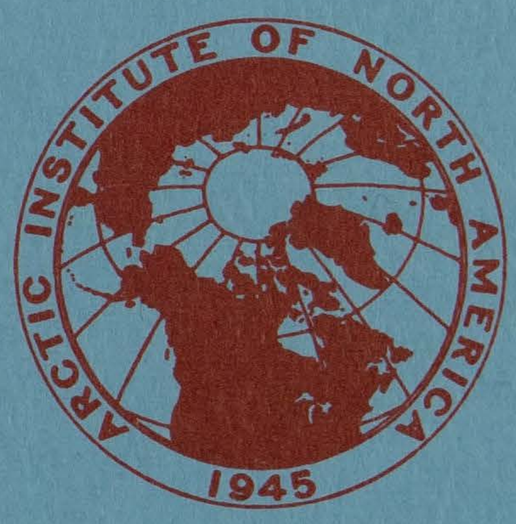
ARCTIC INSTITUTE OF NORTH AMERICA
TECHNICAL PAPER NO. 25

ALASKAN ARCTIC TUNDRA

Edited by

MAX E. BRITTON



Proceedings of the 25th Anniversary Celebration of the
Naval Arctic Research Laboratory

PUBLISHED SEPTEMBER 1973

THE ARCTIC INSTITUTE OF NORTH AMERICA

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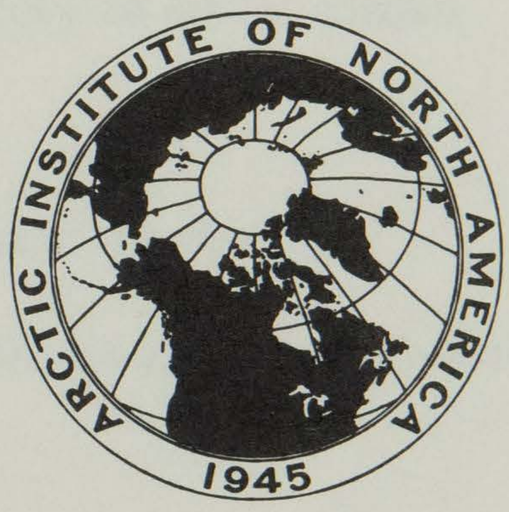
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Technical Editor

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Price: $7.50

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1619 New Hampshire Avenue, N.W.
Washington, D.C. 20009

Printed in the United States of America
Sauls Lithograph Company, Inc.

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ABSTRACT

Alaskan Arctic Tundra is the proceedings volume of the 25th Anniversary Celebration of the Naval Arctic Research Laboratory (NARL). The celebration was held on August 14, 1972 at the University of Alaska. It was sponsored by the Office of Naval Research, by the Army Research Office, by the University of Alaska, and by the Arctic Institute of North America.

There are 15 papers in the proceedings—7 speeches, 7 technical papers, and an introduction by the editor, Dr. Max E. Britton. The speeches recount the history of NARL; acknowledge individuals and groups who have played principal roles in the Laboratory's success; review some of the major achievements of NARL; assess the value of some of the Laboratory's programs; and project the future of the Laboratory itself.

Each technical paper focuses on a particular field of arctic terrestrial research supported by NARL. The authors reveal the results of their work at NARL and review the efforts of others in their research area.

The papers include reviews of permafrost by J. Brown and P. V. Sellmann; North Slope morphology by H. J. Walker; pedology by J.C.F. Tedrow; micrometeorology by J.J. Kelley; limnology by J.E. Hobbie; tundra vegetation by P. L. Johnson and L. L. Tieszen; and lemming ecology by F. A. Pitelka.

INTRODUCTION

Max E. Britton

Symposium Chairman
Arctic Institute of North America
Washington, D.C.

On August 6, 1947, Dr. Laurence Irving, then a professor at Swarthmore College, and six companions arrived at Point Barrow, Alaska to initiate an Office of Naval Research program in physiological research. This date marked the beginning of the Naval Arctic Research Laboratory. Twenty-five years later, on August 14, 1972, Dr. Irving, now professor of Zoophysiology and Advisory Scientific Director of the University of Alaska's Institute of Arctic Biology, delivered a short speech on "The Beginnings of Science in Alaska." His speech kicked off a 1-day program commemorating the 25th anniversary of NARL.

Three years earlier, at a symposium held at the University of Alaska to dedicate the newly constructed laboratory, service, and bachelor quarters complex at NARL, Dr. Irving, who served as Director of NARL during its first two years, was joined in reunion with all but one of the other distinguished directors who have guided the destiny of the Laboratory. These included Dr. George E. MacGinitie, Dr. Ira L. Wiggins, Dr. G. Dallas Hanna, and the then incumbent Dr. Max C. Brewer. Only Mr. Ted C. Matthews could not attend. Sadly, this was the last occasion for the possibility of bringing together all former directors. Since that event, death has come to gentle, intelligent, versatile, and well-loved Doc Hanna.

This 25th anniversary program was held at the University of Alaska in conjunction with, and on the day preceding, the 23rd Alaskan Science Conference. Among ex-NARL directors, Dr. Irving presented a paper, as previously noted; Dr. Wiggins served capably, as always, as chairman and discussion leader of the afternoon program session; and Dr. Brewer was the featured after-dinner speaker. Mr. John Schindler, the present director, also gave an after-dinner speech. Dr. MacGinitie, reportedly active and in good health, could not attend because of personal commitments, and Mr. Matthews was on a business trip to Africa.

The Office of Naval Research, in marking the First quarter century of successful operation of NARL, was joined in cosponsorship of the anniversary by the Army Research Office, by the University of Alaska, and by the Arctic Institute of North America. The Chief of Naval Research, Rear Admiral Carl O. Holmquist, was represented by Dr. William Raney, Deputy and Chief Scientist; the Army Research Office by Dr. Desmond O'Connor, Chief, Environmental Sciences Division; the University of Alaska by its president, Dr. William R. Wood; and the Arctic Institute by the author

for Brigadier H. W. Love, Executive Director. The comments of each of these gentlemen, who spoke on behalf of his organization, appear in this volume.

The Arctic Institute was responsible for organizing and managing the program with the guidance and cooperation of Mr. Ronald K. McGregor, director of ONR's Arctic Program. The author, who preceded Mr. McGregor in his position and who departed ONR in 1970, after 16 years of association, to join the Arctic Institute staff, arranged the program and served as general chairman. This role posed a problem in planning, since the anniversary event followed so closely the dedication symposium of 1969. Thus, those attributes of anniversaries exemplified by reviews, reminiscences, plaudits to all worthies, self-congratulations, criticisms, and looks to the future had been largely preempted. There was no desire to allow more than a dignified minimum of repetitive commentary of this type. There was, however, a strong desire to match the excellence of technical papers that derived from the earlier symposium. Both objectives were achieved.

The proceedings of the dedication symposium (Monson and Sater 1969) may be consulted for facts regarding the origin, growth, and accomplishments of NARL and the Navy's relationship to it (Frosch 1969, Owen 1969, and Reed 1969). Also, details of NARL's history and background are published in the histories of Naval Petroleum Reserve No. 4 (Reed 1958), which provided the Laboratory's first field support, and of the Laboratory itself (Reed and Ronhovde 1971). Additional reasons for keeping the program short and nonrepetitive lay in the fact that the site of both meetings was identical; that many participants in the program would be the same; and that many familiar faces, administrative and scientific alike, who follow the course of NARL would comprise most of the audience.

The theme of the program, "Arctic Terrestrial Research and Military Requirements Ashore," was chosen by ONR as best representing some of the kinds of research essential to the shore-based operations of the Navy and the land operations of the Army in the Arctic. These military departments have long histories of investigations in arctic terrestrial science and engineering, accomplished mostly through the Naval Arctic Research Laboratory and the Army's Cold Regions Research and Engineering Laboratory (CRREL).

The far-flung field studies by CRREL scientists and engineers have included extensive use of NARL facilities, which has resulted in a great deal of cooperative research between elements of the Army and Navy. The same is true, of course, for the Air Force, which has shared a long and rewarding relationship with NARL in arctic research. Interestingly, the Air Force pointed the way to the sea-going Navy in how to conduct research in the Arctic Ocean by utilizing drifting ice as bases of operation. The history of Fletcher's Ice Island (T-3) is a well-known Air Force logistic and research accomplishment. Not until 1959, however, did ONR/NARL become meaningfully and continuously involved in drift station research. In that year Station Charlie, a pack ice station, was established cooperatively with the Air Force.

