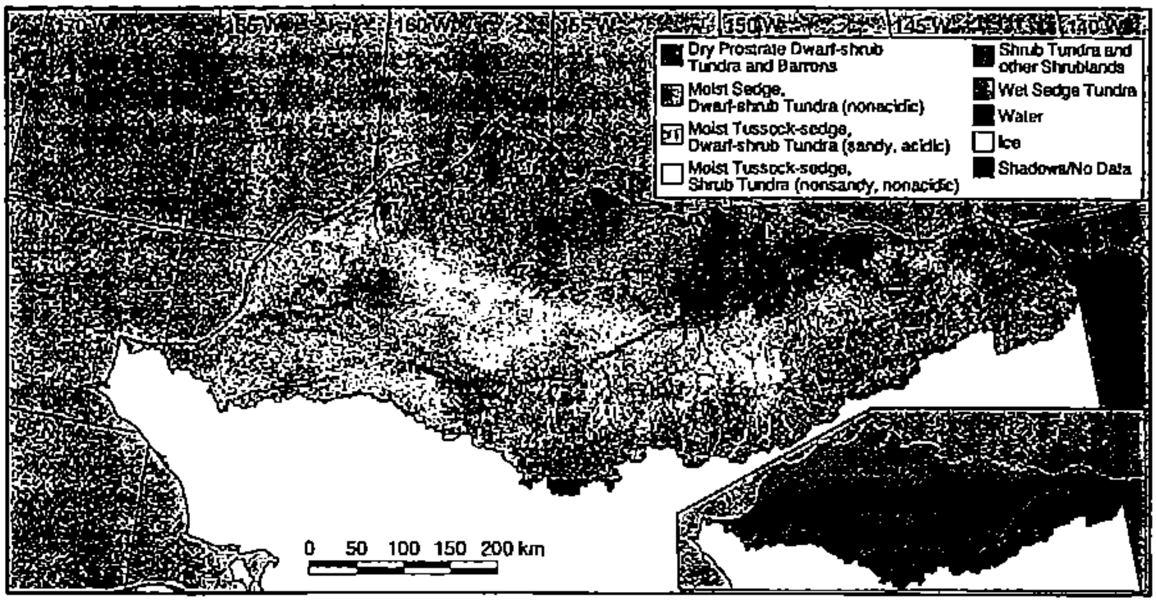

FIGURE 3-1. Major North Slope ecological regions and vegetation types. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

Table 3-1 Area, Percentage Cover of Land-Cover Classes

Unit	Vegetation	Arctic Coastal Plain		Arctic Foothills		Brooks Range		Arctic Slope	
		km^2	%	km^2	%	km^2	%	km^2	%
1	Dry prostrate dwarf-shrub tundra and barrens	1,778	3.58	1,493	1.56	13,566	24.31	16,887	8.37
2	Moist sedge, dwarf-shrub tundra (nonacidic)	12,088	24.32	20,340	21.29	11,248	20.16	43,676	21.72
3	Moist tussock-sedge, dwarf-shrub tundra (sandy, acidic)	4,958	9.97	2,540	2.66	0	0.00	7,499	3.73
4	Moist tussock-sedge, shrub tundra (nonsandy, acidic)	5,693	11.45	38,728	40.53	11,101	19.90	55,522	27.61
5	Shrub tundra and other shrublands	1,969	3.96	26,117	27.33	9,252	16.58	37,338	18.57
6	Wet sedge tundra	13,303	26.76	3,702	3.87	1,020	1.83	18,025	8.97
7	Water	9,874	19.86	2,369	2.48	535	0.96	12,778	6.36
8	Ice	17	0.03	97	0.10	1,283	2.30	1,397	0.69
9	Shadows	0	0.00	164	0.17	6,881	12.33	7,045	3.50
10	No data	31	0.06	6	0.01	909	1.63	946	0.47
	Total	49,711	100.00	95,556	100.00	55,795	100.00	201,062	100.00

Source: Modified from Muller et al. (1999).

Climate varies greatly with distance from the coast. A narrow band along the Beaufort Sea coast is influenced by the ice pack and by cold ocean waters; mean July temperatures are about 4-7 °C (39-45 °F). Shrubs near the coast are low growing or prostrate. Local flora near the coast consists of fewer than 150 vascular plant species. Most of the coastal plain is somewhat warmer in summer, with mean July temperatures of 7-9 °C (45-48 °F); the flora includes 150-250 plant species. Shrub heights in open tundra reach about 40 cm (16 in.) near the southern edge of the coastal plain. In the foothills, mean July temperatures are about 9-12 °C (48-54 °F). Tussock tundra covers vast areas, and the local flora exceeds 400 species. In the warmer areas of the foothills, shrub tundra occurs with shrubs that are taller than 40 cm (16 in.). Willows taller than 2 m (6.5 ft) and alders grow along the rivers in the foothills. Some cottonwoods grow in the warmest oases and at some springs along the rivers.

Soil pH varies considerably across northern Alaska, and it is an important factor in controlling patterns of vegetation and many other ecosystem processes. It also affects the distribution of wildlife. Much of the Arctic Foothills and a large sandy area west of the Colville River on the coastal plain have acidic, nutrient-poor soils that support tussock-tundra vegetation types dominated by tussock cottongrass, dwarf shrubs, and mosses (Units 3 and 4). Those vegetation types generally have few plant species that have low nutrient concentrations and high concentrations of anti-herbivore protective chemical compounds. In contrast, moist nonacidic tundra (Unit 2) occurs in areas with mineral-rich soils, such as loess (windblown glacial silt) deposits, alluvial floodplains, and late-Pleistocene-age glacial surfaces. These areas have relatively high soil pH; shallow organic layers; relatively warm, deeply thawed soils; more plant species; and plants with fewer anti-herbivore chemical compounds than those found in areas of acidic tundra (Walker et al. 1998). The importance of moist nonacidic tundra to wildlife has not been studied specifically, but the combination of the factors described above and the fact that all of northern Alaska's caribou herds calve in areas dominated by nonacidic tundra suggests that it is important wildlife habitat (Walker et al. 2001b).

Tundra Ecosystems

Tundra ecosystem productivity is limited by the short Arctic growing season, by low temperatures, and because plant growth cannot begin in spring until thawing of the active layer releases nutrients and water. Much of the initial growth of tundra plants in spring and early summer is supported by stored nutrients, not by current uptake (Chapin and Shaver 1985, 1988; Chapin et al. 1980, 1986). An adequate supply of nutrients, especially nitrogen and phosphorus, is required at the start of the growing season when growth is most rapid. Nutrients stored in the plants' tissues are available when most needed and are replenished later in the growing season when the soil is thawed more deeply and when aboveground growth has greatly diminished. Nitrogen-fixing species, such as legumes, alder species, and several species of moss and lichen (Chapin and Bledsoe 1992), rarely dominate tundra vegetation, but they control the input of nitrogen during vegetation succession. Nutrient storage reduces annual variations in community productivity because growth rates are strongly influenced by average conditions over several years rather than by those of the current year.

Plant species affect the quality of the soil substrate for microbes, the primary decomposers of litter. In general, deciduous leaf litter decomposes faster than does evergreen leaf litter. Mosses, lichens, roots, and woody stems decompose even more slowly (Clymo and Hayward 1982, Nadelhoffer et al. 1992). Plants also influence microbial activity by altering soil temperature, moisture, pH, and redox potential. Mosses promote low soil temperatures and permafrost development by conducting heat under cool, moist conditions and by insulating soils under warm, dry conditions (Oechel and Van Cleve 1986).

Plant species influence biogeochemistry by affecting rates of herbivory. In general, browsers and grazers prefer deciduous and graminoid (grasses and sedges) species to evergreens. If plants have a low tolerance for herbivory because of their low nutrient availability or low regrowth potential, sustained herbivory can shift the community composition toward less palatable species, thereby reducing nutrient recycling rates (Pastor et al. 1988).

The most important consumers of living and dead plant tissues in terrestrial Arctic tundra are mammals (hoofed mammals, rodents), birds (geese, ptarmigan), arthropods (insects, mites, tardigrades), and nematodes. Vertebrate herbivores of the arctic tundra all have varied diets, but the mixture of graminoids and woody species normally eaten varies among species. Few species feed heavily on lichens, other than caribou, which depend on lichens for winter feeding.

Arthropods are abundant in tundra ecosystems, but the diets of most species are not well known. About half of the insect fauna in the Arctic consists of flies (Danks 1990). The larvae of some of these species eat living plant tissues, but most of them live in the soil or mud in tundra ponds and feed on dead plant material. Other consumers of plant material are springtails (*Collembola*), moths (*Lepidoptera*), and beetles (*Coleoptera*), but their relative importance in tundra ecosystems is unknown. Water bears (tardigrades) and nematodes are abundant in tundra soils, but most species are undescribed and their feeding habits are unknown. Earthworms are unaccountably absent from North American tundra although they are found in Eurasian tundra (Chernov 1995). Lapland longspurs and snow buntings and several species of plovers and sandpipers are important avian predators of tundra arthropods.

Herbivores are the food resource for an array of carnivores that spend part or all of the year on the North Slope. The mammalian carnivores of the Arctic Coastal Plain—wolf, arctic fox, and ermine—are active year-round. Omnivorous mammals—red fox, wolverine, and brown bear—eat plant and animal matter and are important scavengers. Except for the bears, which hibernate during winter, all are active throughout the year.

Raptors in the Arctic Coastal Plain (snowy and short-eared owls and northern harriers) are generally restricted to ground-nesting species because of the small number of cliff nest sites in this region (Ritchie and Wildman 2000; Swem, unpublished material). Abundances of these species are low and highly variable (Batzli et al. 1980; Swem, unpublished material), and they fluctuate in synchrony with the lemming cycle (Batzli et al. 1980). Peregrine falcons, gyrfalcons, golden eagles, and rough-legged hawks are concentrated in the foothills of the Brooks Range, where they nest on cliffs, shale, and soil cut-banks adjacent to rivers and some lakes (Ritchie and Wildman 2000, Wildman and Ritchie 2000). Their abundances have been stable or increasing (Wildman and Ritchie 2000).

Aquatic Ecosystems

Freshwater Ecosystems

Much of the Arctic Coastal Plain is covered by shallow lakes and ponds. Those deeper than 1.8 m (6 ft) do not freeze to the bottom during winter and typically harbor fish. Shallower lakes that freeze completely during winter do not have fish but they have high densities of benthic and planktonic invertebrates. Live and decaying vegetation in those lakes is consumed primarily by larvae of arthropods, principally craneflies and midges. Those insects constitute the primary food supply for the thousands of shorebirds that breed on the wet tundra during the brief summer.

Ponds that contain emergent sedges are essential brood-rearing habitats for most ducks (Bergman et al. 1977), and islands in those ponds are preferred nesting sites for some waterfowl. Consequently, bird densities tend to be high in the mosaic of wet meadow, ponds, and drained lake basins near the coast (Cotter and Andres 2000, Derksen et al. 1981), and in riparian areas (FWS 1986). The Colville River delta also supports high densities of waterfowl and shorebirds. Lakes northeast of Teshekpuk Lake are important molting areas for brant and white-fronted geese (King 1970).

Most bird species that breed on Alaska's North Slope nest in tundra habitats, associated wetlands, or adjacent marine lagoons. More than 130 species have been recorded on the coastal plain of the Arctic National Wildlife Refuge (FWS 1986). Dominant groups, both in number of species and in abundance, are waterfowl—ducks, geese, and swans—and shorebirds. Loons are of interest because their populations are generally declining elsewhere in Alaska (Groves et al. 1996). Yellow-billed loons and eiders are of special concern because their range within the United States is concentrated in northern Alaska, where they occur in low densities. Some other species are of special concern because they congregate in large numbers to molt in coastal lagoons and wetlands.

Marine Ecosystems

The Arctic Ocean has very low biological productivity despite supporting a specialized biotic community. In winter, when marine nutrient concentrations are at their annual peak, there is little or no sunlight to drive photosynthesis. In summer, when there is ample sunlight, nutrient concentrations are low because the lack of mixing results in a stratified water column. The southern Chukchi Sea has high primary production, some of which is exported to the northern Chukchi Sea and the Arctic Ocean (Walsh et al. 1989). The ecology of the northern Chukchi Sea is poorly understood, but the presence of the ice edge and upwelling suggests high biological production (Weingartner 1997). In general, sea ice plays a complex ecological role through spring lead zones, polynyas, and other seasonal changes in structure.

Inorganic nutrient concentrations in the surface waters of the Beaufort Sea are typically lowest during summer, when nitrate and phosphate are almost undetectable (Horner 1981) because of phytoplankton uptake and water column stratification. During winter, stratification slows and increased vertical mixing replenishes surface-water nutrients. Strong upwelling in some regions of the Beaufort Sea supplies deep, nutrient-rich ocean water to nearshore areas. River discharge is another source of nutrients, especially nitrates and silicates, during the spring thaw when river flows are at their peak (Wilson 2001b).

Primary production in the Arctic Ocean is carried out by three groups of organisms: phytoplankton, epontic ice algae (algae that grow on the under surface of ice), and attached benthic macroalgae. Benthic microalgae, which consist primarily of diatoms, do not contribute significantly to primary production in the Arctic Ocean (Dunton 1984, Horner and Schrader 1982).

More than 100 phytoplankton species, mostly diatoms, dinoflagellates, and flagellates, have been identified from the Beaufort Sea (MMS 1987b). Phytoplankton are generally most abundant in nearshore waters shallower than 5 m (16 ft) (Horner 1984, Schell et al. 1982). Except for isolated areas near Barrow and Barter Island, there are none of the dramatic plankton blooms in the Beaufort Sea that are typical of more temperate waters (Horner 1984). Rather, there is a gradual, moderate increase in phytoplankton biomass that begins in late spring with ice break-up, peaks in mid-summer when sunlight is most intense, and decreases in late summer when the days shorten.

Because of the low primary production, zooplankton communities are characterized by low abundance, low diversity, and slow growth rates (Cooney 1988). Herbivorous copepods dominate the Beaufort Sea zooplankton (Johnson 1956, Richardson 1986); amphipods, mysids, euphausiids, ostracods, decapods, and jellyfish (Wilson 2001a) also are present.

The abundance and diversity of infauna—invertebrates in the substrate—tends to be low during summer in nearshore areas shallower than 2 m (6.5 ft) because that zone is covered by land-fast ice in winter. Sedentary infauna are slow to recolonize the disturbed benthic environment. Biomass and diversity increase with depth, except in the shear zone—15-25 m (50-80 ft)—which is subject to intensive ice gouging that presumably destroys substrate-inhabiting organisms. Seaward of 40 m (130 ft), ice no longer disturbs the benthos (Carey 1978). Infaunal species include foraminifera, polychaetes, nematodes, amphipods, isopods, bivalves, and priapulids.

Organisms that live on the surface (epifauna) are more motile and readily dispersed by currents. Some groups, such as mysids, migrate on and offshore seasonally (Alexander et al. 1974, Griffiths and Dillinger 1981). Epifaunal organisms are an important food source for several bird and fish species that inhabit coastal waters during summer (Craig et al. 1984).

Epontic communities consist of microorganisms, mostly diatoms, that live on or in the under-surface of sea ice (Horner and Alexander 1972). Light is the major factor that controls the distribution, development, and abundance of those assemblages (Dunton 1984, Horner and

Schrader 1982). Epontic algae are estimated to contribute 5% of the annual total primary production in nearshore Beaufort Sea coastal waters (Schell and Horner 1981). Ice algae assemblages serve as a food source for a variety of invertebrates, including copepods and amphipods, particularly during early spring when other sources of food are in short supply (Wilson 2001a).

Much of the Beaufort Sea floor is covered by silt and sand (Barnes and Reimnitz 1974), but there is an isolated area of rock- and cobble-littered seafloor, called the Boulder Patch, several kilometers offshore from the mouth of the Sagavanirktok River in Stefansson Sound (Dunton and Schonberg 1981, Dunton et al. 1982, Martin and Gallaway 1994). The Boulder Patch supports a community of several species of large red and brown algae and a diverse assortment of invertebrates representing every major phylum (Dunton and Schonberg 2000, Dunton et al. 1982, Martin and Gallaway 1994).

The most conspicuous member of the community is the kelp, *Laminaria solidungula*. Beneath the overstory is another seaweed assembly dominated by several species of red algae. Kelp produce 50-56 % of the carbon available to Boulder Patch consumers. Growth of kelp is both energy- and nitrogen-limited because those two resources are not available in sufficient quantities simultaneously (Dunton 1984). Sponges and cnidarians are the most abundant and conspicuous invertebrates in the Boulder Patch community. Bryozoans, mollusks, and tunicates are common on rocks and attached to other biota. A species of chiton constitutes a large percentage of molluscan biomass and is one of the few species that graze on kelp.

The abundance and diversity of epifauna in nearshore waters that are shallower than 2 m (6.5 ft) in summer is similar to the abundance and diversity in deeper surrounding zones because mobile invertebrates can rapidly recolonize shallows once the ice lifts off the seafloor and the ice cover recedes. Some species find winter habitat in deep holes within the land-fast zone. Mysids and amphipods dominate the nearshore epifaunal community (Griffiths and Dillinger 1981, Moulton et al. 1986). Epifauna from 33 trawls done in the northern Chukchi and western Beaufort Seas in 1977 were described by Frost and Lowry (1983), who identified 238 invertebrate species or species groups and two major community types.

The mobility of epifauna, either active or via passive transport, can be critical in maintaining a robust food web. Griffiths and Dillinger (1981) estimated that feeding by birds and fish within Simpson Lagoon would be sufficient to deplete the basin of mysids rapidly were it not for a substantial and continual immigration of mysids from offshore coastal waters.

Seventy-two species of fish have been identified in freshwater and marine habitats on and around the North Slope, although only 29 of them are common. Some 17 species, of which arctic cisco (*Coregonus autumnalis*) and broad whitefish (*C. nasusare*) are of highest value, are important for the subsistence harvest.