In 1961, NARL began operations on ARLIS II, its first ice island base, which was occupied for four years until it drifted into the Greenland Sea and broke up near Iceland. Also in 1961, the Air Force turned over custody of its T-3 camp to NARL—the ice island at that time was aground off Point Barrow. In February 1962, with the island again adrift, ONR research programs were started there which continue to this date.

Colonel Louis DeGoes, then Director, Terrestrial Science Laboratory, Air Force Cambridge Research Laboratory, was in charge of Air Force arctic research, including drift station operations, between 1957 and 1961. In support of terrestrial research on

Alaska's North Slope, he established, in 1958, a small facility at Lake Peters in the Brooks Range. This facility, partly supported by NARL, was ultimately turned over to the Laboratory, and the now enlarged and improved camp is a favorite and much used site for terrestrial and freshwater lake studies.

Before leaving the subject of the Air Force, deserved recognition is given to the Alaska Air Command for support services to NARL. From 1955 to 1972, Elmendorf Air Force Base, Anchorage, was responsible for operation of the base camp facilities near Barrow. The common services provided without cost to ONR, as well as many special services which were reimbursed, were an invaluable contribution to the operation of the Laboratory.

From the beginning, research at NARL has been heavily weighted toward the physical and biological features of the land. Little was known about the Alaskan Arctic, so every field of science was wide open for study, with fascinating problems to be explored at every turn. Just after World War II, eager scientists were ready to tackle the Arctic, and happily there were thoughtful planners in the federal government with the funds to stimulate action. Thus, NARL was one result of the innovative and invigorating approach to research which characterized the Office of Naval Research. The broad needs of the Navy were understood, and administrators in ONR were given the freedom to pursue these needs with regard to the land, the sea, and the atmosphere. The course of research at NARL has been much influenced by the directors of the Laboratory, by those in ONR responsible for programs, and by the early investigators at NARL who stimulated others to look northward.

The difficulties of working in arctic seas, including simple access to their waters, have always deterred naval research missions. Shore-based marine research was conducted at NARL from the outset with small boats during the brief, unpredictable ice-free season of summer. Not, however, until NARL began using light aircraft as research tools on the pack ice and initiated a program of establishing and supporting drifting ice stations was appreciable progress possible at sea. At times, though, even these efforts have proved inadequate to the task.

The land, then, was more accessible, and there was everything to be learned about the environment and its effects on shore-based operations. The rigorous environments, especially the problems created by permafrost, were critical to every naval activity, including health, safety, and comfort of personnel; potable water supply; waste disposal; road, airstrip, and building construction; communications; and transportation, to mention a few. What needed to be known and what has been learned about the care and maintenance of permafrost alone justify the wisdom of studying all physical and biological properties and processes of tundra surfaces. Hundreds of investigators have contributed to our understanding of the environmental system—the energy and material balances upon which all tundra operations depend.

In this context, naval requirements are not greatly different from those of other agencies or groups. The Navy, however, was there on the arctic land, and to its lot fell a first responsibility, and what might be considered a moral commitment, to learn both how to use the environment and how to protect it. This challenge was met in every degree possible, although it cannot be argued that the accomplishments were enough. Still, the national gains have been enormous, and the North Slope in many ways was ready for petroleum development, pipeline construction, and the like. It is interesting but not pretty to contemplate the environmental mistakes and tragedies which would have afflicted the North Slope over the past four years had it not been for the research of the past quarter century. Credit for this research goes to a host

of individuals as well as private and government organizations, but most of it was supported in one way or another by NARL.

Industry as well as the public has benefited from the research at NARL. One result is that industry is now setting some excellent standards in environmental management along the Arctic Coast. Whether governments or the public will emulate these standards remains to be seen. There can be no double standards in this regard. The environmental misdeeds of oil exploration in PET 4—or even of investigators at NARL—must not be repeated. If rumored naval plans to resume petroleum exploration in PET 4 materialize, the eyes of many will follow the evolving evidence of government commitment to tundra protection. Terrestrial research has pointed the way, but more is needed. A hopeful note is provided by the Tundra Biome ecosystem studies in progress at NARL as part of the International Biological Program. These investigations, primarily financed by the National Science Foundation with support from ONR/NARL, raise tundra research to a new level of sophistication which should be exploited for many years in the future. Funding, however, is expected to be a major problem.

Several times during the past 15 years, attempts have been made to organize a symposium featuring tundra studies in the ONR/NARL research programs. When money was available for symposiums at all, it had to be applied in areas more pertinent and timely to the Navy; for example, on Arctic Sea Ice in 1958 (NAS-NRC 1958), on the Arctic Basin in 1962 (Arctic Institute of North America 1963), and on Arctic Drifting Stations in 1966 (Sater 1968). The Dedication Symposium in 1969 (Monson and Sater 1969) included a number of papers on the tundra, but in no sense gave emphasis to it.

At last, the 25th anniversary presented the opportunity to give individual attention to terrestrial aspects of naval research. A 1-day program lacked the scope for a proper symposium that would touch upon all the highly diverse and competent research at NARL. Not only was there a large subject matter to choose from, but also there were hundreds of scientists who could be called upon for outstanding papers. And so the decision was made to present a series of papers that would review and sum up accomplishments in seven disciplines contributing conspicuously and importantly to a concept of the tundra ecosystem. That the picture could not be complete was acknowledged and that there would be limited synthesis of knowledge into an over-all view of the ecosystem was accepted.

Further, decisions were made to stress research fields with long histories of investigation at NARL and to include in the program scientists long identified with the first 25 years of its existence. At the same time, an effort was made to avoid, as much as possible, a duplication of subjects and authors involved in the Dedication Symposium. These goals were only partially achieved and, in the true NARL tradition, were flexibly set aside when reason dictated otherwise. All are mindful of the excellent contributions others could have made, and genuinely regret the anniversary spotlight could fall upon so few.

The tangible record of the 25th anniversary program resides in this volume and in the separately published *Bibliography of the Naval Arctic Research Laboratory* (Gunn 1973). Both do honor to the event. The bibliography, compiled and published by the Arctic Institute of North America under contract with ONR, is the first complete listing of the scientific products of the NARL experiment in research support. Reference to the 2,426 entries reveals the broad spectrum of research accomplished, the hundreds of investigators who have participated, and the diversity of agencies that have sponsored research at NARL.

The Laboratory has pursued an often faltering course and endured a frequently tenuous existence in arriving at its silver anniversary. The credits for achievement are spread so widely and belong to so many that recitation would be tedious. To the investigators and their sponsors goes the greater credit. It is for them that the Laboratory exists, and it is the application of their scientific results that provide the true measure of NARL's success.

Over the years, several contractors have operated the Laboratory, and more likely than not the importance of their roles goes unrecognized. Among these, the University of Alaska, which has served this function since 1954, is singled out for special thanks. The University has carried out its functions in outstanding fashion through some of NARL's most difficult times in terms of growth and change. Its president, Dr. William R. Wood, has been one of the proudest and most stalwart supporters of NARL during the years of the university's involvement.

The Arctic Institute of North America has had numerous and significant roles in the success of NARL. When the Laboratory was only a germinal idea within ONR, the Institute supplied advice on its organization, programs, and operation. During its "growing" years, the Institute advised, recommended, funded, and administered many of NARL's research programs. In recent years, the Institute has also been publishing some of the fruits of its 25-year association, also to the good of NARL. All these functions have been invaluable to the total ONR/NARL program.

Not to be forgotten are the contributions of excellence from those responsible for the leadership of NARL. On the Washington end have been the several admirals who have served as Chiefs of Naval Research; on the Point Barrow end have been the NARL directors. Praise is given for all of these who have steadfastly supported the Laboratory through triumph and travail alike.

Finally, an individual salute is in order for Dr. Louis O. Quam, who recently retired as Chief Scientist, Office of Polar Programs, National Science Foundation. It was he who, in 1951, took over ONR program responsibility for NARL and gave it new life. He steered it through times, as in 1953, when it was perilously close to extinction; did innovative things, such as starting the ONR drifting station program; and generally set a course for the Laboratory which led to its present national and international reputation.

NARL has been, and continues to be, the only U.S. research laboratory in the Arctic. Just by being there it has uniquely influenced and enhanced the accomplishment of research, and has attracted and supported investigators whose field work would otherwise have been essentially impossible. ONR has wisely operated the Laboratory as a national facility rather than as one serving only naval missions. One attribute of significant impact to arctic research has been the policy of accepting at NARL all programs, large or small, contracted or sponsored by any federal agency. By officially participating in those programs appropriate to naval research interests, NARL field and laboratory support was furnished as the Navy's contribution. Projects lacking federal sponsorship–national, international, private, public, commercial–if representing appropriate and competent research, were generally accepted for NARL support with assessment of modest reimbursement charges for services. Although in recent years there has been an increase in user charges for investigators not under direct ONR funding, the charges remain modest and the door remains open for the support of research on traditional grounds.

This writer is convinced that the Laboratory, all in all, has met the expectations of its founders and has served its assigned functions with distinction. It has taken on new roles and responsibilities; it has been innovative in developing support services–such as

using aircraft for ice landings, operating drifting stations as research platforms, and setting up a network of small research facilities across Alaska's North Slope; and it has grown slowly but soundly as research needs and resources have permitted.

On the attainment of NARL's 25th anniversary, one of the "old boys" might speak glowingly of the "Golden Years." Not so. The Golden Years lie ahead. Progress has been made, targets and standards have been set, the value of arctic research has been demonstrated, and hundreds of individuals have been safely indoctrinated to the North, but much remains to be done. Things golden, then, belong to the "new boys" of the present and future.

Acknowledgments

Thanks are due to many but expressed to few for assistance in organizing and participating in the anniversary program, and in bringing to publication its two commemorative volumes. Appreciation is given for the cooperation and assistance of Mr. Ronald K. McGregor, Director, the Arctic Program, Office of Naval Research; for the generosity and hospitality of Dr. William R. Wood and his staff, who made the University of Alaska a happy choice for the NARL celebration; for the loyal support of NARL investigators who found it possible to attend the formal activities; and for the good efforts of all speakers, who carried the major burden in making this volume possible.

Also acknowledged is the cheerful and willing helpfulness of Dr. Gordon Harrison, Institute of Social, Economic and Government Research, University of Alaska. As organizer of the 23rd Alaskan Science Conference, he cooperated in planning and coordinating the NARL functions with those of the science conference. With regard to the publication of this volume, thanks are extended to the Editorial Committee—Dr. Max C. Brewer, Dr. Frank A. Pitelka, Mr. Ronald K. McGregor, Mr. John F. Schindler, and Mr. Wade W. Gunn. The greatest credit goes to Mr. Gunn, Technical Editor, Arctic Institute of North America, who bore the responsibility for editing and printing this volume as well as the NARL bibliography. His diligence, care, patience, and devotion to high editorial standards are acknowledged with special thanks.

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WELCOMING ADDRESS

William R. Wood

President
University of Alaska
Fairbanks, Alaska

The North? I cannot tell you anything about the North. What I have learned about it you know already. But I could observe that the North is big, beautiful, and rich. And it would be naive for me or for anyone to assume that change will not come to the North, that it is going to be left in its pristine state, that it can be preserved as a kind of world park, that its resources can lie under the tundra forever, or that man will not disturb them. And I say this is pure naiveté on my part or on anyone's part. The North is rich. It is beautiful. It is big. And man is not going to leave it alone.

But how man confronts the development of the resources of the North is important. We can attempt to understand the North and plan how we can best use it without destruction. And herein the Laboratory has played a magnificent role. Early on, ONR and a group of scientists conceived that we must know more about the land and the people who inhabit it; that we must know more about its resources and its potential; that we must know more about the seas that surround it. Basically, though, we must learn to understand it, and for 25 years, through the Laboratory, we have been attempting to do just that.

At first, the pace was slow but steady. Significant contributions were made to knowledge, to learning, to understanding. And then change came, and we found that we did not know enough. We had not been operating on a large enough scale. Man needed to know a thousand times more than what had been learned. Today I think we face at the Laboratory, and also here at the University, an acceleration of effort that will lead to an understanding of the basics of the land, the waters that surround the land, and the air that encompasses them both.

I am delighted to see here today some of the foremost scientists of the world who are concerned with getting on with the job. It is fitting that we should pause at the end of a quarter century of significant effort to be a little nostalgic, to reminisce a bit, to pat ourselves on the back, to remember old friends and the memorable experiences of the last quarter century, and then to set all this aside and get on with the new tasks that confront us.

I conclude where I began. The North is big, and beautiful, and rich, and extraordinarily attractive to certain individuals. I believe that one advantage we possess as we face the future is the low-density population existing there now. I would prophesy

that this low-density population would persist, but how does one know for certain when something is there that is attractive and that people will desire more and more as the years go by. Development in the North will come. I only hope that, through the efforts of the great people at the Naval Arctic Research Laboratory, at universities, and at agencies around the world, your work in scientific studies to understand the environment will comprehend the wisest use of the North for the benefit of man. I hope you will succeed to the point where we will not have the wrong type of development undertaken.

Well, on with the 25th anniversary! I am pleased to welcome you to the campus of the University of Alaska. Most of you do not need this welcome. You are old friends, and you are familiar with the stages of growth that we have been through. We are not at the end, for there is much yet to do. As a general guide, though, we have conceived what is in the process of accomplishment on West Ridge as a sort of national research center for understanding this high-latitude environment of the North. I once predicted that by the end of this century we would have at least a thousand scientists and technicians on that West Ridge hill. Now I think we will probably have to advance that target date by a number of years.

The University's partnership with the national government and its many agencies is extremely important to Alaska. We should continue to encourage an augmentation of this cooperative effort. With your help, your enthusiasm, your understanding of what is needed, and your advice, I think we shall definitely be able to get on with the job to the benefit of all of us.

BEGINNINGS OF SCIENCE IN ALASKA

Laurence Irving

Institute of Arctic Biology
University of Alaska
Fairbanks, Alaska

When I began to compile some information dealing with the beginnings of science in Alaska, I decided that, after all, you knew it all better than I did and that time would not permit the true relation of anything like the scheme of beginnings of science in Alaska. And so I will direct my remarks to that part of it which is relevant for me. I was privileged to have been associated with the many people and activities of the Navy that led to the establishment of the Naval Arctic Research Laboratory.

Scientific exploration in the Arctic cannot be initiated through experimental models in academic institutions. It requires direct observation of the life and conditions in arctic lands and seas by methods that go beyond the means of institutions of learning. The logistic means existed in the federal military services, but it required imagination and high appreciation regarding the value of scientific information about the arctic world for the Navy to support and sustain a laboratory for research at Barrow.

In 1946, the Office of Naval Research indicated its desire to set up some biological research at Barrow in connection with exploration for petroleum in Naval Petroleum Reserve No. 4. A year's preparation for this research was ably managed at Swarthmore College through the skill and enthusiasm of Dr. P. F. Scholander. The first group of scientists reached Barrow in August 1947.

That first winter produced physiological views of arctic land mammals, birds, fishes, and invertebrates that appeared to represent schemes of adaptation to arctic life. Dr. Scholander proposed that arctic adaptation could only be tested by comparison with tropical life. Examples from the Arctic and the tropics clearly indicated a common scheme of climatic adaptation that has become the basis for comparing physiological and biochemical adaptation for the cold or warmth of climates.

As a biologist I acknowledge especially the benefit of association with scientists who looked at the arctic world through different eyes. In the academic system it is only by difficult effort that a biologist associates with geologists, physicists, or social scientists. At Barrow the interests of scientists in the living and nonliving environment overlap. Expeditions in the field commonly combine several types of scientists, partly for logistic convenience but fortunately, I would say, often for the sheer pleasure of each other's good company. It is this ability to combine the different views of the

world in systematic fashion that enlarges specialist disciplines to an intellectual process. Rational combination of many methods of observation and systems of thinking seems a characteristic of arctic scientists.

The Naval Arctic Research Laboratory has provided experience for a large number of scientists. The results of NARL's activities have led to other establishments for arctic research. Its new scientific expertise and better facilities have allowed the use of intricate modern hardware and software for research in the arctic environment. It seems like fortunate foresight for Alaska, for the nation, and for international affairs that these broad programs of scientific research in the Arctic have received support, for we have come to realize that scientific knowledge of the environment will be critical during the coming years.