Several bird species use arctic marine environments for food, including gulls, loons, and the sea-duck species. The coastal barrier island and lagoon systems are important molting and staging areas for waterfowl. Most waterfowl species depend more on freshwater than saltwater for their habitat and food requirements. The Beaufort Sea is also important habitat for whales, seals, and polar bears.

4

History of Oil and Gas Activities

The Inupiat used oil and gas seeps for fuel in Arctic Alaska long before the first whalers or other outsiders ventured to the North Slope. Active industry exploration began in the late 1950s when federal geological studies supported the premise that a significant reserve potential existed, and the land was released for industry leasing.

By 2001, oil development on Alaska's North Slope consisted of 19 producing fields and a network of roads, pipelines, and power lines that connect drill sites, production facilities, support facilities, and transportation hubs. Most of those facilities were in place before 1988, by which time the rate of growth had declined because of the full development of the large Prudhoe Bay and Kuparuk oil fields and as a result of changes in technology.

Highlights of the North Slope's oil and gas exploration and development history are summarized in Table 4-1. Appendix C is a more thorough description.

Table 4-1 Oil Exploration and Development on the North Slope

Before recorded history	Visible oil seepages used by Native inhabitants of the North Slope
1882	U.S. government representatives hear of oil seepages while traveling in the area
1886	First non-Natives see seepages at Cape Simpson
1909	First description of Cape Simpson deposits published
1914	First oil-related claim staked
1921	Additional claims staked by individuals and industry
1921	Large deposits of oil discovered in Oklahoma and Texas; industry loses interest in the remote Arctic
1922	First industry-sponsored geological investigation of North Slope oil potential
1923	Naval Petroleum Reserve No. 4 (PET-4) established
1923-1926	First analysis of National Petroleum Reserve-4 potential
1943	Territory of Alaska Bureau of Mines sends field party to the North Slope to investigate oil and gas seepages
1944	Start of PET-4 petroleum exploration program. PET-4 headquarters established at Barrow Land north of the drainage divide of the Brooks Range withdrawn from public entry by the secretary of the interior, Public Land Order 82

Table 4-1 (continued)

1945-1952	Numerous geophysical studies conducted across PET-4 find oil and gas
1947	Office of Naval Research establishes Arctic Research Laboratory
1953	National Petroleum Reserve-4 unexpectedly recessed
1953-1968	Federal geologic field studies continue in National Petroleum Reserve-4; several major oil companies begin exploration
1957	Oil discovered in Cook Inlet (south-central Alaska)
1958	Public Land Order 82 modified; federal leasing begins on the North Slope; first industry-sponsored geological field programs; Alaska Statehood Act passed
1962	First industry-sponsored seismic program
1963-1967	First industry exploration well drilled on the North Slope; 11 unsuccessful wells drilled; industry interest in the North Slope wanes
1964	First State of Alaska lease sale on the North Slope
1965	Area that eventually includes Prudhoe Bay leased
1967	Initial exploratory drilling at site that would become Prudhoe Bay field
1968	ARCO announces the discovery of Prudhoe Bay oil field, the largest in North America
1969	Kuparuk, West Sak, and Milne Point fields discovered; lease sales suspended on the North Slope for the next 10 years because secretary of the interior imposes freezes due to Native Claims
1970	Alaska Environmental Policy Act passed
1971	Alaska Native Claims Settlement Act passed
1974-1976	Federally sponsored exploration along the Barrow Arch
1976	National Petroleum Reserve-4 is transferred from the Navy to the Department of the Interior and renamed the National Petroleum Reserve in Alaska; sale of crude oil from the Petroleum Reserves 1, 2, and 3 authorized
1977	Trans-Alaska Pipeline system operational
1979	Initial leasing of portions of state and federal outer continental shelf (OCS) waters of the Beaufort Sea
1980	Alaska National Interests Land Conservation Act passed
1981	First OCS exploration well drilled
1982	Initial leasing of portions of the National Petroleum Reserve-Alaska
1984-1985	Seismic exploration of the Arctic National Wildlife Refuge 1002 Area conducted
1985	First industry exploration well drilled in the National Petroleum Reserve-Alaska
1986	Arctic Slope Regional Corporation well drilled within the coastal plain of the Arctic National Wildlife Refuge
Various times	Initial leasing of portions of Arctic Slope Regional Corporation lands
Early 1990s	Last of the National Petroleum Reserve-Alaska leases from the initial leasing program are relinquished
1994	Discovery of Alpine field
2001	Northstar field begins production Development of Liberty field suspended

Maps depicting active leases (Figure 4-1) and exploration wells (Figure 4-2) indicate where industry interest, intensity of exploration, and infrastructure have been concentrated, but both leasing and exploration have covered additional areas not mapped. During the 1990s, interest expanded from the Prudhoe Bay area to the west into the National Petroleum Reserve-Alaska and offshore. More recently, leasing has moved south into the foothills of the Brooks Range and in the Point Thompson area.

The Prudhoe Bay oil field was established in 1968 with a small airstrip, a camp, and a peat road to an exploration well (Figure 4-3). The only permanent structures in the area before those were the distant early warning line facilities at Point Strokerson and Oliktok, and a few sod houses built by the Inupiat. By 1970, after the confirmation of the Prudhoe Bay oil field, airstrips, roads, and other gravel infrastructure was built or expanded to connect distribution centers to camp facilities and remote drilling sites. The growth of this development is shown in Figures 4-4, 4-5, and 4-6. An important milestone was the completion of the North Slope Haul Road, eventually called the James Dalton Highway, which formed the work path for constructing the Trans Alaska Pipeline and links Prudhoe Bay to the outside world.

Box 4-1 The Haul Road

The Haul Road (James Dalton Highway) runs 667 km (415 mi) from Livengood, which is near Fairbanks, to Deadhorse, Alaska. The sole overland route to the North Slope, the northern portion of the Haul Road was closed to the public until 1995, when the highway was opened to public access as far as the security gate at the Prudhoe Bay oil field. Annual truck traffic has increased substantially since the early 1990s. In 1996, 45,000 trucks used the road (National Petroleum Reserve-Alaska FEIS III.C-55).

To the west, the Kuparuk oil-field road network began to expand in 1978. The average length of roads added each year during expansion (26.1 km [16.2 mi]) (Walker et al. 1986a) was similar to that at Prudhoe Bay (22.5 km [14 mi]) (Walker et al. 1986a), although gravel pads at Kuparuk were smaller and spaced farther apart than were those at Prudhoe Bay.

After 1977, gravel mining in upland tundra sites replaced floodplain scraping as the source of roadbed material. Those deeper mines reduced the area of disruption caused by mining, and the effects on diverse riparian systems were reduced as a result.

ANATOMY AND OPERATION OF NORTH SLOPE OIL FIELDS

Oil-field operations on the North Slope involve four distinct but closely related phases: leasing, exploration, development, and production and transportation. We present these sequentially for clarity, but they can occur out of sequence. For example, seismic exploration can occur before leasing or during the development phase. Each phase has unique elements and some that are shared with other phases. The result is the complex diagrammed in Figure 4-7.

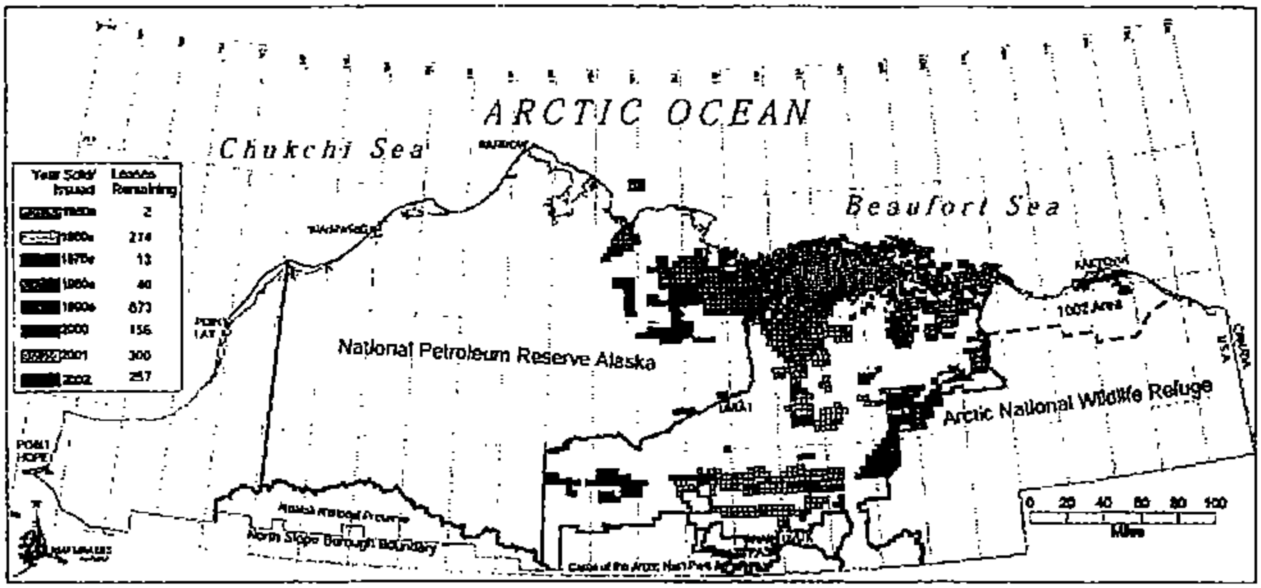

FIGURE 4-1. Time of acquisition of current leased lands on the North Slope of Alaska. The leases acquired during the 1900s are shown by decade and those since 2000 by year. The age of the leases indicates the recent shift in exploration interest to the south and west. Earlier leases that have been relinquished are not shown. Drawing by Mapmakers Alaska 2002.

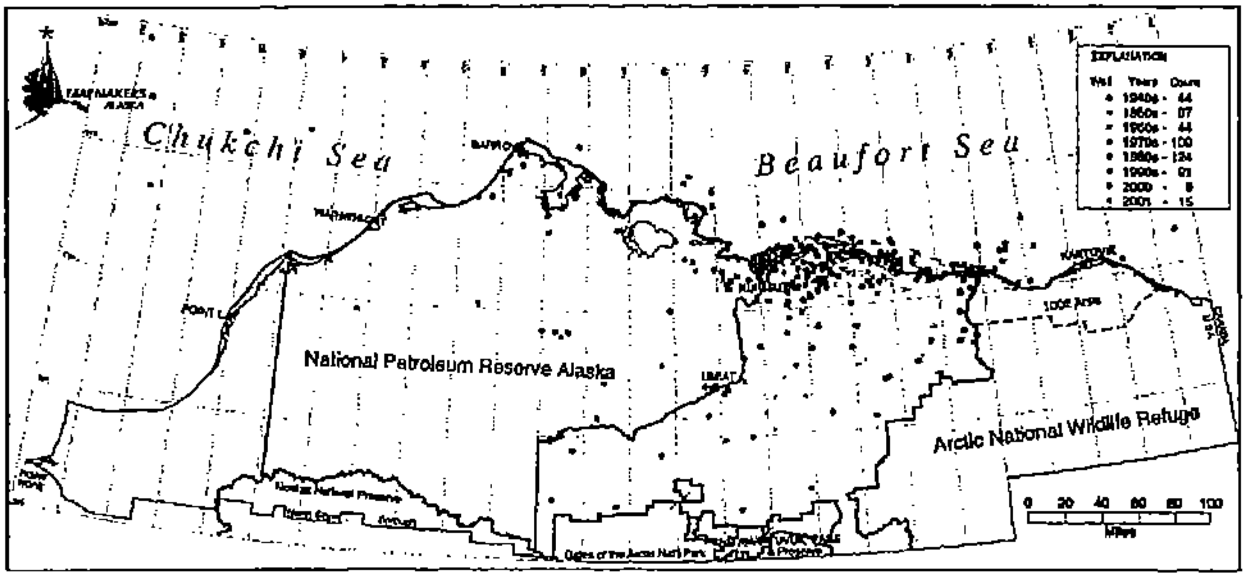

FIGURE 4-2. Location and drilling date of exploration wells on the North Slope of Alaska. Wells drilled during the 1900s are grouped by decade and those since 2000 are depicted by year. Note the heavy concentration of exploration drilling along the Barrow Arch, between the National Petroleum Reserve-Alaska and the Arctic National Wildlife Refuge. Drawing by Mapmakers Alaska 2002.

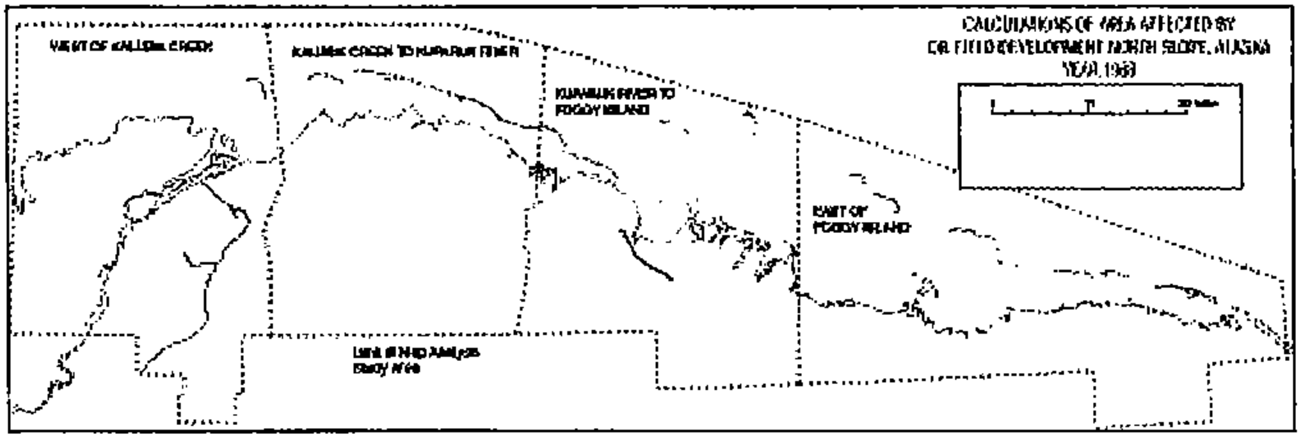

FIGURE 4-3. Road network for oil-field development, 1968. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

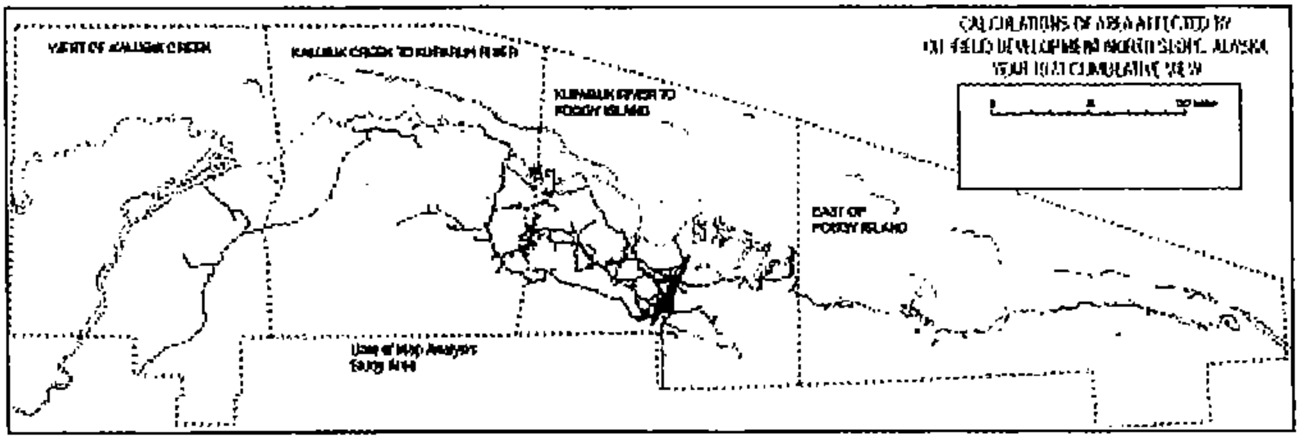

FIGURE 4-4. Road network for oil-field development, 1973, cumulative view. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

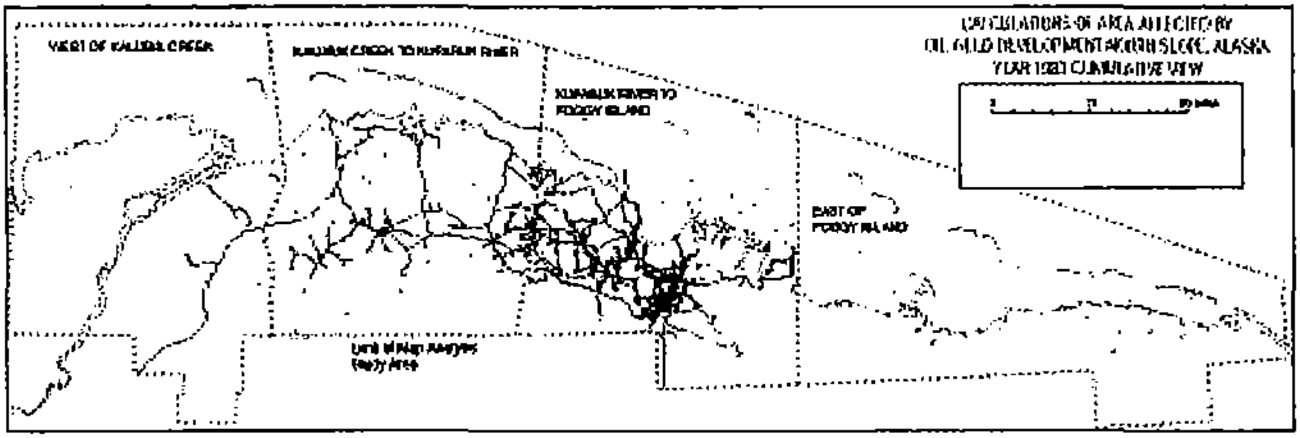

FIGURE 4-5. Road network for oil-field development, 1983, cumulative view. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

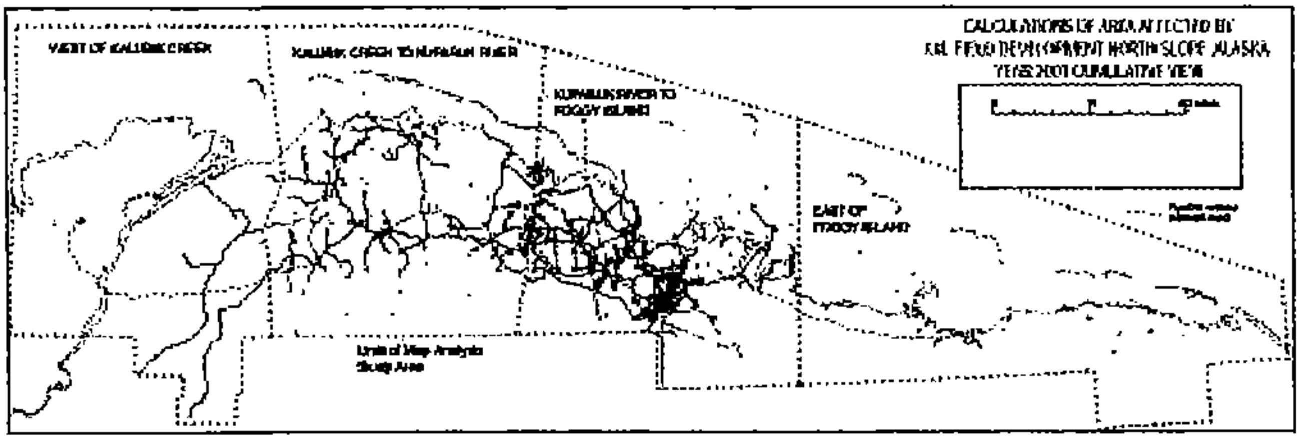

FIGURE 4-6. Road network for oil-field development, 2001, cumulative view. Area calculations were obtained from topographic maps and historical aerial photography provided by BP Exploration (Alaska) Inc. Funded by the National Academies. Interpretation and calculation were done by Ken Ambrosius, Aeromap USA 2002.