ARMY TERRESTRIAL SCIENCES RESEARCH AT NARL

Desmond C. O'Connor

Chief, Environmental Sciences Division
Army Research Office
Arlington, Virginia

I am honored to be here today participating in the observance of the 25th anniversary of the founding of the Naval Arctic Research Laboratory. We in the Army wish to add our congratulations to those already being voiced. The foresight of those who established the Laboratory, as well as the skills and dedication of those who have made it work so well, deserves the praise of both scientific and government communities. I think the success of this scientific outpost in the Arctic has been amply demonstrated. There are hundreds, perhaps even thousands, of scientific reports which gratefully acknowledge the support of the Naval Arctic Research Laboratory. These are not perfunctory statements. Rather, in most cases the research simply could not have been done at all had not the Laboratory existed.

The Army has had a close, cordial, and most profitable relationship with NARL throughout the Laboratory's 25 years. It might not be stretching things too much to say that the Army was on hand for the birth of the Laboratory. An ancestral organization for the Army Cold Regions Research and Engineering Laboratory (namely, the Permafrost Division of the St. Paul District Engineer) was involved in work at Barrow in 1947 in connection with the surveys of PET 4. It is likely that army personnel were on the scene that day in August 1947 when Professor Irving and his six companions arrived at Point Barrow to set up the Laboratory.

The army's relationship with NARL has continued through the years from this first joint work with the Naval Arctic Test Station in 1947. This is true in spite of the fact that for a number of years the Army concentrated most of its arctic research in other areas. As you know, we were rather heavily involved in Greenland and at times in the Fort Churchill region of Canada from the early fifties to the middle sixties. Even during that period, however, we continued to carry out scientific and engineering support with the help of NARL.

The army's terrestrial sciences research program and related engineering investigations have been the principal basis for our work at NARL. Most of the work has been done by the Cold Regions Research and Engineering Laboratory. Permafrost studies have been a major category of effort, but our interest has encompassed a variety of studies, including geomorphology, botany, and ecology of the arctic landscape. Our investigations have not been restricted to land surfaces. For example, our interest in

ice engineering has led to sea ice studies, and our concern for remote sensing of ground and sea ice conditions has resulted in aerial photographic, radar, infrared, and related ground truth surveys with support from NARL. Similarly, our interest in arctic climates has resulted in the collection of meteorological data on the Arctic Slope, again with the support of NARL.

In recent years, army scientists and engineers have been even more in evidence at NARL during the field research season. In fact, it would seem at times that we have people more or less in permanent residence there. Much of the recent effort has been related to the IBP Tundra Biome Program. Dr. Jerry Brown and others from CRREL probably are coming to look upon NARL as a second home.

We believe that an appreciable part of our work has been beneficial for both NARL and the Army. Joint or cooperative efforts have been common. For example, CRREL is carrying out a continuing study of the structural performance of the NARL hangar, with the information being derived benefiting both maintenance and future construction at NARL and elsewhere in the Arctic.

As a second example of cooperation, I can cite the veterinary services that the Army Medical Corps at Fort Wainwright has provided NARL in recent years. This has involved assistance in caring for, and conducting observations on, laboratory animals. It has ranged from pulling the abcessed tooth of a polar bear to implanting sensors in the bodies of animals under study by scientists.

I know I speak for the many army scientists and engineers who have worked at NARL and have depended upon its facilities and logistic support when I say thanks for all the help you have given. We look forward to many more years of cooperative effort.

NARL RELEVANCE AND MISSION SUPPORT

W. P. Raney

Deputy and Chief Scientist
Office of Naval Research
Arlington, Virginia

Greetings and felicitations on the 25th anniversary of NARL. I am here today for Admiral Holmquist, Chief of Naval Research, who could not make it. I am delighted to stand in for him.

Since I have only recently come to ONR, my acquaintance with the Arctic and with NARL is slight. My impressions, then, really have to deal with what I have learned from talking to people and from examining the history, which, by the way, turned out to be quite fascinating. Through it all there was a thread of arguments about relevance and mission support. The question of why the Navy should be supporting work in the Arctic deserves a few remarks.

The Navy has a long history of association with science. We have, after all, had to do navigation for quite some time. In the good old days we even supported outright exploration, in the simple sense of exploration. That seemed a natural thing to do. We were a government organization with resources that could be used to do things, and from time to time we would go ahead and do sensible things. Nowadays, however, everybody has become self-conscious about relevance and mission orientation, and whose duty it is to do what in the federal government. It seems to me that the Naval Arctic Research Laboratory represents a good case study which illuminates several facets of the relevance business. I think some of these facets are significant.

It took a good deal of faith and courage to get the Laboratory started. Of particular help in the beginning, however, was the clear need for undertaking work in the Arctic. In a general sense, of course, the Navy needed to know how to operate in the Arctic. Almost anything one chose to do in those early days was worthwhile, because there was so little detailed scientific knowledge about the Arctic. Resources in those days were slim, but not much could be done about that. The projects thus tended to be small and conducted mainly during the summer, with the choice of projects being somewhat dictated by the personal interests of people who were willing to involve themselves. This state of affairs was excellent, progress was satisfactory, and the knowledge gained was significant.

As time went on, however, we shifted emphasis from mostly biological studies to other work that seemed to have more direct relevance to naval operating missions. As this occurred, we got better facilities which, in turn, constrained us to be efficient in

the use of those facilities. To do this, we switched from mainly summer programs to year-round programs. You can see the beginning of creeping bureaucracy, but that's the way it is with government expenditures. After all, we are spending public monies and we must do the best we can with those monies.

Over the years, then, there has been a change in the philosophy of operation, which has led to a change in the flavor of the establishment. That change has come about for several reasons. As we moved more into the physical sciences and as we got more and better facilities, it became possible to shift emphasis in those areas in which work was being done. Thus the definition of relevance changed. When we started out, the work in biology was perfectly relevant to the Navy. As it became possible to do other things, it became possible also to shade the definition of relevance.

All I am suggesting is that relevance is a changeable concept, and one has to be careful how he uses it.

What has happened as a result of this? As you know, there has been a continuing excellent program of quite basic work in the sciences that relate to understanding the Arctic. Occasionally, there has been a handsome payoff for this investment. The payoff has not been regular, but then one should not count on a regular payoff. From time to time, though, progress reaches a point where you can compile some data and discover that what you have been doing is, in fact, useful. The work goes on patiently for many years, with the relevance being an act of faith for a good many of those years.

I would like to recount three examples of where, after many years of patient work, there has been a handsome payoff. First, there is the soil mechanics (permafrost) work. There has not yet been a substantial payoff for the Navy from the permafrost work. In principle, the Seabees have to know how to construct things in any part of the world. In fact, they have not done much construction in permafrost areas, but other people have. There was a handsome payoff for the Air Force, and that is fine. There was a handsome payoff for commercial interests, and that also is fine. Finally, there was a handsome payoff for anticommercial interests, which I think proves that when you do basic work in any area it is a little hard to predict just where the substantial payoff will be.

The second area is hydrography of the Arctic Ocean. For years, there was no payoff. In fact, the studies were in advance of any solid operational requirement by the Navy. Yet suddenly, the basic work that had been done wound up being absolutely essential for what operational capability the Navy now has in the Arctic Ocean. Here is the classic case of nothing for years, only to discover that the knowledge accumulated turned out to be dramatically useful. A further payoff here is that other mission-oriented agencies have been stimulated to learn more about what is now an operational situation. Suddenly it is very relevant, whereas in the early days the relevance was a good deal more subtle and had to be supported with more persuasive argument than is needed today.

The third example concerns the work in the biological sciences, where we have been trying for these many years to learn how people adapt to various climates. We started out by studying how animals adapt. This work is not finished, but it has been excellent and the progress has been good. The payoff is not yet with us, but I hope we keep on going. The problem boils down to this: direct relevance is sometimes a little hard to demonstrate, unless you look at history and understand that payoffs occur from support of basic science by a mission agency.

As we move into the future, what do we find significant about NARL's history. For one thing, we are now able to conduct investigations that were simply impossible

25 years ago. For example, we have the equipment and the technology for doing things that just could not be attempted earlier. And since we have the equipment and technology, we plan on doing things that are more ambitious and more expensive. This leads some people to the conclusion that research in the Arctic is vastly more expensive than it used to be. I do not think that is true at all. It simply means that we are now able to do more difficult things and we wind up spending more money. When we spend more money, people notice. As soon as people notice, especially with the current climate in the government, then there must be more emphasis on direct payoff and direct relevance to the supporting agency. I do not see this as a problem. It is simply a consequence of having grown successfully and of having moved out of the small stage into the grand stage.

Most of you are aware of the recent change in the formal governmental responsibility for the facilities at Barrow. The Navy has taken over from the Air Force the responsibility for logistic support. This has resulted in a negligible change in cost to the government, but nevertheless it has created a substantial impact on the Navy's budget. Hopefully, this change will produce economies that will permit us to put more money in the research program as opposed to the logistic support program. This consolidation, however, is another consequence of bigness. Instead of the organization you have been familiar with for many years, we now have a somewhat formalized situation, and we have a naval presence which we hope will be helpful.

We have better facilities now than I think many people dreamed possible. These facilities were provided by Congress from public monies. I am delighted that Congress was willing to provide these facilities, but I must remind you that, since public monies were involved, these facilities must be used in the whole national interest.

My final comment on this business of relevance is that it depends to some extent on where the money is. For example, relevance can be shifted, not so much from any change in the absolute situation but simply from a change in who has the money in the federal budget. Some areas which used to be supported almost solely by the Navy are now being supported largely by other agencies, which sometimes allows us to spend our limited funds on things much closer to our specific needs. The Navy also keeps an eye on what is going on in the programs of other agencies. Sometimes the information from these programs fills the gaps in what the Navy needs to know, and this permits our budget to be used in other ways. All this just makes the planning a little more complicated, but hopefully it will come out all right.

There are two examples of this: oceanography and arctic science. Not many decades ago, the Navy was essentially the sole supporter of serious work in oceanography, as navies in their respective countries all over the world are essentially the only players in the oceanographic game. There are a few private institutions specializing in oceanography, but mainly the navies provide the support. This is changing in our country, and the majority of the research support, exclusive of logistic support, rests with other agencies. It has reached the point where a serious distinction is being made between civilian oceanography and military oceanography. In fact, there is some discussion in international negotiations about whether the military will be allowed to continue oceanographic research at all. I can only suggest that this shift in support and in what is regarded as relevant to the military mission is still active. I hope throughout all of it the scientific interest will keep cool heads and succeed in arranging the program that is necessary.

In arctic science, the Navy perceived a need and was willing to support work in the ocean areas and, for a while, in terrestrial and atmospheric areas. That is changing, too, and about all I can say is that the Navy will still be interested in good science. We

will be spending navy money in the Arctic; but, partly at the behest of Congress and partly because we are under serious budget pressures, we will be looking more closely to make sure that the monies we spend in arctic research are astutely used. For the most part, we will be spending our money on things that are clearly of direct interest to the Navy. We will be keeping an eye on the balance, however. Often, the total program–what others are funding and what we are funding–makes good sense for the Navy, while individual pieces of work command only tenuous interest. In conclusion, I hope our association with the Naval Arctic Research Laboratory will continue as happily in the future as it has in the past.

A SHARED QUARTER CENTURY

H. W. Love*

Executive Director
Arctic Institute of North America
Ottawa, Canada

The Naval Arctic Research Laboratory was created in 1947, some 2 years after the Arctic Institute of North America was formed. The reasons for creating NARL (then called the Arctic Research Laboratory) were similar to those for forming the Arctic Institute. World War II established the strategic importance of the Arctic to both the United States and Canada. It also pointed up the scarcity, sometimes complete lack, of knowledge about the environment of the Arctic as well as the difficulty of conducting operations there.

The need for scientific research in the Arctic led to the formation of the Arctic Institute. Formed to serve the common needs of both the United States and Canada, it has promoted the orderly development of the Arctic, has sponsored research to gain knowledge about the arctic environment, and has fostered interest in the North through its information program.

Creation of NARL resulted directly from operational and scientific needs by military and government agencies that could be satisfied only by the acquisition of knowledge. This meant basic research which, in turn, meant facilities in the Arctic and competent people to manage the facilities, direct the programs, and conduct the research.

Shortly after the Office of Naval Research was created, it wrote Dr. A. Lincoln Washburn, Executive Director of the Arctic Institute, about the advisability of setting up a research laboratory in the Arctic. Dr. Washburn promptly replied: "An arctic laboratory for the pursuit of basic scientific research is one of the best ways to facilitate the acquirement of new information. It affords a base of operations for scientists, encourages cooperative observations in different fields of science, and is the only means of effecting some types of research requiring frequent observations at fixed points over a period of years . . . . The Arctic Institute is keenly interested in all fields of endeavor outlined in your letter and will be glad to cooperate in every way it can."

Chief architect of ARL was Dr. M. C. Shelesnyak, head of the Environmental Biology Branch in the Medical Sciences Division of ONR. Much of his planning for

*This speech was delivered for Brigadier Love by Dr. Max E. Britton of the Arctic Institute of North America.

ARL was based on an Arctic Institute publication titled *A Program of Desirable Scientific Investigations in Arctic North America.*

In August 1947, a few days after he arrived in Barrow to start the Arctic Research Laboratory, Dr. Laurence Irving recommended that ONR establish an advisory board. In his letter, he suggested consultation with such organizations as the Arctic Institute of North America.

The Advisory Board, called Arctic Research Laboratory Advisory Board (ARLAB), was appointed in March 1948. At ARLAB's first meeting, its members named Dr. John C. Reed of the U.S. Geological Survey as chairman. Dr. Reed later served as Executive Director of the Arctic Institute. Other members of the Arctic Institute who served with distinction on ARLAB were Dr. Washburn and Dr. Shelesnyak, who resigned from ONR in 1949 to set up and head the Arctic Institute's office on the campus of Johns Hopkins University (at that time administrator of the basic operating contract for ARL).

The joint interests of ARL and the Arctic Institute, that of encouraging and promoting arctic research projects, led to a close working relationship. The Arctic Institute sponsored many of the early projects at ARL, and its members on ARLAB assisted in generating research projects. In fact, the Arctic Institute was technically the supporter of most institutional (university) projects. Financial support for these projects came from ONR, from the National Science Foundation, and from federal defense and civilian agencies. By a basic contractual arrangement with ONR, the Arctic Institute became the official sponsor of most research projects arranged with private institutions and individual researchers.

The basic contract has been continued to the present. The size of the Arctic Institute's share in the program has varied from year to year, depending mostly on Congressional controls, upon government agency requirements, and upon special programs such as IBP. During NARL's first quarter century, however, an important share of its research work, especially in the social and biological sciences, has been carried out under Arctic Institute subcontracts financed by ONR under terms of the basic contract.

In April 1953, ARLAB was abolished. This resulted in new procedures for the operation of some ARL research programs. In 1954, the Arctic Institute set up an Arctic Research Laboratory subcommittee within its Research Committee. The subcommittee was given to understand that, although an Executive Order had designated the National Science Foundation as the principal source of funds for basic research, there still were several important categories of research which ONR would support at Barrow. Cooperative procedures were soon developed between the ARL Subcommittee and an ONR Research Group Committee on the Arctic Research Laboratory. Under these procedures, a large share in the research program at Barrow continued to be arranged and financially supported by ONR.

In 1956, a new custom was established, whereby some responsible NARL or ONR representative attended meetings of the Research Committee of the Arctic Institute. The practice proved useful.

In June 1958, the Arctic Research Laboratory subcommittee was abolished, and the role of that group was taken over by the Research Committee. At the same time, closer ties between ONR and the Arctic Institute were worked out. Under these procedures, the Arctic Institute brought to the attention of ONR project proposals that did not fall within its established guidelines but which, nevertheless, might be of interest to ONR for possible sponsorship.

During the 1960's, the NARL research program was greatly expanded, with emphasis being given to ice island programs on ARLIS II and later on T-3. The Arctic Institute continued to support research projects mainly in the biological and social sciences which, despite growing demands for research in certain physical sciences, remained an important part of the total program. Roughly, a quarter of the NARL research program was performed under the basic contract with the Arctic Institute.