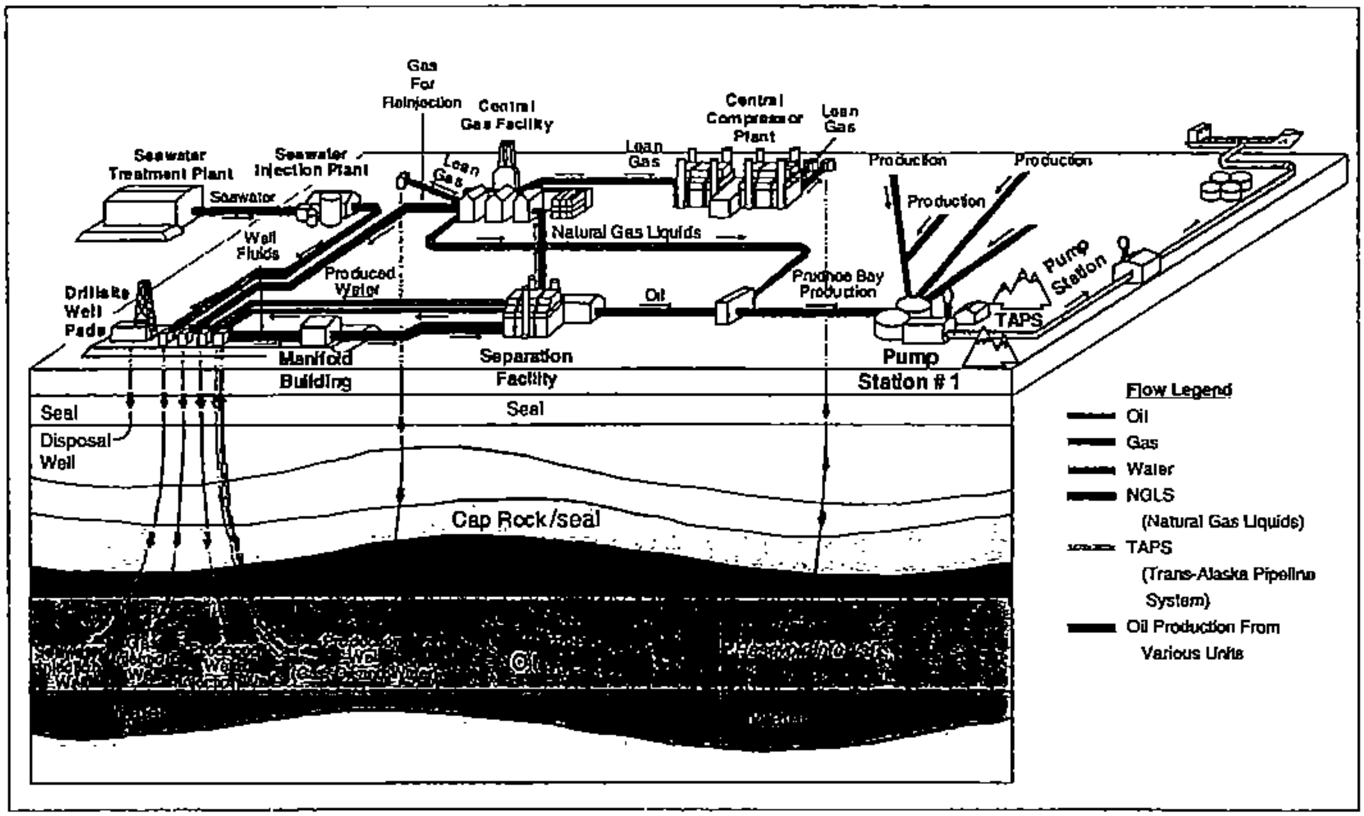

FIGURE 4-7. Schematic diagram of North Slope oil-field operations. Source: Modified from Alaska Department of Natural Resources, Division of Oil and Gas, unpublished material 1996.

Leasing

Mineral rights, or the right to extract resources from beneath the ground, are sometimes, but not always, attached to the ownership of the surface area. Either way, clear title to mineral rights must be obtained through purchase or lease.[1]

When rights are owned by a public institution, such as a state or the federal government, the leasing process is public, and it usually is preceded by announcements of lease sales and by competitive bidding. Information concerning leasing, or even potential leasing and development, usually affects various interested parties.

Exploration

Exploration, the most widely dispersed activity, leads to development and production when economically developable quantities of oil or gas are discovered. Historically, such quantities have been found 10-20% of the time in "frontier" areas and as much as 60-70% of the time in mature areas near established fields.

Seismic Exploration

Unless a well is in a previously tapped reservoir, one or more seismic surveys usually are conducted before drilling begins. An initial summer survey of a proposed area is followed by winter surveys that use vibrating equipment and receivers placed on the tundra along a rectilinear grid. The vibrators generate sound waves that bounce off underground rock. The returning sound is picked up by the receivers and analyzed and mapped by computers. Mobile survey camps responsible for collecting seismic data are typically moved by D-7 Caterpillar tractors, although some of the tractors have been replaced by roller-tracked vehicles. Support vehicles shuttle to permanent facilities to deliver fuel and supplies.

Land-based two-dimensional (2-D) and three-dimensional (3-D) seismic surveys are done in winter when the tundra is frozen and snow-covered and when most animals have left an area, are in maternity dens, or are hibernating. Three-dimensional seismic lines usually are spaced a few hundred meters (several hundred feet) apart in grids. Lines in 2-D grids are spaced up to 10 km (several miles) apart. Today, 2-D surveys have been largely replaced by 3-D data acquisition. Because of the vulnerability of the tundra to disturbance of the organic mat and underlying permafrost, these off-road surveys have been restricted by the Alaska Department of Natural Resources. Seismic exploration is permitted when the ground is frozen to an average depth of 30 cm (12 in.) and when snow depth averages 15 cm (6 in.). From 1990-2001, 24,938 km (15,499 mi) of seismic lines was surveyed in northern Alaska.

Offshore vessels cruise similar grid patterns during the ice-free season, using high-pressure airguns instead of vibrators to generate sound waves. In the intermediate area of land-fast ice, seismic data often are acquired during winter with land-based instruments.

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[1] On the North Slope, most oil production is on state land; leasing and exploration mostly occur on state and federal land. Some leasing, exploration, and production occur on Native land. The Arctic Slope Regional Corporation has subsurface mineral rights in some areas. The Beaufort Sea out to three miles is under state control; beyond that it is federal. Northstar is the only facility currently producing oil in federal waters off the North Slope.

Exploratory Drilling

After seismic surveys indicate that commercially feasible quantities of oil or gas are present, exploratory drilling begins. Today, onshore exploratory drilling is a winter activity based on ice roads and ice drilling pads; no permanent structures are built. In remote locations, an ice airstrip is built so that people and supplies can be flown to the site. In areas where prospects are closely spaced, or where confirmation wells are required, a single rig can drill 2 or 3 wells in a season. A typical exploratory well requires 14-45 days to drill.

Large amounts of water are used in these operations. Drilling a single exploratory well can use 5.7 million L (1.5 million gal); another 1.4 million L (360,000 gal) generally would be required for camp use. The Bureau of Land Management estimates that 3.8 million to 5.7 million L (1 to 1.5 million gal) of water is needed per mile to build an ice road 15 cm (6 in.) thick and 9-11 m (30-35 ft) wide (USACE 1998). Ice roads can extend for many kilometers, and they are increasingly used as a less expensive and less environmentally damaging alternative to gravel roads. For the winter of 2001-2002, 420 km (260 mi) of ice-road building was planned.

Offshore, exploration wells are drilled in the winter from ice islands, artificial gravel islands, natural islands, or drilling vessels or structures, depending on water depth and distance from the shore. Nearshore exploration—including most exploration in state waters—can be conducted from existing onshore facilities or from ice pads.

Exploratory drilling uses diesel engines to turn a drill bit, which cuts through the surface and the rock beneath. Drilling "mud" or fluid, a thick barite solution with various additives, is pumped down the center of the "drill string" (sections of pipe that are added as the bit descends). The mud returns to the surface in the space between the drill string and the casing for cleaning and re-use or for disposal.

Drill mud has three purposes. First, it lubricates the drill bit. Second, it brings the "cuttings," small pieces of rock that the bit grinds, to the surface. These are filtered at the surface and the mud is re-injected. Finally, the weight of the mud seals the well against pressure that is encountered in the well. Well casings, drill strings, mud, cement, diesel fuel, various types of equipment, and people are all transported to drill sites over ice roads or by aircraft.

In remote locations, such as the North Slope, oil-field activities require a concentrated work schedule. Commonly, workers meet and are transported to the drill site, where they stay for 1-2 weeks. Drilling continues around the clock, and two complete crews at the drill site rotate in 12-hour shifts. After 1 or 2 weeks of work, workers generally have time off, usually for the same period as the work cycle.

Development

Once an economically viable discovery is made, development begins. This phase involves additional drilling, and so begins construction of roads; airstrips; and waste-disposal, seawater treatment, gas-handling, power generation, storage, maintenance, and residential facilities (Figure 4-8). Most roads and other permanent facilities must be built on thick gravel pads, and pipelines and heated structures must be elevated on pilings to prevent thawing of the underlying permafrost and subsidence of the ground. Some 954 km (596 mi) of roads, 2,338 hectares (ha [5,777 acres]) of pads, and 116 ha (287 acres) of airstrips are spread across a contained development area of more than 2,600 km^2 (1,000 mi^2) of the North Slope, an area

FIGURE 4-8. Fields and Units, North Slope and Beaufort Sea. Drawing by Mapmakers Alaska 2002.

roughly as big as the land area of Rhode Island, which is 2,707 km^2 (1,045 mi^2). The area covered by gravel is about 3,700 ha (9,200 acres). This does not include the area covered by gravel fill or excavation for the Trans-Alaska Pipeline and Haul Road on the North Slope or the exploration facilities in the National Petroleum Reserve-Alaska.

Offshore gravel islands support production operations. Twenty such islands have been constructed in the Beaufort Sea (ADNR 2001a), including two at Endicott and one at the Northstar site. The Endicott islands are connected to each other and to the mainland by an 8 km (5 mi) causeway and are situated in waters generally less than 2 m (6.5 ft) deep (AOGA 2001). The 2 ha (5 acre) Northstar island site is located 6 km (4 mi) northwest of the Pt. MacIntyre field in 12 m (39 ft) of water (BP Northstar 2002).

The shallowness of the Beaufort Sea in the Prudhoe Bay prevents large vessels from docking there. Three gravel causeways have been constructed to facilitate docking, to provide access to artificial-gravel production islands, and to draw seawater for waterflooding. The causeways are 335 m (1,100 feet), 4 km (2.5 mi), and 8 km (5 mi) long, respectively (AOGA 2001).

Large quantities of gravel are required for building roads, and pads and for other purposes. From 1972 on, more than 56 million m^3 (73 million yd^3) of gravel (ADNR 2001b) was extracted from 24 open-pit gravel mines affecting some 2,546 ha (6,364 acres) of stream and river beds and upland sites on the North Slope (MMS 2001a; Gary Schultz, ADNR, personal communication, 2001). Similarly, construction and postexploration drilling require large amounts of water. Overall, the Alaska Department of Natural Resources (ADNR) estimates that 1.5 billion gal (5.7 billion L) of water was used by North Slope oil and gas operations in 2000 (ADNR 2000).

Facilities needed during development phase generally are constructed elsewhere, and transported to the North Slope on barges in late summer, and then moved by road to the pads. Workers and materials are brought in on the Dalton Highway or by air.

Production and Transportation

Production and transportation follow completion of development, but development activities often continue long after production begins. The major difference between this and the previous stages is that large volumes of fluids are handled, transported, and disposed. This phase involves drilling wells for enhanced oil recovery or waste disposal and the construction of pipelines to move oil, gas, "produced water" (water, often in very large volumes, that is extracted with the oil from a reservoir), and drilling wastes to the existing transportation infrastructure or to injection facilities. To maintain reservoir pressure, water is withdrawn from the Beaufort Sea and injected into oil-bearing formations. Because North Slope natural gas currently is uneconomical to market, gas that is not needed to fuel operations is injected back into the originating formation.

Until recently, gathering and distribution networks required gravel roads; currently those pipelines are built during winter via ice roads. All oil produced on the North Slope is fed through gathering lines to the Trans-Alaska Pipeline. The 1,300 km (800 mi) long pipeline leads to a tanker terminal in Valdez, on Alaska's south-central coast, from which oil is then shipped to refineries in the lower 48 states and, since 1996, in Asia.

On- and off-road vehicles, helicopters, fixed-wing aircraft, and seagoing vessels of various sizes transport equipment, materials, and people throughout the life of the oil field. Air, ground, and marine transportation needs are substantial. For example, the construction phase of the Northstar project involved about 35,000 surface trips by bus, truck, and other vehicles. Transportation needs drop dramatically after construction is complete.

Power generation and waste disposal continue throughout the life of an oil field. On the North Slope, power is generated by gas-fired turbines and heaters; diesel engines power most exploratory equipment as well as trucks, buses, and heavy equipment. These facilities and vehicles emit substantial amounts of air pollutants. Oxides of nitrogen (NO_x) constitute the largest single category of pollutants emitted. In 1999, oil and gas operations on the North Slope emitted some 70,000 metric tons [t]) of NO_x per year[2] (ADEC 2002). In 1994-1995, North Slope facilities[3] also emitted about 11,000 t of CO, 1334 t of SO_2, 5,400 t of particulate matter, and 2,400 t of volatile organic compounds during 1994-1995 (USACE 1999). Annual CO_2 emissions from Prudhoe Bay facilities are estimated[4] at 7.3 million t (Jaffe et al. 1995) to more than 40 million t (Brooks et al. 1997). Methane emissions have been estimated at 24,000 t (Jaffe et al. 1995). A final category of emissions is airborne particles, generated by construction activity and vehicular travel on gravel roads, than can significantly affect adjacent tundra.

Most North Slope waste is generated in exploration and production activities. More than 76,500 m^3 (100,000 yd^3) of solid waste is generated by oil-field operations on the North Slope each year (ADEC 2001, BP 1998). Waste includes oil-contaminated wastes, spill-cleanup materials, batteries, scrap metal, paper and polystyrene waste, tires, construction debris, wrecked vehicles, insulation, old drilling rigs, and food and domestic waste. These wastes are recycled, disposed of in the Deadhorse landfill, or incinerated. The North Slope Borough received 74,161 m^3 (97,000 yd^3) of waste in 2000. The committee did not have enough data to perform additional analyses.

Liquid wastes include sewage and domestic wastewater, desalination treatment discharges, and seawater-treatment-plant discharges. No data on the amount of liquid wastes generated by oil and gas operations on the North Slope were available to the committee (ADEC 2001). Treated sewage and domestic wastewater typically were discharged to tundra ponds or to surface impoundments until recently. Desalinated and seawater treatment wastewater are discharged to the ocean (ADEC 2001).

Waste associated with oil-field exploration, development, and production includes waste from drilling operations, which generate up to 1.1 million L (300,000 gal) of waste muds and "cuttings" per well (BP 1998); produced water, an average of 1.23 million barrels (bbl, 51.7 million gal, 196 million L) per day, typically containing a variety of organic pollutants and toxic metals (MMS 2000), usually reinjected; and "associated waste," which is other waste from oil or gas exploration and production—hydrostatic test fluid, oil and oily water, tank-bottom sludge, waste from well workovers and stimulations, pipeline pigging waste, and gas dehydration

[2] ADEC memo and spreadsheet, 5/17/02, ascribe 56,000 t to facilities emissions and 14,000 t to mobile sources.
[3] Includes emissions from Prudhoe Bay Unit western and eastern operating areas, Milne Point, Endicott, and Lisburne. Does not include Kuparuk, Alpine, North Star, Badami, or Pt. McIntyre, or any drilling or vehicle emissions (U.S. Army Engineer District, Alaska). Current allowable emissions are much higher for CO (18,040 t) and SO_2 (2,330 t) (Phillips, personal communication, 2001).
[4] Jaffe and colleagues (1995) calculated CO_2 emissions based on fuel use data reported to the state by the oil companies. Brooks and colleagues (1997) extrapolated observed emissions during 30 flights downwind of the oilfields. Their estimates were 6 times greater than those in Jaffe's report, and 4 times greater than total carbon emissions reported by oil facilities for the same months during which measurements were made.

wastes. In addition, the more than 9 t of waste generated each year on the North Slope that qualifies as hazardous, according to the Environmental Protection Agency (EPA) rules, is shipped to disposal facilities in the continental United States (BP 1998).