One of the early advantages accruing to the Arctic Institute and the Arctic Research Laboratory was the involvement of Canadians in planning the research programs. Since the Arctic Institute was a binational organization, it could draw upon the advice of outstanding Canadian arctic authorities. Thus, there is an impressive list of Canadian civilian and defense research leaders who cooperated closely in evaluating individual projects as well as the basic aims of the NARL research efforts.

This account should not be concluded without paying tribute to those persons who have labored to make the most of the simultaneous existence of the research facilities of NARL and the collected experience and interest of the Arctic Institute in the promotion of arctic research. Among the many who have fostered and sought close cooperation have been such farsighted early ONR stalwarts as Dr. Shelesnyak, who had the vision to plan in a practical way for an arctic research facility and who later contributed to the program development for the Arctic Institute; Dr. John Field, who in 1949 took over responsibility for NARL while also serving as head of the Ecology Branch of ONR; Dr. Louis O. Quam, then head of the Geography Branch of ONR, who steered NARL through many crises, especially that of 1953 when termination of the PET 4 program threatened the Laboratory's existence; and Dr. Max E. Britton, who guided the fortunes of NARL for 16 years.

Although there are many others who should be mentioned in this connection, one man—Dr. John C. Reed—deserves special attention. He has given of his broad knowledge, long experience, and imaginative leadership both to the growth of NARL and to the continued maintenance of close relations between the Laboratory and the Arctic Institute. Through successive years, he served with distinction as Chairman of ARLAB; as Chairman of the Arctic Institute's subcommittee on Arctic Research; as a Governor of the Institute; and for 9 years as Executive Director of the Institute. A special tribute is certainly due him.

Finally, one might mention the literally hundreds of investigators who have received from the Arctic Institute and NARL the encouragement, the means, and the facilities to explore the scientific mysteries of the Arctic. To mention a few names would be to discriminate, and in any event the outstanding ones have made their own mark among contributors to science in the Arctic. Their names can also be found, if anyone is curious, in the history of NARL now available from the Arctic Institute. In a sense this history is the Arctic Institute's most tangible tribute to NARL and to ONR which has supported it.

The Arctic Institute is proud to have played a role in the programs of the Naval Arctic Research Laboratory, and we look forward to continued cooperation during the next quarter century.

PERMAFROST AND COASTAL PLAIN HISTORY OF ARCTIC ALASKA

J. Brown
and
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Permafrost as a major phenomenon was first discussed by Middendorf in the USSR in 1848, but not until World War II did its true significance emerge in North America. Construction of the Alaska Highway as well as construction and exploration throughout Alaska, particularly in Naval Petroleum Reserve No. 4 (PET 4), brought the extent and significance of permafrost into prominence. Not until the late 1940's, however, did efforts get underway to investigate permafrost in the Alaskan Arctic.

Permafrost and related research have comprised a significant cross section of terrestrial scientific and engineering investigations during the first 25 years of the Naval Arctic Research Laboratory. Emphasis is placed on *related research* since, unlike the situation in the USSR, the science of permafrost has not reached a stage of development in North America, and particularly in the United States, where individuals are identified as permafrost specialists (geocryologists). For this reason, geophysicists, geologists, geomorphologists, pedologists, and engineers have pioneered early permafrost research in this country. These researchers have been ably assisted by biologists and ecologists.

Both academic and federal participants have shared in pioneering arctic permafrost research in the United States. For northern Alaska, the Naval Arctic Research Laboratory, through the Office of Naval Research in Washington and the staff and facilities at Barrow, has provided a focal point through which permafrost science and technology have developed. The book *Arctic Laboratory* recounts much of this development (Reed and Ronhovde 1971).

This discussion of permafrost research will be restricted mostly to the Alaskan Arctic. What has been observed and learned there has its counterparts in other northern regions. Permafrost is a circumpolar phenomenon, and the commonality of principles governing its formation and modification is shared regardless of national boundaries. In addition to permafrost research, a brief account of current understanding of the late Quaternary history of the Arctic Coastal Plain will be presented. The understanding of the origin of the subsurface sediments and their subsequent modification is important in appreciating and interpreting permafrost terrain.

The Concept

The arctic terrestrial environment consists of two major components: abiotic and biotic. Each has specific characteristics which in this paper are termed *properties.* The rates at which these properties change are termed *processes.* Permafrost is a major and dominant abiotic component of the terrestrial system. Figure 1 illustrates the vertical distribution of the upper boundary conditions of permafrost: the plant canopy, the thin insulating organic mat, the thawed mineral soil, and the underlying permafrost. It is within the upper zone (less than 1 m) that most biological and energy exchange processes take place. In turn, these are responsible for modulating many of the temperature histories within the permafrost.

By definition, permafrost is earth material whose temperature is perennially below 0°C, irrespective of the amount or state of moisture, texture, degree of induration, or lithologic characteristics. This temperature phenomenon covers approximately 20 percent of the earth's land surface and results from a negative annual heat balance at the ground surface. Over long periods of time, this negative balance produces a layer of frozen ground hundreds of meters thick. Local environmental factors other than air temperature influence the occurrence and distribution of permafrost, and these include plant cover, snow cover, slope and aspect, and drainage.

Permafrost is divided into two major zones on the basis of mean annual ground temperature, which is measured at the depth of zero annual amplitude. The northern (continuous) zone has temperatures less than −5°C. The southern (discontinuous) zone has temperatures between 0° and −5°C. Within the former, permafrost underlies all types of terrain except deep rivers and lakes. In the latter, widespread areas of unfrozen ground are intermingled with masses of permafrost. The boundary between the continuous and the discontinuous zone (−5°C mean annual ground temperature) generally corresponds to the −8°C mean annual air isotherm.

We will discuss permafrost and related subjects within the framework demonstrated in Figure 2. The permafrost pyramid illustrates the major properties which characterize the permafrost section and those processes which modify the permafrost. The principal characteristics are thermal, physical, geophysical, stratigraphic, and chemical. The near-surface organic remains and some viable organisms constitute the less abundant biotic properties of permafrost (Boyd and Boyd 1964, and Brown 1965). Prominent processes which influence the permafrost regimen are ecological, pedological, and geomorphological. These plus the energy transfer at the air-ground interface interact to form and modify the permafrost terrain.

During the past 25 years, many of the properties of, and processes occurring on, the permafrost terrain in the vicinity of Barrow have been described, analyzed, and reported. Often we find that an individual permafrost researcher has published on several of the processes and properties illustrated in the pyramid. It will, therefore, be difficult at times to remain strictly within the constraints of the permafrost subject. A selected bibliography of published papers and reports is included at the end of this paper, not all of which are cited in the text.

Permafrost

Thermal. Thermal characteristics have been the most intensively investigated of all permafrost properties. It will not be necessary to review this subject in detail, particularly since Lachenbruch and Marshall (1969) have concisely done so. Other repre-