Generally, wastes are grouped as Class I (nonhazardous) or Class II (exempt) and are handled and disposed of in distinct classes of disposal wells. Oil-field wastes associated with exploration and production were specifically exempted from hazardous-waste regulation by Congress in 1980 (Section 3001 {b}[2](A), Resource Conservation and Recovery Act) regardless of whether that waste would otherwise meet EPA's criteria for hazardous-waste classification. The quantity of those wastes generated on the North Slope is unknown (ADEC 2001). Most of it is injected into subsurface formations.

Class I wastes consist principally of water and are considered nonhazardous. They are largely disposed of through injection into Class I disposal wells (Billington, Shafer, and Billington Environmental Consultants, unpublished, 1997), of which there are 7 in all, at Alpine, Badami, Prudhoe Bay, and Northstar (Maham 2001). The volume of fluid injected to date exceeds 12 million bbl (1.9 million L, 504 million gal). The principal injection horizons are porous Cretaceous sandstones at depths of 610-2,400 m (2,000-7,900 ft) that provide well-confined disposal zones. In the westernmost portions of the area, the formations are in the permafrost zone. The Alpine well injects wastes into formations at a depth of about 2,700 m (9,000 ft).

Class II wastes come directly from oil or gas wells. They include all produced fluids, muds, and associated wastes that have circulated in the well and solids and ligands that originate down-hole, such as formation water (BP 1998). Drilling muds are water-based materials with clays, weighting materials, and various additives. Cuttings are rock fragments derived from drilling the well. The cuttings are finely ground and injected with drilling muds. Produced water comes to the surface with oil and gas and must be removed before the oil can be sent to the Trans Alaska Pipeline. In 1998 (BP 1998), the volume of produced water was approximately 1.23 million bbl (196 million L, 51.7 million gal) per *day*—comparable to North Slope oil production. Most produced water is treated and re-injected into the reservoir; some is injected into approved disposal wells. The volume of associated wastes at the Prudhoe Bay field is approximately 1 million bbl (159 million L, 42 million gal) per year (API 1996). Class II wastes are injected into disposal horizons through 37 Class II disposal wells. More than 1.5 billion bbl (238 billion L, 63 billion gal) of produced water and associated wastes has been pumped into subsurface disposal formations.

Until recently, waste materials from the drilling of wells, including muds and cuttings, crude oil, spill materials, and other substances were disposed of in open gravel-bermed areas called reserve pits (BP 1998), that typically contained from 17 million to 51 million L (4.5 to 13.5 million gal) of waste (ADEC 1985). There were many problems with reserve pits however, including leaching of contents to the surrounding tundra. Disposal of accumulated pit fluid on roads for dust control or spilling directly on the tundra also has contaminated those areas. Studies by the U.S. Fish and Wildlife Service reported significant effects on water quality in nearby ponds (West and Snyder-Conn 1987, Woodward et al. 1988).

Under a consent decree reached between the industry and environmental groups, most old reserve pits in the Kuparuk and Prudhoe Bay fields are being cleaned out and the waste ground and injected into subsurface formations. In addition, ARCO and BP agreed to clean up 170 additional reserve pits as part of the charter agreement governing BP's acquisition of ARCO (BP Charter Agreement). A grinding and injection plant, the largest of its kind in the world, injected some 332,000 m^3 (434,000 yd^3) of reserve-pit solids in 2000 alone (Friar, personal communication, 2001).

The disposal process requires that porous, water-bearing formations below the surface casing accept fluids at pressures that will not propagate fractures through the upper confining zones. The disposal fluids must be compatible with the formation water, which must not be a potential source of drinking water.

CURRENT STRUCTURE OF THE NORTH SLOPE INDUSTRY

Historically, oil companies were directly involved in many of the physical aspects of the location, production, refinement, distribution, and sale of oil. Gradually, as the scale of oil and gas operations grew, more and more of the activities associated with the oil industry were contracted out to specialized service companies. In general, the major oil companies today own or control (lease) the mineral rights to the resource itself (oil or gas), the production facilities, and the pipeline distribution facilities (sometimes through cooperative ventures, as with the Alyeska Pipeline Service Company, a consortium of companies that operates the Trans Alaska Pipeline). Those companies also generally own or contract for other distribution networks (for shipping, for example) and refinery capacity, and they often franchise wholesale and retail distribution. Different service companies generally conduct seismic exploration, drill and complete wells, construct production facilities and pipelines, and supply technical experts to address most problems that occur during normal operation (down-hole problems, equipment failures, spills). In turn, many of those contractors subcontract to other specialized companies. For example, a drilling contractor could subcontract with other companies to support the drilling operation or provide food service, potable water, drilling mud, casings, drill strings, and even personnel. Many of those companies contract even further with other support companies that provide additional services.

If an exploratory well reveals the oil or gas is commercially feasible to extract, then the oil company will contract with fabrication companies to construct the various production facilities that are needed on land or off shore. In the case of the North Slope, those structures are fabricated in the continental United States or elsewhere in Alaska and shipped by barge to the North Slope during the open-water season. Then, a pipeline company connects the facility to the existing pipeline network, also supported by crews, fuel, water, pipe, and coating. If something breaks down during any of these operations, or if modifications need to be made, additional companies provide specialized services and tools. Once the oil is available for delivery, the oil company resumes control to produce and market the product.

NORTH SLOPE OIL-FIELD INFRASTRUCTURE

The history of the North Slope road and infrastructure network is traced in Tables 4-2, 4-3, and 4-4 and in a series of maps (Figures 4-3, 4-4, 4-5, 4-6). A full description of the mapping and tabular analyses is contained in Appendix E. The analyses were done by Aeromap, Inc. using information provided by BP and from other sources. The tables show North Slope oil-field infrastructure history by year and geographic area. Numbers are cumulative. Dashes are used if there were no data for a given year. Figures have been rounded, and may not add exactly in all cases. Exact figures and category definitions are detailed in Appendix E.

Table 4-2 Point Measurements

	1968	1973	1977	1983	1988	1994	2001
Gravel pads							
Production pads, drill sites	0	16	22	62	95	104	115
Processing, facility pads	0	6	10	14	18	18	20
Support pads (power stations, camps, staging pads)	1	36	63	98	108	113	115
Exploration sites	3	42	63	103	104	106	103
Offshore exploration islands	0	0	2	12	13	13	13
Offshore production islands	0	0	0	0	2	3	4
Airstrips	1	11	15	16	16	16	16
Exploration airstrips	0	4	4	4	4	4	4
Culverts	-	-	-	-	-	-	1395
Bridges	-	-	-	-	-	-	17
Caribou Crossings	-	-	-	-	-	-	50
Landfills	-	-	-	-	-	-	1

Table 4-3 Infrastructure Length (Miles)

	1968	1973	1977	1983	1988	1994	2001
Roads	0	100	139	294	358	370	400
Peat roads	30	101	101	101	96	96	96
Causeways	0	0	2	3	8	8	8
Tractor trails, tundra scars	19	54	59	57	57	57	56
Exploration roads	0	36	36	36	36	36	36
Total road length	49	290	336	491	554	566	596
Pipeline corridors							
1-5 Pipes per bundle	-	-	-	-	-	-	366
6-11 Pipes per bundle	-	-	-	-	-	-	73
12-17 Pipes per bundle	-	-	-	-	-	-	6
18-26 Pipes per bundle	-	-	-	-	-	-	4
Total pipeline length	-	-	-	-	-	-	450
Power transmission lines	-	-	-	-	-	-	219

Table 4-4 Infrastructure Area (Acres) (not including Dalton Highway)

	1968	1973	1977	1983	1988	1994	2001
Gravel roads and causeways							
roads	-	677	1002	2029	2448	2536	2745
causeways	-	0	48	82	235	229	227
Total gravel road and causeway area	-	677	1050	2110	2683	2765	2971
Airstrips (gravel or paved)	6	136	252	287	313	313	287
Offshore gravel pads, islands							
Exploration islands	0	0	5	54	57	57	53
Production islands	0	0	0	0	76	92	101
Total offshore gravel pad, island area	0	0	5	54	133	149	155
Gravel Pads							
Production pads, drill sites	0	276	647	2199	2917	3019	3126
Processing facility pads	0	74	390	692	874	890	917
Support pads (camps, power stations)	14	441	769	1340	1444	1470	1463

Table 4-4 (continued)

Exploration site	0	109	175	339	317	314	305
Total gravel pad area	14	901	1981	4570	5552	5692	5817
Total gravel footprint	20	1713	3288	7022	8681	8919	9225
Other affected areas							
Exploration site-disturbed area around gravel pad	55	346	467	613	627	650	645
Exploration airstrip-thin gravel, tundra scar	0	68	68	68	68	68	67
Peat roads	143	547	546	546	520	517	517
Tractor trail, tundra scar	110	250	272	263	258	258	258
Exploration roads-thin gravel, tundra scar	0	177	179	177	178	178	177
Gravel pad removed, site in process of recovery	0	1	21	27	46	81	100
Gravel pad removed, site is recovered	-	-	-	-	-	-	95
Total other affected area	308	1388	1552	1694	1698	1753	1765
Gravel mines							
In rivers	25	4732	4996	5011	5063	5061	5082
In tundra	0	34	151	745	1179	1186	1283
Total Gravel Mine Area (acres)	25	4766	5146	5756	6241	6246	6364
Total Impacted Area (acres)	353	7868	9987	14472	16620	16918	17354

The development history of the road network and gravel pads was traced in a series of aerial photographs taken in 1968, 1973, 1988, and 2001. The length of the roads and the area of roads, pads, gravel mines, and some other affected areas were determined for each year. The analysis was divided into four major areas:

- The area between Foggy Island and the Kuparuk River contains the main Prudhoe Bay oil field, Lisburne, Niakuk, Endicott, and several smaller oil fields. This area generally represents the technology used to construct the early oil fields.
- The area between the Kuparuk River and Kalubik Creek contains the Kuparuk and Milne Point fields represents an intermediate era of oil-field technology.
- The area between Foggy Island Bay and the Canning River contains the Badami oil field and a few remote exploration sites.
- The area between Kabulik Creek and the Colville River contains the Meltwater, Tarn, and Alpine oil fields. Badami Alpine, and Tarn are the newest oil fields, and they represent newer technology.

The portion of the oil-field network that is connected by roads stretches to 97 km (60 mi) from the Endicott field in the east to the Tarn oil field in the west. The gravel road network expanded during the past 33 years from a 79 km (49 mi) network of peat roads and tractor trails in 1968 to the current 960 km (596 mi) network of gravel roads and abandoned roads and trails (Figure 4-9). Most of the expansion of the road network was done before 1988, the development phase of the field, during which the rate of growth was about 40 km (24 mi) per year. Since 1988, the rate of growth in the road network has been about 5.3 km (3.3 mi) per year. The currently used portion of the network consists of 640 km (400 mi) of gravel roads. About 350 km (215 mi) of the gravel road network is associated with the Prudhoe Bay oil field and with other fields between the Kuparuk and Sagavanirktok rivers. There is 293 km (182 mi) of road in the oil fields west of the Kuparuk River. The newest extensions to the road system have been mainly winter ice roads to link new drill sites in the National Petroleum Reserve-Alaska and elsewhere, but 32 km (20 mi) of new road built since 1998 connects to oil fields southwest of

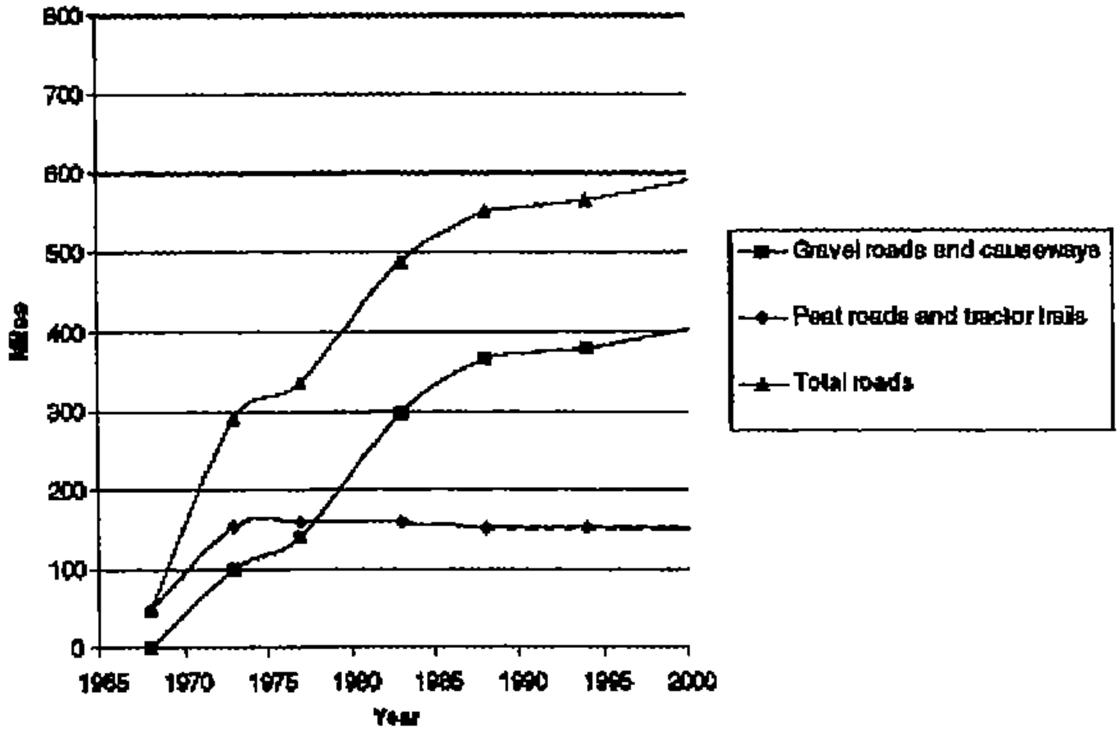

FIGURE 4-9. History of roads in the North Slope oil fields. Early roads, including tractor trails and peat roads, are indicated with circles. The squares are the existing length of gravel roads. Dalton Highway ont included. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

The total gravel-covered area increased from about 8 ha (20 acres) in 1968 to about 4,000 ha (9,200 acres) in 2001 (Figure 4-10). The rate of gravel placement declined noticeably after 1988, because the main road network and most of the pads in the Prudhoe Bay and Kuparuk oil fields had already been built. The average rate of growth was 320 ha (780 acres) per year before 1988 and 23 ha (57 acres) per year after 1988. Most of the gravel-covered areas are associated with onshore drilling and construction pads (2,338 ha [5,777 acres]). The rest is in roads and causeways (1,204 ha [2,974 acres]), airstrips (108 ha [267 acres]), and offshore gravel pads and islands (63 ha [155 acres]). Other mapped disturbances include gravel mines (2,575 ha [6,363 acres]) and exploration pads and airstrips, peat roads, and exploration trails (714 ha [1,765 acres]) (Figure 4-11). Gravel consumption from state lands on the North Slope is shown in Table 4-5. The 1.2 million m^3 (1.5 million yd^3) mined (5 million yd^3 permitted) for Alpine from Native corporation lands is not included.

Table 4-5 North Slope Gravel Consumption, 1974-1999*

Years	Permits Issued	yd^3 Permitted	yd^3 Extracted
74-79	7	15,408,445	11,415,693
80-84	52	73,312,099	39,218,481
85-89	12	10,767,800	3,640,448
90-94	18	3,328,500	1,254,821
95-99	22	5,704,100	2,326,820
00-01	12	4,384,500	24,218

Source: ADNR (1 yd^3 is equal to 0.765 m^3)
*Trans Alaska Pipeline and Haul Road not included; 00-01 data incomplete.

There are 115 gravel drill sites or pads, 20 pads with processing facilities, 115 pads with other support facilities (power stations, camps, staging pads), 91 exploration sites, 13 offshore exploration islands, 4 offshore production islands, 16 airstrips, 4 exploration airstrips, 1,395 culverts, 960 km (596 mi) of roads and permanent trails, 725 km (450 mi) of pipeline corridors (containing 2,720 km [1,690 mi] of pipe), and 353 km (219 mi) of transmission lines.

The Aeromap analysis did not address the areas indirectly affected—seismic trails, ice roads, or off-road vehicle tracks—nor did it identify the types of terrain that were affected by different activity or use. Those issues are discussed in Chapter 7. It also did not cover the Trans-Alaska Pipeline, the National Petroleum Reserve-Alaska, and other areas of the North Slope; the analysis is provided as an example where good information is available and where most of the development has occurred. Much of that development used technology no longer in use.