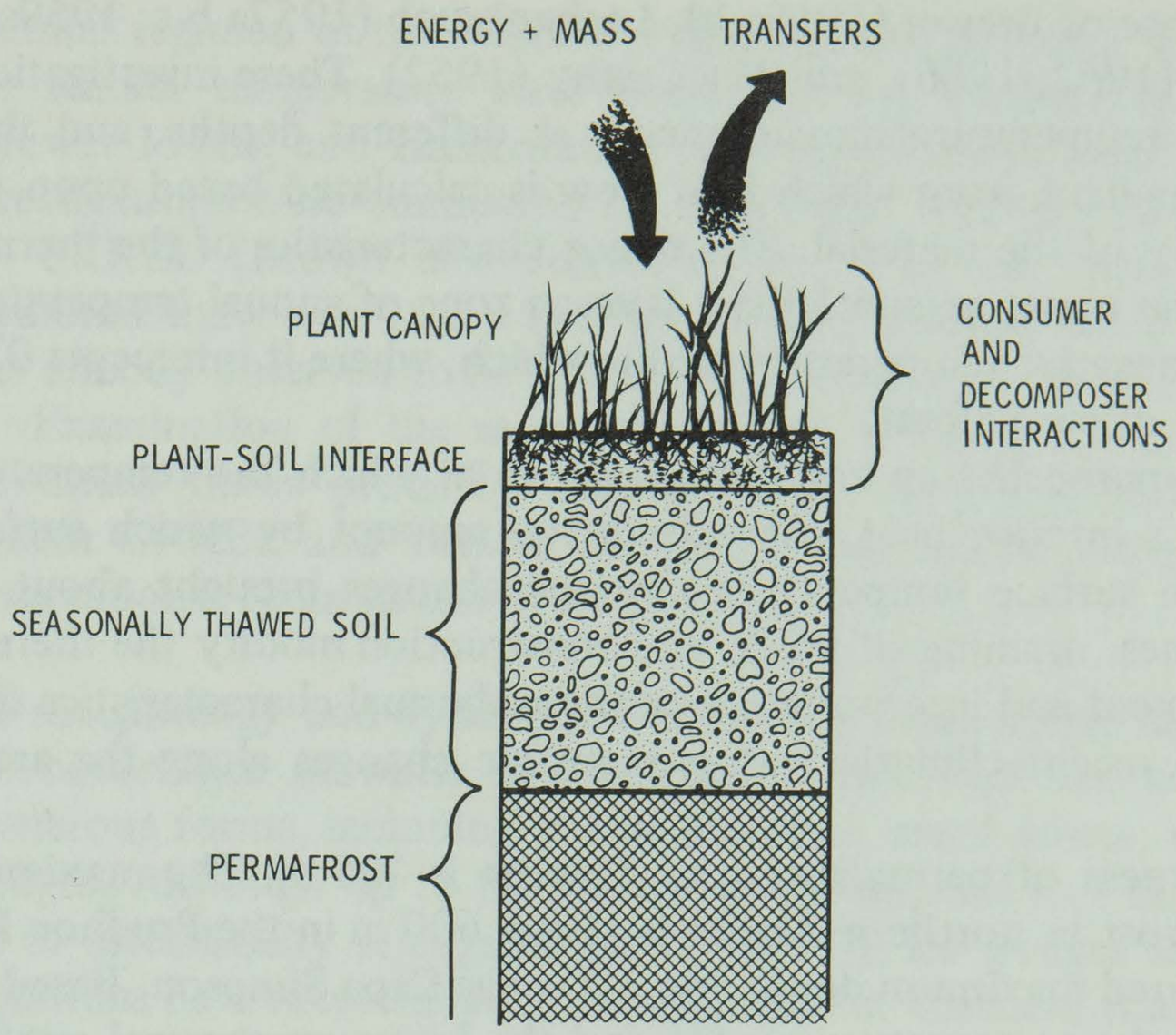


Figure 1. Abiotic and biotic components of tundra ecosystem.

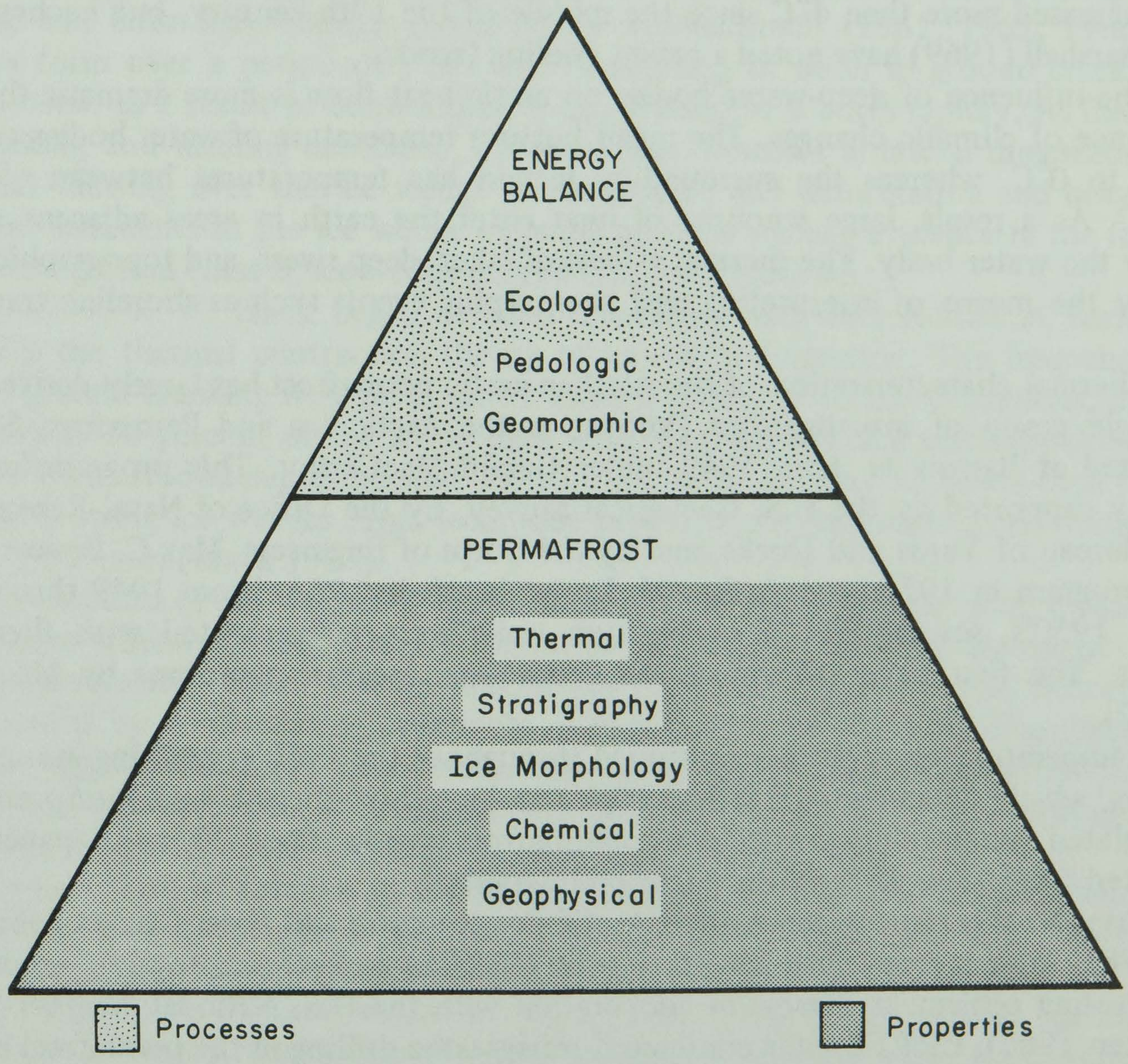


Figure 2. Pyramid illustrating characteristics associated with permafrost and its modifying processes.

sentative papers include those of Brewer (1958a,b), Lachenbruch (1957a,b,c; 1959a,b; 1969), Lachenbruch *et al.* (1962, 1966), and MacCarthy (1952). These investigations primarily involved *in situ* temperature measurements at different depths, and they provide the temperature gradient from which heat flow is calculated based upon the known thermal conductivity of the material. The major characteristics of the thermal profile in permafrost are the upper seasonal thaw layer; a zone of annual temperature fluctuation; and the lower negative temperature profile which, where it intercepts 0°C, defines the lower boundary of permafrost.

Permafrost ultimately approaches an equilibrium depth at which the temperature increase due to the earth's interior heat just offsets the amount by which surface freezing exceeds the mean surface temperature. Surface changes brought about by climate, shifting of shorelines, draining of lakes, and construction modify the thermal gradient. It is the measurement and interpretation of these thermal characteristics that have provided insight into recent climatic and geomorphic changes along the arctic coast.

The extrapolated thickness of permafrost near Barrow is 405 m. The maximum measured depth of permafrost in northern Alaska is about 600 m in the Prudhoe Bay area. Previously, the measured maximum depth was 320 m at Cape Simpson. Based on the observed curvature of the temperature profile and the lower geothermal profile, calculations show that both Barrow and Cape Simpson had a former mean surface temperature of −12.1°C. For Barrow, however, the mean annual surface temperature has increased more than 4°C since the middle of the 19th century, but Lachenbruch and Marshall (1969) have noted a recent cooling trend.

The influence of deep-water bodies on arctic heat flow is more dramatic than the influence of climatic changes. The mean bottom temperature of water bodies remains close to 0°C, whereas the surrounding terrain has temperatures between −5° and −15°C. As a result, large amounts of heat enter the earth in areas adjacent to and below the water body. The thermal effects of lakes, deep rivers, and topographic highs supply the means of interpreting past geomorphic events such as shoreline transgressions.