RECENT TECHNOLOGY DEVELOPMENTS

Over the past two decades, new technologies have been developed and applied to exploration, development, and production on the North Slope. Some technologies, such as the use of ice roads and ice pads for exploration wells and the Arctic Drilling Platform, are unique to the Arctic and were largely developed in Alaska. Other advances, such as the use of coiled tubing, 3-D seismic-data acquisition, horizontal and multilateral drilling, measurement while drilling, low ground-pressure vehicles (Rolligons), and remote sensing, were developed

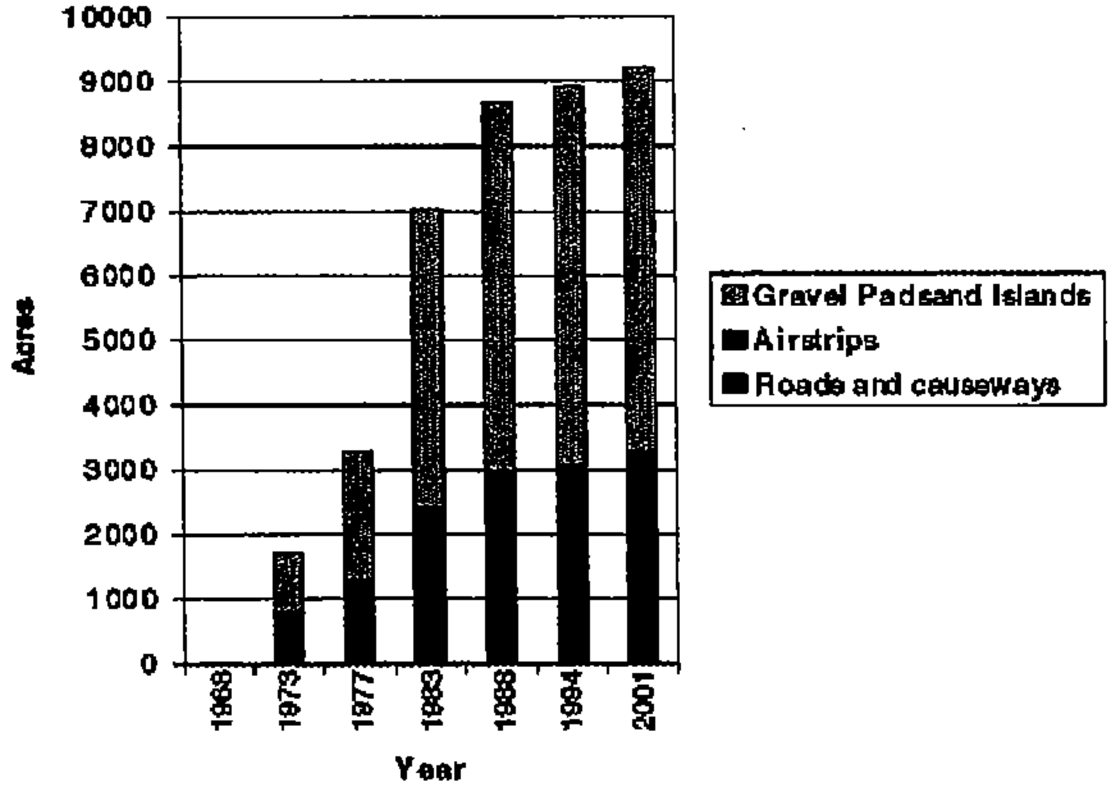

FIGURE 4-10. History of gravel placement. The area of gravel pads includes all exploration sites, drill sites, production pads, and support pads (camps, power stations). Gravel islands include offshore exploration and production islands. Dalton Highway and Trans Alaska Pipeline not included. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

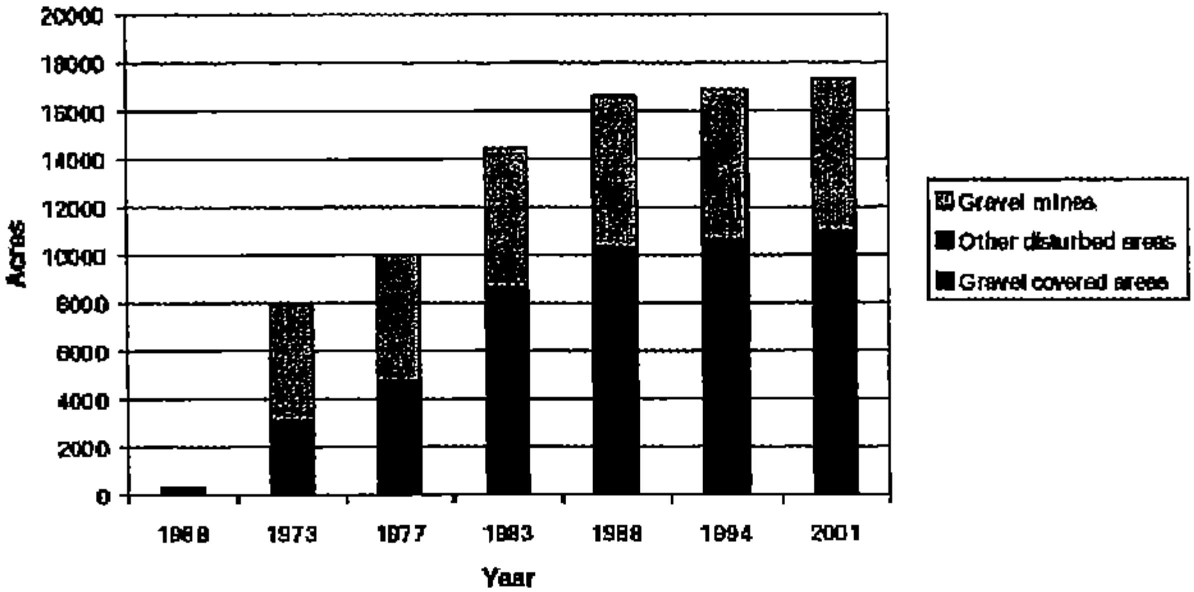

FIGURE 4-11. History of total disturbed area. The gravel-covered areas portion of each bar is equivalent to total gravel placement in Figure 4-10. Other areas include disturbed areas around exploration sites, exploration airstrips with thin gravel, peat roads, tractor trails, and exploration roads. Seismic exploration trails, ice roads, and off-road vehicle tracks are not included. Gravel placement and the resulting total direct disturbance leveled off after 1988. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

elsewhere and adapted for use on the North Slope. Although some of those newer technologies have been used extensively, and the newer fields (such as the one at Alpine) use them almost exclusively, older technologies are still integral parts of the older portions of the Prudhoe Bay and Kuparuk fields.

The new exploration-related technologies have reduced the overall use of gravel and presently eliminated it from the exploration-drilling process, have provided data for better siting of facilities, and have reduced the number of wells required to find and evaluate a new field. Although the physical effects have been greatly reduced by the use of these technologies, there are still valid concerns regarding the potential for some amount of damage to the environment. In addition, changing climate might reduce the utility of some newer technologies in some circumstances.

The environmental effects of the older road and pad construction techniques and seismic trails are matters of genuine concern. In some instances, the effects have not diminished with the passage of time; in others, a natural but slow recovery is occurring. The visual impact in some cases will be evident for years-if not for decades.

The density of 3-D seismic activities can cause short-term visual impact. In areas where there is little snow cover or steep vegetated terrain, damage to the tundra and shrubs can be locally significant and long lasting. Long-term studies of the trails built for the closely spaced 3-D acquisitions are required to document the potential effects.

The introduction of newer technologies has reduced the amounts of water and gravel required for some types of operations because of their more efficient well operations and smaller pad sizes. The greater reach of horizontal wells and the use of multilateral drilling reduces the need for large pads and it allows extraction of oil from larger areas; thus reducing the number of pads required to develop an oil field. Because the fields use more effective drilling and fewer wells, the quantities of waste, mud, and cuttings are smaller. Because fuel consumption is lower, there are fewer emissions.

Environmental damage continues to be associated with the use of raw materials and resources, such as gravel and water. And their extraction and use will continue, although at reduced rates per unit of oil recovered because 3D seismic technology reduces the percentage of dry wells. Also, it is possible that ice pads will be superseded by new types of drilling platforms, and by use of Rolligons. Gravel mining and tundra coverage and water use for ice roads or pads, drilling mud, and the like are expected to continue for the foreseeable future. Any risk associated with well drilling remains, although ameliorated somewhat by newer drilling and completion technologies. The possibility of losing a tool downhole, of mud or cuttings spills, and of emissions of air pollutants will continue to exist—if to a lesser extent than in the past. A reduction of ground traffic is likely to result in an increase in aircraft movements.

Absent new technological advances, the pipelines must be above the ground; if they are buried, they could lose support by thawing permafrost (Chapter 6). Increasing their elevation has facilitated the movements of caribou, and remote monitoring of pipelines has lessened the probability of spills. Remote-sensing techniques have improved early detection and tracking of spills, and have helped with recognition of key habitat for caribou. As a result, facilities could be located to minimize impacts on sensitive caribou populations.

Some consequences of using newer technologies also can threaten the environment. Any spills associated with pipelines buried deeply under river crossings would be difficult to clean up and might damage those rivers. There is a remote possibility that injection of waste into subsurface disposal zones could contaminate a potential groundwater source, or locally overpressure an interval and result in an escape of fluid to the surface. A poor cement or casing job could provide an avenue of escape for annular injected wastes. The newer technologies have resulted in increased protection for the environment, but they have not eliminated the potential for accidents. Appendix D offers a more complete discussion of the technologies and their consequences.

HOW OIL-FIELD ACTIVITIES CAN AFFECT THE ENVIRONMENT

This section describes briefly how the activities of an oil field can affect the environment. Assessments of the effects of those activities and how they accumulate, which requires analyses of the effects on various receptors, are presented in Chapters 6 through 9.

Oil and Seawater Spills

Accidental spills of crude oil, petroleum products (such as diesel fuel or crankcase oil), and saline water (produced with the oil or seawater used in enhanced oil recovery operations) occur on the North Slope. No large oil spills (more than 1,000 bbl (159,000 L, 42,000 gal) have occurred on land on the North Slope as a result of exploration and production operations, although many smaller spills have occurred. Three major spills have occurred from the North Slope segment of the Trans Alaska Pipeline. No major offshore oil spills have been reported. Many saline water spills have occurred on land. Most crude oil, petroleum products, and saline water spills were confined to gravel pads and roads. Some have affected small areas of tundra, resulting in long-term damage.

Spills can occur at and around exploration and production facilities, pipelines, and pump stations; at support facilities, such as storage tanks; and from various vehicles in the area. Oil spills on the North Slope have ranged from 0.006 bbl to 925 bbl (0.98-14,703 L, 0.26 to 38,850 gal). Each year from 1977 to 1999 there was an average of 234 spills of crude oil and petroleum products associated with exploration and production activities on the North Slope. The annual average spill volume was 537 bbl (85,376 L, 22,554 gal). The annual average during that period was 69 spills of crude oil and products associated with the operation of the Trans Alaska Pipeline from Pump Station 1 to Atigun Pass. The average annual spill volume was 265 bbl (42,132 L, 11,130 gal).

Information on seawater spills is less complete (Maxim and Niebo 2001a). From 1986 through 1999, there were 929 seawater spills associated with North Slope exploration and production and the North Slope portion of the pipeline (up to Atigun Pass). In all 40,849 bbl (6 million L, 1.7 million gal) of seawater was spilled during the period, for an average of 66 spills per year with an annual average volume of 2,918 bbl (463,923 L, 122,556 gal). A detailed analysis of spills, including their causes and frequency, the fate and effects of spilled material, and remediation, is in Appendix G.

Seismic Exploration

Seismic exploration is usually done by sending sound waves into the substratum and deducing information about its oil-bearing potential based on the speed and strength of the returning echoes. On land, the vehicles that transport the testing equipment can affect the tundra and leave tracks that can persist for years and be visible from considerable distances, especially from the air. Vehicle traffic can disturb denning polar bears and muskox herds. Offshore, seismic exploration can affect the distribution and migration of marine animals.

Mining and Redistribution of Gravel

As described above, gravel is used for roads, causeways, pads, islands, and other structures. The gravel is obtained locally, primarily from river beds and gravel pits excavated into the tundra. Its removal and redistribution affect drainage patterns, flow volumes, melting and freezing of the active layer, movements of humans and animals, the visual landscape, and snow accumulation. Gravel also kills the vegetation it covers.

Freshwater Use and Redistribution

Fresh water is used in the construction of ice roads and pads and in oil fields. An annual average of 4.4 billion L (1,163 million gal, range: 776-1,458 million gal) was used this way between 1996 and 2000 (Table 4-6). Removing water from lakes can change their character, especially if the water that remains is so shallow that the lake freezes to the bottom. Removal and redistribution of water can affect the organisms that depend on it for habitat, migration, food, and safety (Chapter 8).

Table 4-6 Quantity and Source of Current North Slope Freshwater Use in Established Oil Fields

Source	Field, Activity, or Operator	1996	1997	1998	1999	2000
Surface water						
	Prudhoe Bay					
	East	181	189	112	95	108
	West	132	130	140	92	61
	Kuparuk*	159	78	127	96	181
	Alpine*	0	0	150	244	213
	Milne Point	38	51	40	11	28
	Endicott	0	0	3	0	5
	Badami	0	10	22	9	1
	Northstar	6	1	5	0	8
	BP exploration	3	36	31	40	4
Total surface water		519	495	630	587	609
Number of lakes		125	131	154	181	174
Deep Wells and Other Sources		257	606	681	582	849
Total Water Use		776	1,101	1,311	1,169	1,458

(Millions of gallons)
*Includes exploration.

Source: Data compiled for this report by BP Exploration (Alaska), Inc., with assistance from Alaska Department of Natural Resources and Phillips Alaska, Inc.

Seawater Use and Diversion

Large amounts of seawater are withdrawn from the coastal region and injected into subsurface formations to maintain or enhance pressure in the formation for oil recovery (Table 4-7). The four existing intakes can remove almost 600 million L (158 million gal) of seawater per day, and between 1996 and 2001, they removed a daily average of 174 million L (46 million gal). Longshore currents have been altered by coastal structures, such as causeways, and those alterations can affect migrations of fish and perhaps other animals. In the summer, onshore seawater spills kill vegetation.

Table 4-7 Intake Capacity and Use of seawater by North Slope Facilities

Facility	Intake Capacity	1996-2001 Mean
Prudhoe Bay Unit waterflood	103.6	26
Kuparuk waterflood	28.2	13
Endicott waterflood	23.5	7
Northstar	2.6	0.05
Totals	157.90	46.05

Millions of gallons per day.
Source: Data compiled for this report by BP Exploration (Alaska), Inc., with assistance from ADNR and Phillips Alaska, Inc.

Sea Ice Structures

Exploration and development in nearshore and offshore waters of the Beaufort Sea require a variety of temporary and permanent structures, such as causeways, islands, and drilling platforms. A major concern about causeways is their potential to alter nearshore currents and fish migrations. Drifting ice accumulates on the up-current sides of gravel causeways, islands, and drilling platforms, and areas of open water (polynyas) form on the down-current sides (Stirling 1988a). Gravel structures and grounded ice roads and islands can affect the stability and persistence of shore-fast ice when they serve as anchoring points or cause cracks and leads to form in the ice sheet.

Construction, Presence, and Aging of Infrastructure

The traffic and noise associated with the construction of infrastructure—roads, pipelines, buildings, pads, platforms, airstrips—can disturb or alter animal migration. In addition, the presence of structures themselves on the landscape can disrupt migration and thus alter the distribution of organisms. The presence of infrastructure affects the amount and distribution of dust and ambient noise; it also affects air quality, either directly (by emissions) or indirectly (by providing a substratum for the movement of emitting vehicles and supporting the construction of emitting structures). There are visual consequences as well: The structures change the way the landscape is perceived by residents, visitors, and transients. Finally, roads and airstrips affect the environment by increasing access to it and thus by increasing the intensity of the effects of human activities in time and space.

As the infrastructure ages or is abandoned, other unintended environmental effects can result. Aging increases the likelihood of failure, which can lead to accidental discharges (spills) or to other accidents, such as fires. Abandoned roads and other structures can degrade from melting permafrost and continue to alter the visual environment, especially if the climate continues to warm.

Most North Slope oil-field equipment dates from the last quarter of the 20th century. It will continue to age over the next 25 years, the period of this report's scope. Components that could fail include pipelines through corrosion, subsurface safety valves, and safety systems to suppress fires and explosions. The older oil-field areas such as Prudhoe Bay will be most susceptible to aging. Thus, age-related maintenance demands will increase as oil revenues from declining oil fields decrease. As an aging field's production declines and the cost of extracting oil increases, the economic incentive to postpone or eliminate maintenance and replacement will increase. The environmental effects of aging infrastructure will depend on interactions between the economics of declining fields, increased replacement and maintenance costs, the regulatory regime, and other factors equally hard to predict.

Transportation

Noise and disturbances from water, air, on-road, and off-road transportation of machinery, materials, and people can significantly affect marine and terrestrial animals and people's experiences in the environment.

Waste Disposal

Disposal of large amounts of industrial and domestic waste produced by industrial operations can contaminate environments and affect the population dynamics of animals, both positively, by providing food, and negatively, by contaminating environments.

Redistribution of Wealth

Oil and gas activities bring money to the North Slope both directly and indirectly. They provide jobs and tax revenues, and they fuel demand for local goods and services. They attract tourists, regulators, government officials, members of the news media, scientists, and others, and those visitors contribute to the local economy. The oil industry had a significant effect on changing the social structure of North Slope communities from subsistence alone to a mixed subsistence-cash economy. A variety of organizations have been established as a result of oil and gas activities—the Arctic Slope Regional Corporation, the Kaktovik Inupiat Corporation, and various government departments of the North Slope Borough and communities. Those organizations have made, lost, and spent money.

Information Dissemination

Oil, gas, and related activities disseminate a great deal of information. For example, lease sales are announced, oil finds are announced, and the expected methods of extraction are described; scientific studies are conducted and published; political discussions are held; laws and regulations are considered and passed or rejected. All of this information has profound direct and indirect effects on North Slope residents. The announcement of a lease sale can cause fear of environmental damage at the same time it raises expectation of profit from private land sales or an influx of new jobs. As a result, investment decisions, lifestyle changes, and the way people spend their time and energy can be substantially altered. Scientific studies can confirm or contradict people's opinions, knowledge, hopes, and fears. Political discussions can change perceptions, behavior, investments, and mental health.

These effects of information dissemination—even in the absence of physical activity—are as real as and often even more important than the direct effects of physical activities such as construction of infrastructure.

5

Future Oil and Gas Activities

The directive to the Committee on Cumulative Environmental Effects of Alaskan North Slope Oil and Gas Activities included assessing the likely future cumulative effects of industrial activities that have occurred on the North Slope and the cumulative effects of future industrial activities. All projections of activities and the accumulation of their effects are uncertain because many factors, some of which are highly unpredictable, will influence the location and extent of exploration for and extraction of oil and gas on the North Slope. For example, extraction and marketing of oil depend on the price of oil, which in turn depends on the ability of the Organization of Petroleum Exporting Countries (OPEC) to maintain high prices for oil on the world market. Wars or terrorist activities could dramatically alter all industrial activities on the North Slope.

Nonetheless, without a plausible scenario the committee could not make substantial progress in predicting cumulative effects on the physical and biologic systems of the North Slope. We therefore evaluated the consequences of a development scenario that assumes a continuing.favorable market price for oil and "normal" international relations during the next several decades. Such a scenario is plausible even though the probability of its occurrence cannot be determined.

PLAUSIBLE SCENARIO

Even if prices and political stability were to continue to favor exploration and extraction of North Slope oil and gas, many variables bear on the amount of activity and the success of future exploration and development: land availability, the regulatory environment, pricing, technology, exploration concepts, competition, and infrastructure.

The committee's scenario is based on the way the petroleum industry operates now, and it assumes a continuation of trends, as indicated by recent activities and the actions undertaken or supported by the key federal and state oversight agencies. Exploration in the 1002 Area of the Arctic National Wildlife Refuge (see Figure 3-1) is not considered because it is currently prohibited. However, the area is included as a possible additional and potentially significant component of the recoverable oil reserves on the North Slope in case exploration there is approved by Congress. The scenario has a list of important assumptions:

- Oil prices will remain high enough to support continued exploration and development.

- Climate change will not be so great during the next 50 years as to render current exploration methods obsolete or foreclose modifications, such as use of Rolligons and new drilling platforms.
- All new exploration and development activities will use technologies at least as good as those in use at Alpine.
- Offshore exploration (and probable extraction) will continue, but at a slower pace, along the Beaufort Sea coast from Point Barrow to Flaxman Island and possibly eastward to the Canadian border.
- Onshore exploration (and probable extraction) will continue both southward into the foothills of the Brooks Range and westward well into the National Petroleum Reserve-Alaska.
- Gas will become a significant component of exploration and development activity, and a gas pipeline will be built.
- The number of exploration companies, especially with gas interests, will expand and competition will increase.

The committee's projection assumes significant new discoveries and developments and a gradual decline in output from older oil fields. This in turn is likely to influence development of satellite fields. We assume there will be significant oil discoveries in each of the exploration subprovinces, with the possible exception of the southern area of the National Petroleum Reserve-Alaska, where gas deposits are more likely to be recoverable. We consider the probable exploration and development activities from the present to 2050.

Exploration Provinces

Our forecast separates potential activity in three major operating provinces that correspond to the jurisdictional framework within which future developments are likely: the state and native lands of the Colville-Canning Province, the Beaufort Sea, and the federal lands of the National Petroleum Reserve-Alaska. These subdivisions are under the jurisdiction of different regulatory agencies, and they have different leasing schedules, regulatory regimes, infrastructure needs, and resource potential. The Beaufort Sea is considered as two subunits, the federal outer continental shelf (OCS) and the shallower state nearshore area. The National Petroleum Reserve-Alaska and Colville-Canning are subdivided into gas- and oil-prone subprovinces.

Three related sets of units of measure are often used in discussions about oil reserve or resource estimates: original oil in place (OOIP), technically recoverable reserve (TRR), and economically recoverable reserve (ERR). Gas reserves are treated similarly. OOIP estimates the volume in a reservoir or reservoirs before production starts. It does not represent the quantity that can be produced from the field. OOIP at Prudhoe Bay was approximately 23 billion barrels (bbl). (A barrel is 42 U.S. gallons, or 159 L). TRR is the volume of oil or gas that is recoverable—independent of price. ERR, that portion of TRR that it is feasible to recover, is sensitive to price and technology. The current ERR estimate for the Prudhoe Bay field is 13 billion bbl. Under ideal conditions ERR approaches TRR, but rarely does a reservoir yield an ERR that exceeds 0.5 times that area's OOIP.

It is important to distinguish such estimates when reading published information about oil and gas reserves. The numbers that industry releases or discusses for new discoveries or existing fields generally are ERR values. The federal agencies and other groups that perform public domain assessment of oil and gas reserves, as in the Arctic National Wildlife Refuge and the National Petroleum Reserve-Alaska, generally present their results as TRR. For example, in the 2002 appraisal of the National Petroleum Reserve-Alaska, the USGS provided a mean reserve estimate of 9.3 billion bbl of TRR. They then may give an estimate, as a function of assumed oil price ranges, of ERR. In the 2002 National Petroleum Reserve-Alaska appraisal ERR was estimated to range between 1.3 and 5.6 billion bbl of oil over a range of market prices between $22.00 and $30.00 per barrel.

Once production has been established in an area, with the discovery of a large commercial accumulation of oil or gas, other adjacent, previously technically recoverable but uneconomic, small accumulations become economic despite a relatively low oil or gas market price. This is because the investment in the necessary production and transportation infrastructure has been justified by the discovery of the large field. Examples are the Midnight Sun oil field north of Prudhoe Bay and the satellites north and south of Alpine. The Midnight Sun field is a 20- to 40-million-barrel field that would have no stand-alone economic value. The presence of the Prudhoe Bay field and its infrastructure turns several millions of barrels of technically recoverable reserves into economically recoverable reserves. The same holds true for the Alpine field and its satellites. Much of the current activity in and near the major North Slope fields is related to the development of these small accumulations.

In many of the following sections, two sets of reserve numbers are given. The intent is to provide TRR estimates made by various groups or agencies for these exploration provinces and then to present possible volumes of ERR additions for comparison with the produced volumes and remaining known reserves in the discovered fields. ERR estimates are based on the scenario assumptions presented above and reflect OOIP or TRR volumes, or both.

Reliable estimates for the remaining potential for oil and gas on the North Slope are not available because of a lack of resource evaluations based on current geological knowledge. One recent estimate (Coleman et al. 2001) placed future TRR volumes for the Brooks-Colville system of the North Slope at 14 billion bbl of oil and 32.8 trillion cubic feet of gas (TCFG). The information available indicates that those estimates include the Arctic National Wildlife Refuge. They do not allow for significant reserves in the non-refuge portions of the North Slope, which include all of the National Petroleum Reserve-Alaska, the currently underexplored and nonproductive portions of the Colville-Canning Province, and the Beaufort Sea. The numbers are probably conservative given recent discoveries in and near the National Petroleum Reserve-Alaska and the size of the U.S. Geological Survey (USGS) estimates for the Arctic National Wildlife Refuge.

Older estimates for the entire North Slope and the state waters of the Beaufort Sea range from mean undiscovered TRR of 12.6 billion bbl of oil and 54.1 TCFG (Magoon 1994) to a TRR of 18 billion bbl of oil, exclusive of Arctic National Wildlife Refuge reserves (Anonymous 1991). The disparity in those numbers generates confusion about the magnitude of the remaining undiscovered reserves on the North Slope and the adjacent Beaufort Sea. (Note that the numbers do not include the federal OCS portion of the Beaufort Sea.) Gas has frequently been ignored or downplayed in the resource assessment process, but it has gained new emphasis since the construction of a gas pipeline has garnered renewed support.

The last thorough assessments of those areas, exclusive of the Arctic National Wildlife Refuge, were completed in 1978 and 1980, and USGS is currently reevaluating the estimates. Resource evaluations for the National Petroleum Reserve-Alaska were compiled in May 2002

(Bird and Houseknecht 2002). For the rest of the North Slope, they are expected in late 2003 or early 2004 (Bird 2001).

Colville-Canning Province

This area includes all lands between the Colville and Canning rivers, from the Beaufort Sea south to the northern limits of the Gates of the Arctic National Park and Arctic National Wildlife Refuge. The bulk of the area is state owned, but the Arctic Slope Regional Corporation (ASRC) controls nearly 1.2 million hectares (ha, 3 million acres) in the Brooks Range foothills. Lease sales have been held in the area since 1958, with 4 federal sales and 28 state sales. Hundreds of wells have been drilled, most of them in the major fields of the northern portion of the area; ERR of 17 billion to 18 billion bbl of oil and more than 35 TCFG have been found. The major oil discoveries include the Prudhoe Bay, Kuparuk, Endicott, Point McIntire, and Alpine fields as well as numerous small satellite fields. Prudhoe Bay and Point Thomson are the sites of the principal gas accumulations. All of these fields are in the northern area, on or near the Barrow Arch. Farther to the south the source rocks and reservoirs are deeply buried and are generally too mature to contain oil. This southern gas-prone region is called the Brooks Range foothills belt. Based on the presence of 35 TCFG in the area of the developed and developing fields, it is obvious that the oil-prone area also has significant gas resources. The converse is not necessarily true. The oil potential of the foothills belt could be modest at best.

Northern Colville-Canning

This area, between Canning and Colville rivers, extends south from the Beaufort Sea coast to approximately 69° 45′ N latitude and has been the focus of most of the exploratory drilling and oil development on the North Slope since 1969. All of the onshore producing oil fields are located here.

The area is expected to continue to be one of the most active regions of the North Slope, at least for the near-term, as major producers add production through the discovery of new medium-sized oil accumulations and the development of satellite fields. If the economic indicators continue to be favorable, gas pipeline and gas-producing facilities could be brought online by 2010. If so, gas exploration would become routine. The expansion of the gas-producing and gathering system would continue into the early 2020s. Most of the attractive area would be leased by 2010 and fully developed by 2030. The existing fields and infrastructure should continue be the backbone of North Slope production, either directly or indirectly, by supplying the facilities to allow nearby, otherwise uneconomic, oil and gas accumulations to be developed. If so, oil production could continue well into the second quarter of the twenty-first century; gas production could go until 2040-2050. Future reserve additions should be approximately 2.5 billion to 3 billion bbl of oil with the possibility of two to three times that quantity if new technologies result in increased recovery from the West Sak and Ugnu heavy oil reservoirs. The potential for additions to the gas reserve base is 10-15 TCFG.

Brooks Range Foothills Belt

The Brooks Range foothills belt extends south from approximately 69° 45′ N to the northern boundary of the Arctic National Wildlife Refuge and Gates of the Arctic National Park and lies between the refuge and National Petroleum Reserve-Alaska. ASRC lands are included with the state area discussion.

The total area is about 4 million ha (9.8 million acres), and ASRC owns or otherwise controls a little less than one-third of the area. Until the 2001 North Slope foothills sale, most of the state area had not been leased; however, large tracts were leased in the late 1950s and early 1960s by the federal government, before conveyance to the state. About 405,000 ha (about 1 million acres) was leased in the May 2001 state sale. Over the past 30 years, the ASRC has actively sought to have its lands explored, and it has assigned exclusive exploration rights to several companies.

About 40 wells have been drilled in this subprovince, including those drilled in the Kavik and Kemik gas fields, 8 of them on Native lands. Although the area is gas-prone, there has been no market for gas, and only one well has been drilled in the area in the past 20 years. With the possibility of a gas pipeline and the discovery of immature to early-mature oil-prone source rocks, interest in the area has increased.

Exploration and production operations require large quantities of gravel and water. The foothills belt has few lakes to supply water for ice roads or pads or for production and waste disposal. As a result, the extent to which ice will supersede gravel is unknown. Rivers could be the preferred water sources in some places. Produced water might be sufficient for most waste disposal and production needs. River gravel also is scarce, and it could be necessary to mine upland areas to supply gravel for production facilities and their associated airstrips and roads.

Existing exploration and development technologies would be used extensively to provide the infrastructure and gas pipeline system. Acquisition of seismic data is under way and will continue into the foreseeable future. A drilling rig is under contract to one leaseholder, and exploration drilling could begin soon. The foothills area is expected to be a major source of gas, and it is reasonable to expect at least five significant fields would be established. Gas development could be under way by the time a trans-Alaska gas pipeline is completed, and production could begin as early as 2010. Gas production should continue into the 2040s.

These gas fields will have small footprints, but the accompanying pipeline system could easily extend 161 km (100 mi) or more to the west from the pipeline. Much if not all of the gas pipeline system probably would be buried. Based on the size of surface geological features (exposed anticlines), an individual gas accumulation could have 10-15 TCFG. Technically recoverable reserves are expected to be at least 25 TCFG.

Oil production and economically recoverable reserves in the area are expected to be modest by North Slope standards and secondary in importance to gas. They would most probably be found in fields of 300 million to 400 million bbl of oil or less and be developed much later, possibly not until after 2020. Additions to oil reserves are expected to be about 1 billion bbl.

A recent paper, presented by Anadarko Petroleum (Nelson 2002), suggests that the foothills area technically recoverable reserves are 0.5 billion to 2.5 billion bbl of oil and 20-40 TCFG.

Beaufort Sea

The Beaufort Sea area consists of federal and state lands off shore from the seaward extension of the Alaska-Yukon Territory border west to a line extended north from Point

Barrow. The federal and state lands are administered through different leasing programs, and the distance from onshore facilities and the differences in water depth dictate that we address the two areas separately.

Federal Outer Continental Shelf

The federal OCS area lies seaward of the three-mile limit, or extensions of this limit, seaward of the offshore islands and bay mouths; the OCS is administered by the Minerals Management Service (MMS) of the Department of the Interior. Thirty exploration wells have been drilled on federal or joint federal-state leases. Eleven were deemed capable of production and five were termed significant discoveries by the MMS. Oil has been the focus of all exploration to date, but if a gas pipeline were built, gas could be the target of exploration and development.

It is probable that there will be a short-term decrease in exploration and consequently little development or production activity in the federal portion of the Beaufort Sea other than at Northstar. An exploration well could be drilled on the McCovey prospect during the 2003 drilling season. Leasing and drilling will be below historic levels for the next 10-15 years, perhaps until the early 2020s.

Individual ERR discoveries for oil can be anticipated to range from 100 million to 2 billion bbl. Northstar is at the lower end of that range. Prospects like McCovey and Kuvlum could reach or exceed a billion barrels. Individual gas fields could range from a few hundred-billion cubic feet to a few trillion cubic feet of gas. These finds could be oil-associated gas, as at Prudhoe Bay, or pure gas accumulations, as at the Barrow and Kavik gas fields. ERR additions of 2.5 billion bbl of oil and 15 TCFG are possible.

Over the long-term, activity could increase if nearby onshore and nearshore state lands are explored and developed. For example, if Point Thomson were developed, it might be more feasible to consider development of other discoveries in that area. The additional 15-20 years also will provide time to more fully research and implement technologies that would reduce the environmental consequences of Beaufort Sea exploration and production, especially under conditions of broken ice. By the second quarter of the twenty-first century, exploration could increase to levels seen in the middle 1980s and early 1990s. If new technologies were developed, the life of the facilities at Prudhoe Bay and other major fields would be prolonged, as would use of the trans-Alaska pipeline.

State Nearshore Lands

Leasing and exploration began in 1979 on state lands that lie within the three-mile limit. Significant discoveries have been made at Endicott, Niakuk, West Beach, Point McIntire, and Midnight Sun. The undeveloped Flaxman Island discovery lies just west of the mouth of the Canning River and offshore from Point Thomson. Exploration for oil has dominated the effort, but gas could be a target of future exploration and development.

The state Beaufort Sea lands are likely to continue to be desirable holdings, and leases will be retained and evaluated as promptly as circumstances and priorities permit. The likelihood of leasing significant new areas probably depends on the eventual availability of the deferred tracts lying offshore from the National Petroleum Reserve-Alaska and in the Arctic National Wildlife Refuge. The amount of activity should remain constant for the next 20-25 years and then gradually decline as the oil fields are depleted over the two to three decades thereafter. The gas fields will, in large part, be found later in the exploration cycle and would be brought to production more slowly. The life of the gas fields can be expected to extend beyond that of the oil fields. Over the next 25-30 years, exploration could add 1 billion bbl ERR of oil and modest amounts of natural gas (5-10 TCFG).

National Petroleum Reserve-Alaska

The National Petroleum Reserve-Alaska is administered by the Bureau of Land Management (BLM), with technical assistance in resource evaluation and lease sales management from the USGS and MMS, respectively. Before 1999, the only National Petroleum Reserve-Alaska lease sales were held in the early 1980s (BLM 1990). The impetus for the 1999 sale was the discovery of the Alpine oil field just to the east of National Petroleum Reserve-Alaska.

The Alpine discovery stimulated interest in the reserve, especially in the oil-prone northern Barrow Arch. However, the possible construction of a gas pipeline also has enhanced the prospects for the southern gas-prone area in the foothills of the Brooks Range. The Gubik gas discovery and several other smaller gas fields demonstrate the potential for gas in this southern area. A Department of the Interior report estimated that the National Petroleum Reserve-Alaska has undiscovered, technically recoverable reserves of 2.1 billion bbl of oil and 8.5 TCFG. A USGS report (Bird and Houseknecht 2002) lists the TRR volume of oil as 5.9 billion to 13.2 billion bbl, with a mean expected value of 9.3 billion bbl. The new estimate of gas potential is 40-85 TCFG, with a mean expected volume of 60 TCFG. That evaluation presents results for new data, new play concepts, and better seismic data; it offers a 3- to 6-fold increase in the TRR estimate.

Barrow Arch Trend

The northern portion of the National Petroleum Reserve-Alaska lies over the Barrow Arch, which trends westward across to Barrow. The Barrow Arch is parallel to subparallel to the coast and serves as a focusing mechanism for hydrocarbons that migrate out of the deep basins and as such favors the accumulation of oil and gas. The search for commercial quantities of oil has focused on this portion of the reserve.

The Barrow Arch trend—that portion of the reserve from the coast of the Beaufort Sea south to about 69° 45′ N latitude—could be an area of active exploration over the next 10-15 years. Despite restrictions on drilling and on placement of surface facilities, leasing is likely to be vigorous, as is drilling activity, which will be aided by new technologies and the use of three-dimensional seismic data. The potential exists for several moderate to large oil fields, in the size range of the Alpine field, and for numerous smaller satellite fields. Competition should increase, especially in those areas more remote from current infrastructure and production, where the established producers would have less advantage. None of the larger fields found in the post-2001 period is likely to be producing before 2008, because the time required to delineate the accumulation and build the necessary infrastructure is seasonally limited and earlier, more proximal discoveries would have priority. The larger fields can be expected to have a life of 20 years or more.

Gas discoveries would lag somewhat behind the oil fields in terms of investment and development. If built, a trans-Alaska gas pipeline probably would not be in operation before 2009, and the gas reserves at Prudhoe Bay would be the focus of any early development, followed by those at Point Thomson and perhaps by discoveries in the Brooks Range foothills because of their proximity to the pipeline. Gas fields in the northern portion of the reserve are not likely to be developed and put in production before 2020.

Exploration in the northern portion of the National Petroleum Reserve-Alaska could add 3 billion bbl to the North Slope's reserve base. The bulk of these reserve additions would occur over the next 10-15 years, but if gas is present in commercial quantities, its development will follow that of oil. A reasonable estimate for gas reserves is 5-10 TCFG. The 2002 resource evaluation (Bird and Houseknecht 2002) suggests that, for the northern portion of the reserve, the mean expected TRR for oil is 7.5 billion bbl and the mean expected TRR for gas is 20-25 TCFG.

The Alpine model, or refinements of it, would be used for exploration, development, and pipeline construction. Although the footprints would be small, even assuming advanced construction techniques and the uncertain ability to forgo a permanent gravel road for maintenance, pipelines to this area would greatly extend the web of aboveground structures. If commercial discoveries extend to the vicinity of Barrow, the pipeline system would extend more than 403 km (250 mi) from east to west, with spur lines 32 to 81 km (20 to 50 mi) long, trending north-south from the trunk lines. The system of pipeline and infrastructure in the newly developed areas would look much like the Alpine field does today, but the accumulation of fields would affect a larger area.

Brooks Range Foothills

The area from the latitude of Umiat and Gubik to the National Petroleum Reserve-Alaska's southern limits is thought to be predominantly a gas-prone province. Studies of the Umiat oil field indicate potential for additional relatively substantial oil accumulations, and the Gubik gas field and other smaller discoveries at Square Lake and Wolf Creek provide evidence of the potential for gas. All previous exploration in this area was for oil.

In the near term, the foothills region could be the least active area, producing less than even the Beaufort OCS. To achieve a large amount of activity, a series of events must occur in the other exploration subdivisions of northern Alaska. They include building a gas pipeline, establishing a reliable market and price for gas from the major gas fields of the northern portion of the Colville-Canning Province, discovering sufficient gas reserves in the Colville-Canning foothills to support a new infrastructure and pipeline system, and maintaining enough capacity in the pipeline system to support additional volume. If those conditions are met, exploration and development would proceed in the same general fashion as elsewhere on the North Slope.

An individual gas field in this region could have reserves of 5.0 TCFG or more, but the size of any oil fields is anticipated to be limited and not to exceed 200 million bbl, which could be too small for development as a standalone field. Currently available data are limited, but undiscovered gas reserves could be 15-20 TCFG. The 2002 USGS estimate (Bird and Houseknecht 2002) places a mean of 35-40 TCFG in the central and southern portions of the reserve.

Oil accumulations are expected to be small by North Slope standards; economically recoverable reserves are estimated between 500 million bbl and 1 billion bbl. In contrast, Bird and Houseknecht (2002) suggest that there is an expected mean TRR of 1.9 billion bbl in the southern portion of the reserve.

Any exploration and development would probably occur after activity in the other exploration subdivisions and probably not before 2015. The scale and style of operations would be similar to that at Alpine. Spills are not a concern with gas, but the extensive pipeline system that would be required to transport the gas to a trans-Alaska gas pipeline would be conspicuous if it were not buried.

Arctic National Wildlife Refuge—1002 Area

Whether Congress will open the area to oil and gas exploration is unknown, but it is useful to assess what might happen if it did. Of the Arctic National Wildlife Refuge's approximately 8 million ha (19 million acres) (Bird and Magoon 1987), the only part with potential for oil and gas exploration and development is the coastal plain 1002 Area of approximately 607,000 ha (1.5 million acres) (Bird and Magoon 1987).

The Kaktovik Inupiat Corporation, which controls the surface, and the ASRC, which controls the subsurface mineral rights, own an extensive in-holding in the north-central portion of the 1002 Area. This portion of the North Slope has long been considered to have great potential for oil and gas. It lies between the Prudhoe Bay area fields to the west and the numerous, but as yet uncommercial, discoveries in the Mackenzie delta area to the east in Canada. If the first federal lease sale were held in 2006, oil production could begin by 2013 and gas production by 2020. Estimates of the oil and gas potential of the 1002 Area vary.

The current USGS evaluation of the Arctic National Wildlife Refuge (Bird and Houseknecht 1998) assigns a mean TRR of 10.3 billion bbl for oil (conservatively, this is an ERR of 3.2 billion bbl) and 8.6 TCFG (no estimates of economically recoverable gas were made). Unpublished industry evaluations suggest that higher ERR volumes of oil and gas are possible. Exploitation of reserves of that size, if realized, would extend the productive life of the older fields.

PROJECTIONS OF DIRECT EFFECTS TO THE YEAR 2025: INFRASTRUCTURE ANALYSIS

The committee's projections of direct effects are based primarily on trends from the past 13 years (Figure 5-1). By 2025, the road network would expand by another 129 km (80 mi) if the growth rate is constant. This projection, however, could underestimate growth if long roads are built to Alpine or Barrow or are used to connect major new oil and gas fields in the Brooks Range Foothills or elsewhere. Based on the 1988-2001 rate of 17 ha (42 acres) per year, the total gravel-covered footprint would increase to about 4,150 ha (10,250 acres) by 2025, and the total area of direct effects (roads, pads, gravel mines) would increase to about 8,000 ha (18,700 acres). An additional 200 ha (500 acres) of gravel mines would be needed to build the roads and gravel pads. Advancing technology and the location and configuration of new oil and gas fields would affect the extent of roads and gravel-covered tundra. Development is likely to include more satellite fields on small gravel pads, similar to those at Endicott and Alpine. They could have airstrips and small road systems disconnected from the main road network. Other gravel roads in the area are being considered by the Alaska Department of Transportation and the North Slope Borough (Petroleum News Alaska 2002), including a 170-km (106-mi) gravel road south from Nuiqsut that would connect to the Dalton Highway near Pump Station 2 (Alaska DOT 2002). More ice roads will reduce the need for gravel roads, although ice roads might not be practical in areas with few lakes, such as the Arctic Foothills; areas with little gravel, such as parts of the

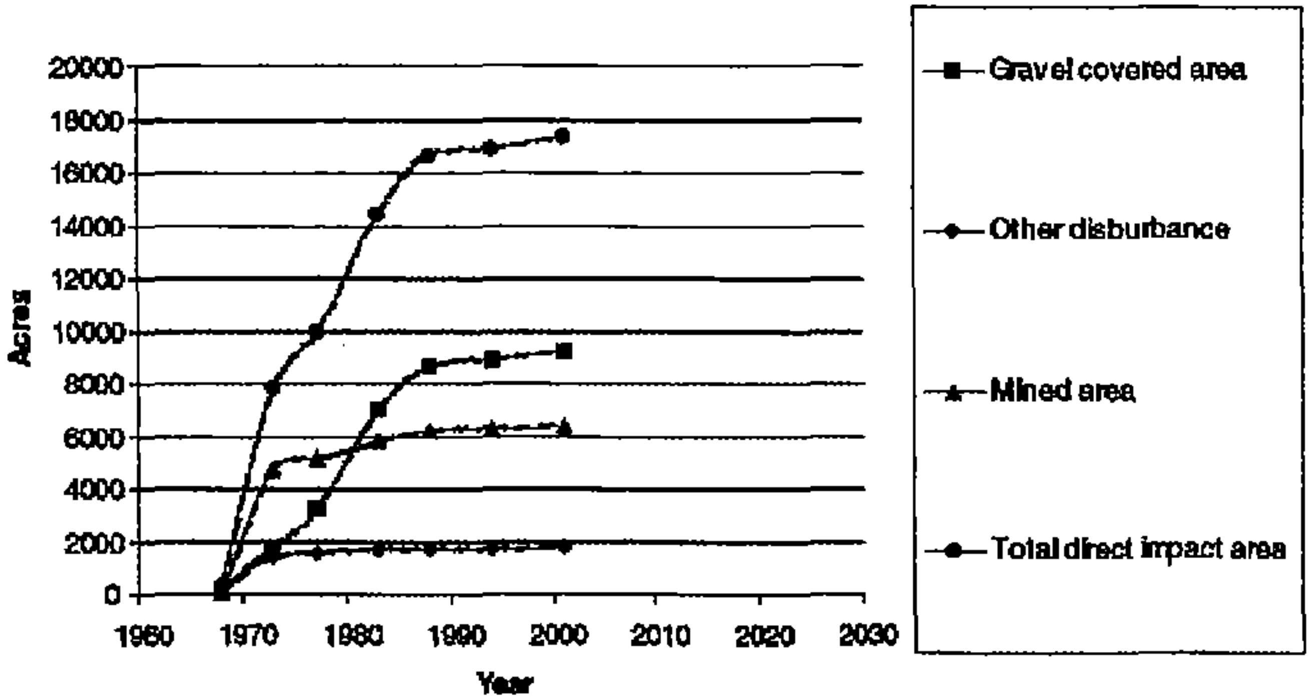

FIGURE 5-1. Direct effects of early exploratory trails and peat roads are shown with diamonds; gravel mines with triangles; gravel covered areas including roads, airstrips and pads with squares; and total area of direct effects with circles. Dalton Highway is not included. Source: Alaska Geobotany Center, University of Alaska Fairbanks 2002.

National Petroleum Reserve-Alaska, or areas that are distant from existing roads. The effects of these roads would accumulate with those of any other roads that might be built for other purposes. For example, the Trans Alaska Pipeline and the haul road, completed in 1974, covered approximately 4,050 ha (10,000 acres) on the North Slope (Pamplin 1979). It also is possible that the projections are an underestimate if major support facilities, new causeways, long roads, or airstrips are needed or if ice roads and pads cannot be used. Fewer roads might require more aircraft traffic; insufficient information is available for quantitative analysis of how any such effects might accumulate.

CLIMATE CHANGE AND OTHER INFLUENCES ON FUTURE OIL AND GAS DEVELOPMENT

The scenario on which we base our projections assumes that climate change will not seriously affect oil and gas activities on the North Slope. However, as a result of global emissions of greenhouse gases, Earth's mean surface temperature is expected to rise by 1-3.5 °C (1.8 to 6.3 °F) over the next century, and changes in Arctic Alaska are expected to be even greater (Houghton et al. 1995, 1996). The two principal climate models used in assessments (the Canadian and Hadly Center models) correctly reproduce the observed late-twentieth-century warming, and they predict continued warming throughout Alaska of 4-10 °C (7.2-18 °F), and 3-6.5 °C (5.4-11.7 °F) respectively, during the twenty-first century (Alaska Regional Assessment Group 1999). The strongest warming is expected in the north, so a plausible (though quite uncertain [Serreze et al. 1999]) twenty-first century warming prediction for the North Slope might be 5-10 °C (9-18 °F), or 0.5-1 °C (0.9-1.8 °F) per decade. This exceeds the estimate for mean global warming by a factor of 3 or so. The Arctic amplification is attributed, at least in part, to "ice-albedo feedback": As the reflective areas of arctic ice and snow retreat, the earth absorbs more heat, accentuating the warming (Chapman and Walsh 1993, NAST 2001).

Other predictions are that most of the North Slope warming will occur in the winter, and that precipitation and evaporation will increase. The predictions and models are supported by the experience of Alaska Natives, who have reported changes in the amount of ice cover and reduced effectiveness of ice cellars. Some warming has already occurred. The onset of the off-road tundra season is about 70 days later than it was in the early 1970s (Chapter 7); springtime warming has led to earlier snowmelt and emergence of vegetation (Griffith et al. 2002). Additional warming could reduce the usefulness of ice roads and pads or of some off-road technologies.

Projected Changes in the Arctic Marine Environment

Ice cover in the Arctic Ocean has been shrinking by about 3% per decade over the past 20 years (Johannessen et al. 1999). The loss of volume could be even greater than that, because Arctic sea ice has been thinning by as much as 15% per decade (Rothrock et al. 1999), from an average thickness of 3.1 m (10.2 ft) in the 1950s to an average of 1.8 m (5.9 ft) today (Weller 2001).

If the trend were to continue, within 50 years the sea ice could disappear entirely in summer (see map, page 18, *NOAA Report of the National Coastal Assessment Group*, October

2000). Even if changes are less dramatic, the amount and duration of open water near the north coast of Alaska is likely to increase substantially. This is significant because ice edges are highly productive regions where interactions between physical and biologic processes result in substantial phytoplankton blooms. Those blooms in turn support populations of zooplankton and arctic cod (*Boreogadus saida*) and their predators (Niebauer 1991, Wheeler et al. 1996). The migrations of belugas (*Delphinapterus leucas)*, narwhals (*Monodon monoceros*), and harp seals (*Phoca groenlandica*) to ice-edge regions are associated with bursts in productivity and the subsequent abundance of arctic cod in those areas during the summer plankton blooms.

The loss of sea ice also would reduce critical habitat for marine mammals and seabirds that use ice shelves and flows as platforms for feeding, resting, reproducing, and molting. Ringed seals (*Phoca hispida)* depend on stable, fast ice for raising their young. They and polar bears (*Ursus maritimus)* are the only marine mammals that regularly occupy land-fast Arctic ice (Tynan and DeMaster 1997). The species that use and depend on sea ice would not necessarily decrease in overall abundance, because new habitats are likely to become available farther to the north. However, if migrations of bowhead whales (*Balaena mysticetus*), for example, were to shift farther offshore and if populations of seals near the coast were to be seriously reduced, the consequences for coastal human subsistence cultures could be dramatic. In addition, increases in the amount and duration of open water could make the usually unnavigable Northwest Passage available for ocean transport. Already in 1999, Russian companies sent two large drydocks to the Bahamas through the Northwest Passage. Oil companies might have improved opportunities for drilling off the coast. The U.S. Navy is assessing the implications of the continuing reduction of sea ice for the scope of its operations in the Arctic Ocean (ONR 2001). The addition of new sea traffic in the Northwest and Northeast passages could lead to new environmental effects, caused by spills, noise, or collisions, for example, that could accumulate with effects of oil and gas development.

Projected Changes in Terrestrial and Freshwater Environments

Changes in tundra will result from the direct and the indirect effects of climate change and its drivers. No direct effects on animals from increased CO_2 concentrations are anticipated, but direct effects on plants (photosynthetic and respiration rates) would be expected. In addition, there will be direct and indirect effects of temperature changes on plants, animals, and microorganisms. Predicting the effects of warming on tundra ecosystems is difficult because of the complexity of the ecosystem. In addition, the time scales at which different consequences appear are highly variable: some processes begin within a day, others will not become fully apparent for centuries.

Few studies have yet been conducted on flat, coastal, polygon-sorted tundra, but the International Tundra Experiment system is using passively warmed, open-top chambers in 26 arctic and alpine tundras to compare the effects of warming on plant growth and flowering (Henry and Molau 1997, Arft et al. 1999). Investigators at Toolik Lake on the north slope of the Brooks Range have shown experimentally that decomposition and mineralization of nitrogen in tundra is strongly limited by low soil temperatures and high soil moisture (Nadelhoffer et al. 1992). Thus, with increased turnover of soil organic matter because of increased warming, a high potential exists for redistribution of nitrogen from soils (with low C:N ratio) to vegetation (with high C:N ratio), but accompanied by little or no net change in ecosystem stocks of nitrogen (Shaver et al. 1992).

If warming were accompanied by decreased soil moisture, large increases in respiration would be expected to cause long-term loss of both carbon and nitrogen from the system. In addition, the increased depth of permafrost thaw of would lead to increased losses of mineralized nitrogen because of drainage. If so, increases in nitrogen uptake and net primary production (NPP) in Phase II would be insufficient to compensate for nitrogen and carbon losses attributable to leaching and respiration. Therefore, even though the ecosystem eventually would return to equilibrium—NPP equals respiration (that is, there is no accumulation of biomass through carbon storage) (Vourlitis and Oechel 1997, 1999; Waelbroeck et al. 1997)—over 50-100 years there would be a net loss of carbon to the atmosphere. Increases in CO_2 concentrations also would result in changes in allocation of carbon and nitrogen among plant tissues, which would affect the palatability of those tissues to herbivores and potentially alter the dynamics of herbivore populations. Warmer temperatures could favor the spread of woody plants over portions of the North Slope and increase insect abundance and periods of activity.

Although the depth of the active layer is likely to increase in a warmer climate, the general pattern of stream flows is unlikely to change much. Increased snowfall, which is possible, would result in greater spring runoff, and warmer winters should reduce the depth to which lakes and streams freeze, thereby altering wintering habitat for fish and other freshwater animals.

Changing Climate and Permafrost

As mean air temperatures rise in a warming climate, the earth's surface generally warms by an amount that varies locally with vegetation, moisture, snow, and other conditions. This surface warming propagates slowly downward into permafrost, typically taking about a century to reach a depth of 100 m (300 ft). Although little direct information is available on the North Slope climate and its 100-year history, temperature measurements in deep wells across the North Slope show that near-surface permafrost temperatures, though variable, typically increased by 2-4 °C (3.6-7.2 °F) in the 20^{th} century before the 1980s (Lachenbruch and Marshall 1986) and that additional rapid changes have occurred since (e.g., Clow and Urban 2002). These results are roughly consistent with the large changes seen in broadly averaged twentieth-century arctic air temperatures (Hanson and Lebedeff 1987, Chapman and Walsh 1993, Hansen et al. 1999, Lachenbruch et al. 1988). Although the early twentieth century warming might include unrelated natural effects (Stott et al. 2000), rapid changes of the past few decades are consistent with anthropogenically driven climate models that predict continued rapid warming in the twenty-first century (Alaska Regional Assessment Group 1999). As the permafrost warms, its ability to support engineering structures diminishes, so it is necessary to consider how much additional warming is likely and how that might influence future effects of oil and gas development.

Permafrost Conditions

The mean annual surface air temperature over much of the North Slope is -12.5 °C to -9 °C (10-16 °F) (Haugen 1982, Zang et al. 1996, Olsson et al. 2002). The corresponding near-surface permafrost temperature is locally variable and typically 2-5 °C (3.6-9 °F) higher (e.g., Brewer 1958a). The difference is caused by winter snow cover and complex processes in the active layer. This is generally cold "continuous permafrost" (no gaps) defined by its temperature (beneath the 20-meter layer subject to seasonal change) below -5 °C (23 °F) (Lunardini 1981). Continuous permafrost is robust in the sense that its temperature could be raised several degrees before destructive thawing would begin. By contrast, spatially discontinuous permafrost (with gaps) with near-surface temperatures near 0 °C (32 °F) is fragile and more easily disrupted by warming.

Throughout the coastal plain and most of the foothills, measured temperatures near the surface in permafrost are so low—typically -10 °C to -6 °C (14-21 °F) (Lachenbruch et al. 1982b, Osterkamp 1988)—that they could withstand several decades of warming at the predicted rate before they start the mechanically troublesome transition from continuous to discontinuous permafrost. As the climate warms, the natural permafrost temperatures rise, leaving a smaller margin for engineering disturbance. The effects of persistent climate warming could eventually involve failure of neglected structures, or the requirement to modify design, or in some cases, to completely abandon some design options or practices. For example, thicker gravel would be required to preserve permafrost as warming proceeds. Abandoned work pads and roads will become unusable as they are cut up by deep polygonal troughs over thawing ice wedges or by other thermokarst degradation. After some degree of warming, preserving ice-rich permafrost with gravel will become unworkable well before the permafrost approaches the discontinuous state near 0 °C (Lachenbruch 1959, Heuer et al. 1985).

Because most of the predicted warming would occur in winter, the period during which nondestructive surface travel can take place over a frozen active layer that is protected by snow cover or ice roads would be shorter, decreasing the capacity for winter operations.

Interaction with Climate

It is generally assumed that as the mean temperature of permafrost rises, the active layer that thaws each season will thicken. However, where moisture and organic material increase the active layer might actually thin as the climate warms (Lachenbruch 2001). More generally, the change in the physical state, and the associated biotic changes, of the active layer with changing climate are difficult to predict with current information.

The difficulty of predicting the effects of changing climate on permafrost and, ultimately, of predicting how effects of oil and gas development might accumulate, involves much more than uncertainty in predicting climate change. We know that the cold deep permafrost that dominates ecosystems and constrains landuse on the North Slope is a consequence of low air temperatures, but we know little about the local distribution of those temperatures or other relevant climate parameters, now or in the past. (The topographically diverse North Slope, with an area of 20 million ha [50 million acres] has two U.S. National Weather Service stations, both on the Arctic coast.) When the climate changes, effects are transmitted to permafrost through poorly understood processes, physical and biological, that operate in the active layer, whose new state becomes difficult to predict. By contrast, once a change in mean temperature penetrates the active layer (and establishes the temperature at the top of permafrost) it propagates downward into permafrost predictably according to simple physical rules of heat conduction. The shape of the temperature-depth profile to 200 m (660 ft) contains a faithfully preserved, if somewhat ambiguous history of permafrost surface temperature changes over the past century or more (Clow 1992, Lachenbruch 1994).

The needed understanding of the connection between climate, active layer, and permafrost requires repeated measurements in the same place of surface heat balance, snow depth, and temperatures through the active layer to permafrost (a few meters). This could be done with remote self-contained instrument stations (now available at modest cost) distributed over the North Slope or other areas of concern (e.g., Olsson et al. 2002, Clow and Urban 2002). Insights into the history of temperature at the top of permafrost (the bottom of the active layer) and its rates of change can be obtained from careful down-hole thermal measurements in wells at any location in the continuous permafrost.

Permafrost and the Encroaching Sea

The steep permafrost bluffs behind the narrow beaches of the Beaufort and Chukchi seas are receding an average of 2.5 m (8 ft) per year; this is the most rapidly retreating shoreline in the United States (Reimnitz et al. 1985). The bluffs have been retreating rapidly for thousands of years because of the destructive thermal effects of the surf, which thaws and undermines the bluffs and carries away the debris (MacCarthy 1953). (The retreat can be expected to accelerate with warming climate and diminishing sea ice.) The retreat poses some engineering problems for pipelines and other facilities that cross the shoreline, and it presents a potential risk from toxic-waste pits abandoned by "freezeback" during earlier coastal exploratory drilling. But most important, the marine encroachment controls the temperature and distribution of permafrost beneath the edge of the sea.

As the shoreline migrates inland, a coastal point on the North Slope undergoes a dramatic climate change—its mean temperature increases from about -11 °C (12 °F), characteristic of land, to -1 °C (30 °F), characteristic of the seabed (Lachenbruch 1957a). This transition occurs over a band of a few kilometers where the water is less than 2 m (6.5 ft) deep and where grounded sea ice cools the seabed in winter (Lachenbruch and Marshall 1977, Osterkamp and Harrison 1982). Over this short distance we pass from robust permafrost with a large subfreezing cold reserve on shore to the more fragile subsea condition where temperatures are close to melting throughout—a condition that is characteristic of discontinuous permafrost 500 km (300 mi) to the south. In fact, the ice-bonded state of the subsea permafrost is likely to be discontinuous because of local variations in salinity (and hence in freezing temperature) of the water (Harrison and Osterkamp 1978, Nixon 1986).

The 600 m (2,000 ft) deep, cold, ice-rich permafrost at Prudhoe Bay would warm to near-melting temperatures from top to bottom about 2,000 years after inundation, but its ice-rich condition could persist down to hundreds of meters (60 km [38 mi] from shore at current transgression rates) for another 25,000 years (Lachenbruch 2001, figure 5; Lachenbruch et al. 1982a; Nixon 1986).

The importance of the retreating permafrost shoreline for human activities is that the shoreline provides a sharp separation between cold permafrost on shore and a warm, near-melting permafrost offshore that is potentially more vulnerable to engineering disturbance. The remarkably rapid retreat yields a transient condition that permits deep, ice-rich (but warm) permafrost to persist to tens of kilometers off shore. Diminishing sea-ice cover from climate warming might further increase seabed temperatures, slowly decreasing the cold reserve of any shallow permafrost there. This is a zone of active exploration and development, including the Northstar project and now-suspended Liberty project. It provides support for artificial islands, causeways, buried pipelines, drill pads, and other infrastructure.

OTHER MINERAL RESOURCES

The scenario used by the committee to predict the accumulation of effects is confined to exploration for and extraction of oil and gas. However, the North Slope contains significant deposits of other hydrocarbons, especially coal and coalbed methane. If those deposits were exploited in the near future, the committee's scenarios could change dramatically. Because of economic and other uncertainties, the committee cannot predict the degree to which any of these sources will be exploited or when such exploration might occur.

Coal

The coal-bearing beds on the North Slope of Alaska, mainly in rock sequences of the Nanushuk Group of Cretaceous age, are well exposed in the western part of the National Petroleum Reserve-Alaska in bluffs along the Kokolik, Kukpowruk, Utukok, Kuk, Meade, and Colville rivers and have been penetrated in several of the test wells drilled in the northern foothills (Figure 5-2). They range in rank from lignite A to high-volatile A bituminous and are low in ash and sulfur (Sable and Stricker 1987). Sable and Stricker (1987) estimated the amount of Cretaceous coal on the North Slope at 1.3 trillion metric tons (t) (1.7 trillion short tons of bituminous coal).

East of the Colville River, coal beds of lesser potential and rank are exposed in sequences of the Sagvanirktok formation of Tertiary age and extend off shore (Sable and Stricker 1987). Those coal beds rank from lignite A to sub-bituminous B with a mean of sub-bituminous C with low sulfur and variable ash content (Roberts et al. 1991). Stricker (USGS, personal communication, 2002) estimates the total hypothetical volume of the Tertiary coals on the North Slope and offshore Beaufort Sea at 608 billion t.

Coals of lower Mississippian age are exposed at Cape Lisburne, in the eastern Brooks Range, and in wells south of Barrow (Sable and Stricker 1987, Wahrhaftig 1994). They rank from low-volatile bituminous to anthracite and are low in sulfur and ash (Tailleur 1965, Conwell and Triplehorn 1976). Merritt and Hawley (1986) listed the coal volume at Cape Lisburne as 842 million t.

Coal was mined on the North Slope at Cape Beaufort to provide fuel for commercial whaling ships as early as 1879 (Schrader and Peters 1904). Alaska Natives have mined coal in the Corwin Bluffs and in the lower Kuk and the Meade rivers, off and on for many years, but they currently rely mainly on natural gas and diesel oil for generating heat and electricity. Various mining companies have sampled and made preliminary investigations into the feasibility

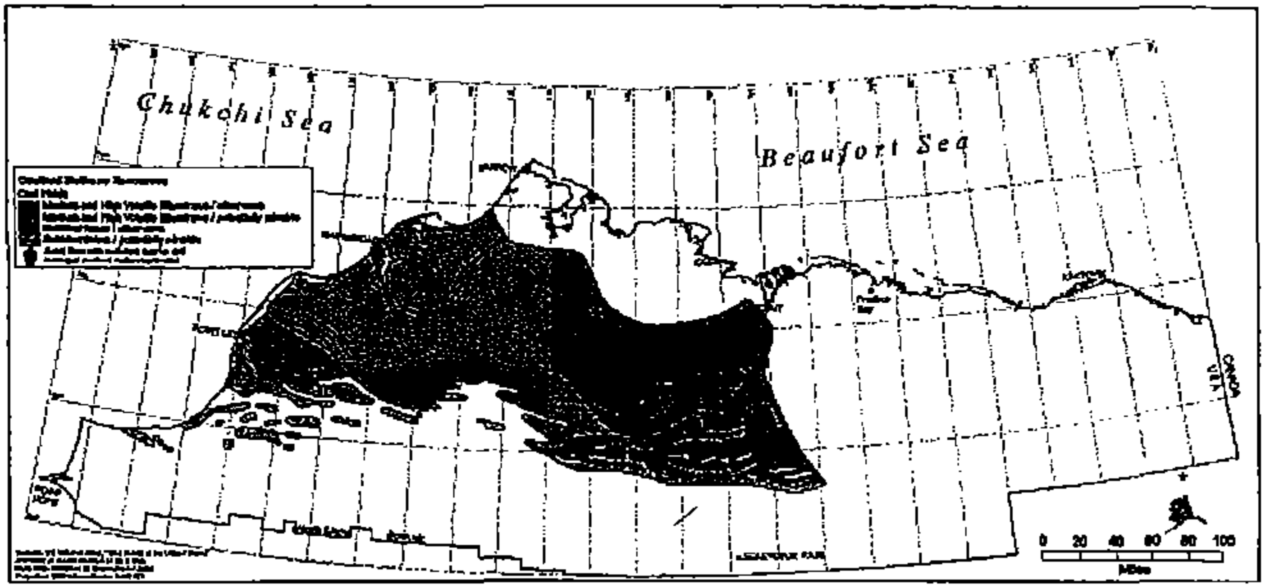

FIGURE 5-2. Coal and Coalbed Methane Resources on the North Slope. Drawing by Mapmakers Alaska 2002.

of commercial mining of coal for export. The ASRC has recently considered such an operation in the western North Slope.

One problem for commercial mining of coal from the western North Slope involves transportation. There are few roads and there is no year-round seaport. The nearest seaport with docking facilities is at Kivalina, about 320 km (200 mi) by air from the best Cretaceous coal exposures. The Kivalina seaport was built for the export of lead and zinc ore concentrates: It is open for shipping about 100 days each year. Ore concentrates must be shipped on barges about 6 km (4 mi) out to sea where ore ships can be anchored and loaded.

A recently built 84 km (52 mi) road in the De Long Mountains runs from the Red Dog lead and zinc mine to Kivalina (Skok 1991). A connecting road to a North Slope coal mine could be built to haul coal to Kivalina, but additional storage facilities would be needed at Kivalina. Construction of a new seaport at Oumalik Lagoon or Kotzebue and access roads have been suggested for shipping coal from the North Slope (Fechner 1991). However, large-scale coal mining under arctic conditions, and hauling overland to Kivalina or to a new seaport with dock facilities, probably is not economically feasible in light of competition from existing lower-cost coal operations in Cook Inlet and elsewhere in the United States. The only commercial mining of coal in Alaska, for export to Korea, is from the Usibelli Coal Mine at Healy on the Alaska Railroad, which hauls the coal to a year-round seaport and to loading facilities at Seward.

Intermittent coal mining for local use probably will continue unless some other local fuel source, such as natural gas or coalbed methane, is developed for use in small communities in the North Slope and elsewhere in Alaska.

Perhaps some innovative engineering plan, such as transporting coal as a slurry in a pipeline to tidewater, or burning coal in place to generate and transport electrical power to market through power lines or by other means, could eventually become economically feasible. However, unless subsidized, substantial coal mining on the North Slope in the near future is unlikely.

Coalbed Methane

The coalbed methane (CBM) potential of the North Slope is estimated to exceed 800 trillion cubic feet (tcf), and could exceed the resources of the contiguous states, approximately 695 tcf. It is estimated that there are 150 significant coal seams, ranging from 2 to 9 m (5 to 28 ft) thick, in the western Colville Basin (Clough et al. 2000). The growth of CBM production in the contiguous states and a new state program in Alaska has spurred interest in developing these resources. The Alaska Division of Geological and Geophysical Surveys (ADGGS) began a program in 1999 to encourage noncompetitive exploration and development by industry of shallow (within 910 m [3,000 ft] of the surface) reservoirs of natural gas, including CBM (Clough et al. 2000). About 25 Alaska communities are atop or adjacent to potential CBM beds. The state, in cooperation with Alaska Native corporations, has set up a demonstration project at three locations, Fort Yukon, Chignik, and Wainwright (Dolan 2001). The ADGGS, USGS, and the ASNC are cooperating on a study program that includes drilling to collect subsurface data on the geohydrology and potentially recoverable amounts of CBM.

Gas Hydrate

Natural gas is expected to be more important in the near term for power generation and transportation because of the general effort to reduce air emissions and the expected decline in liquid oil resources. Methane gas hydrate is a potentially enormous natural gas resource that is hundreds of times greater than the estimated conventional U.S. natural-gas resource base (DOE 1999). Gas hydrate is a solid, icelike material that contains molecules of gas bound in a lattice of water molecules. On decomposition, a gas hydrate solid can produce as much as 160 times its volume of gas. Gas hydrate occurs in the deep-water regions of the oceans and in permafrost regions where temperature and pressure conditions are favorable for its formation and stability. Worldwide estimates of methane in gas hydrate are 700,000 tcf, and U.S. domestic resources are estimated between 100,000 and 300,000 tcf (Kvenvolden 1993, Collett 1995). In the 1980s, extensive research and resource estimation programs were funded by the U.S. Department of Energy (DOE), and recent interest in the feasibility of gas hydrate as a fuel has resulted in the National Methane Hydrate Multi-Year R&D Program (DOE 1999). Major gas hydrate deposits are associated with permafrost regions of Alaska, including those in the North Slope.

Many challenges remain before gas hydrate could become a producible methane resource, including characterizing its quantity, quality, and location; delineating the safety and environmental consequences of various production methods; and determining the economics of production (DOE 1999). The goals of the DOE program include removal of technological barriers to resource extraction by 2010 and development of guidelines for commercial production by 2015. The onshore Arctic is an initial target area for feasibility studies because of the existing infrastructure and the large estimated volume of gas hydrate in that area. Even optimistic estimates suggest that gas hydrate will not become a significant source of methane for 10-20 years, and more conservative estimates place routine gas hydrate production as late as 2030-2060 because of technical difficulties and economic impediments (Milkov and Sassen 2001). Based on these considerations, the committee's scenarios do not include gas hydrate as a viable component of natural gas production on the North Slope. Although the economic and technology barriers could be overcome, the first choice will be existing conventional natural gas deposits already characterized and, in many cases, already being produced but not exported.

Base Metal Deposits

The North Slope region contains potentially important base metal deposits. For example, the Red Dog lead and zinc mine is on the western end of a mineralized belt that extends east through the southern part of the National Petroleum Reserve-Alaska and through the Brooks Range, mainly south of the drainage divide, in the Wulik River drainage near the village of Kivalina. The area has been explored and studied by the BLM, USGS, and ADGGS. Excellent prospects for lead and zinc deposits have been found.

The indicated and inferred original reserves at the main deposit at Red Dog were calculated at 77.1 million t, averaging 17.1% zinc; about 13.2 t, averaging 5% lead; and 2.5 troy oz of silver per short ton (85.7 g of silver per metric ton) of ore. Cadmium and germanium are associated with the silver (Skok 1991). The estimates of the reserves are expected to increase as drilling around the main deposit continues. The main ore body is exposed at the surface and is about 1,300 m (4,400 ft) long; it varies from a few hundred meters to 430 m (1,400 ft) wide and averages about 30 m (100 ft) thick, with a thicker zone near the center of140 m (460 ft). Drill hole 26, near the center, intersected 140 m (460 ft) of ore, grading 29% zinc, 8% lead, and 140 g of silver per metric ton. The Red Dog is the second largest zinc deposit in the world, but probably the richest.

A second deposit, the Hilltop deposit, is located just south of the Red Dog main deposit and is of similar origin and geologic setting. The Hilltop contains copper sulfides, up to 3% copper in some samples, and 1 gram of gold per metric ton. It is estimated to contain several million tons of ore at grades comparable to those in the main deposit (Kulas 1992).

The Red Dog mine is a small open-pit operation. The ultimate pit depth will be about 150 m (500 ft) below the creek bed (Kral and Steve 1992). About 2.27 million t (2.5 million short tons) of overburden and waste were removed during mine development and used for road building and other facilities. About 1.8 million t (2 million short tons) of ore are blasted and removed from the open pit each year (about 6,000 short tons or 5,400 t each day, 365 days per year). The ore is milled on site and concentrates moved to Kivalina port on specially designed 75-ton trucks over a 84 km (52 mi) road. There the concentrates are loaded onto barges and towed to larger ore ships about 7 km (4 mi) offshore. Approximately 15 ships of 25,000 to 75,000 tons (70,000 to 210,000 m^3 internal capacity) call at the port each year during the 100-day shipping season (Cominco 1990). The mine (and related facilities) cost $450 million to develop and is expected to produce for 50 years.