Thermal characterization of the Alaskan arctic permafrost has largely derived from a single group of investigations (known as the Arctic Ice and Permafrost Studies) initiated at Barrow in April 1949 under Gerald MacCarthy. This program has been jointly supported by the U.S. Geological Survey, by the Office of Naval Research, by the Bureau of Yards and Docks, and by the Corps of Engineers. Max C. Brewer joined the program in 1950, and Arthur H. Lachenbruch in 1953. From 1949 through the early 1950's, several PET 4 exploration wells were instrumented with thermistor cables. The first paper to appear on geothermal measurements was by MacCarthy (1952).

Temperature observations continued throughout the 1950's, resulting in numerous papers which documented results, explored heat-flow theory, and interpreted and postulated geomorphic events in the permafrost region. Over 20 major papers have resulted from these investigations (see bibliography).

Prior to this project, the Army's Arctic Construction and Frost Effects Laboratory (ACFEL, later merged with SIPRE to form CRREL) undertook a routine temperature monitoring project at Barrow in cooperation with the U.S. National Weather Service (Aitken 1965). CRREL later conducted refrigerated drilling in the permafrost at Cape Thompson, and these cores were analyzed by Lange and Smith (1966).

These studies were concerned with temperature characteristics from several meters to many hundreds of meters in depth. Brewer and Lachenbruch investigated the

thermal regimen of the seasonally thawed zone in detail. They measured and described the annual temperature wave through a wet tundra soil into the upper permafrost (Brewer 1958a, and Lachenbruch *et al.* 1962). Additional year-round soil temperature investigations were conducted by Kelley and Weaver (1969) under Project Huskie and by CRREL (Brown and Johnson 1965). In the latter study, the average 5-year measured thaw was 43 cm (Brown 1969c), whereas the average limit of recent thaws was directly observed to be 52 cm, based on the ice texture of frozen cores.

Examination of the recorded climate at Barrow over the past 45 years indicates maximum thaws probably occurred there during the summers of 1951 and 1954. Recent CRREL and Tundra Biome soil thermal modeling should validate these field observations (Nakano and Brown 1972).

Ice morphology and dynamics. Perhaps the most unique characteristic of permafrost is the occurrence of water in the form of perennial ice. Ice is found in permafrost in numerous forms, including nonvisible films, small lenses, massive layers, and large ice wedges. Although up to 80 percent of the upper 3 to 4 m of permafrost may be made up of interstitially segregated ice (Figure 3), ice wedges and their surface relief manifestations have received the most attention in northern Alaska.

Ice wedges are vertical veinlike masses of foliated ice that intersect one another in an interconnecting honeycomb structure. The theory of ice-wedge formation was documented by Leffingwell (1919) in his monumental work on the Canning River region, and later theoretically described by Lachenbruch (1961, 1962, 1966). Ice wedges form over a period of years by the infilling of water in ground cracks. The cracks occur as a result of contraction of the ground as it cools rapidly. As this cycle of cracking and infilling continues, the ice wedge increases in lateral dimension. Differential thawing over the ice wedge in the trough, and deformation and heaving of adjacent sediments as the ice wedge expands produce surface evidence in the form of polygonal ground (that is, ice-wedge polygons). (See Figure 4.)

In 1949, R. F. Black began detailed laboratory and field studies at Barrow to quantify the thermal contraction theory of ice-wedge formation. The frequency and size of ground cracking were determined under a variety of terrain conditions. In most cases, 30 to 50 percent of the ice wedges were observed to crack vertically during the winter. These studies suggested that 1.0 to 1.5 mm of ice may be added each year to actively growing ice wedges. This technique provided one approach to estimating the age of the terrain (Black 1963).

The location of ice wedges in the stratigraphic section gives important evidence of past events (Brown 1966b, 1967, 1969a,c). (See Figure 5.) If an ice-wedge top is found considerably below the bottom of the seasonally thawed layer, either it has been buried by accumulating sediments or it reflects a deeper thaw. Flat-topped ice wedges suggest truncation due to thawing. Frequently, thin second-generation ice wedges rise above buried or truncated ice wedges. The chemistry of ice-wedge melt water provides clues about the origin of ice wedges (Brown 1966a).

Another form of massive ice which has received little attention in the literature on northern Alaska is the pingo. The arctic coastal pingo forms from back-freezing of thawed sediments under lakes. Slow downward and sideward freezing results in the massive segregation of water at the downward penetrating freezing front. The increase in volume due to the formation of the ice causes an upward movement of overburden and ice that results in a small hill. Formation of pingos is associated with draining or shallowing of deeper lakes. Quantitative information on pingo occurrence and growth is available from the Mackenzie delta (Mackay 1972).

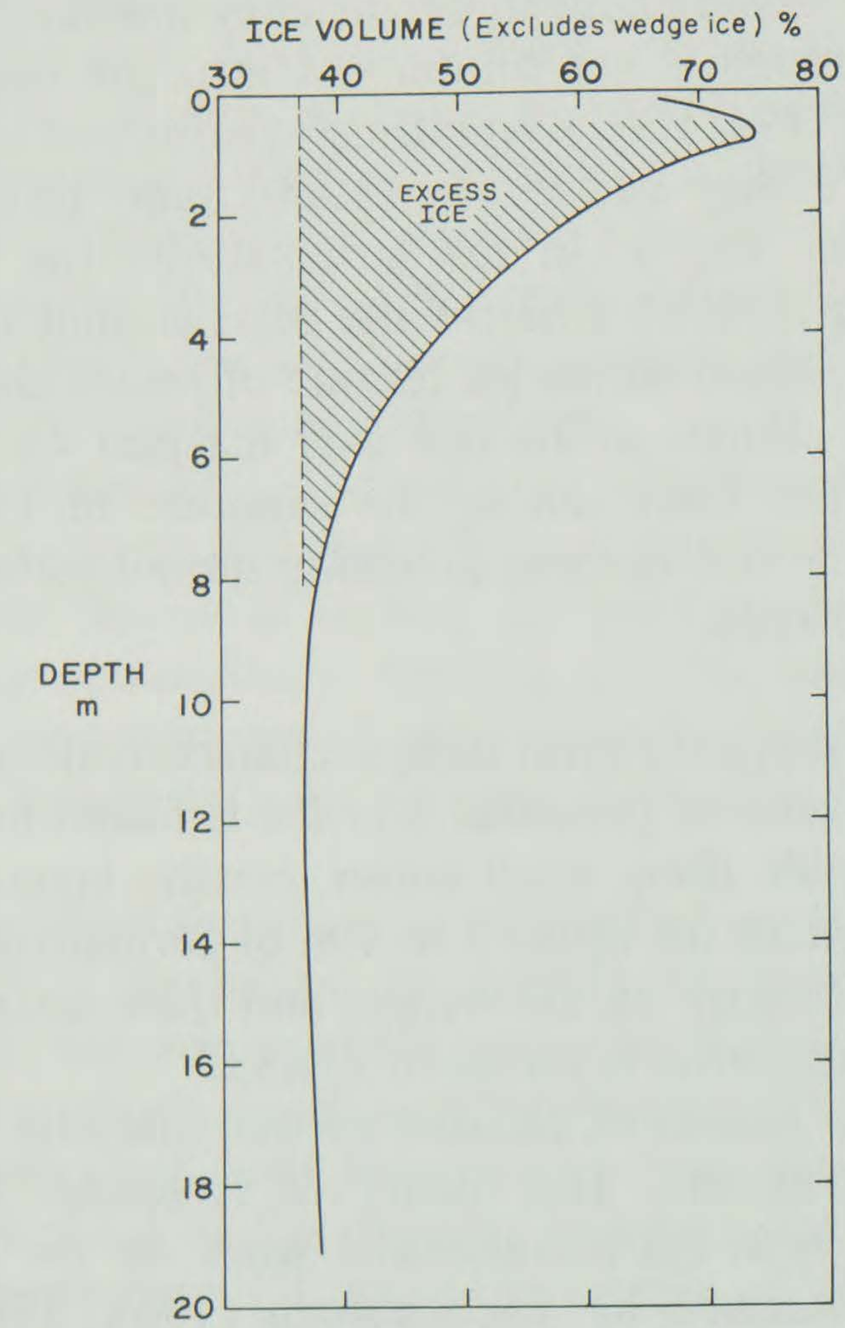


Figure 3. Average ice volume percentage versus depth for segregated ice in the Barrow peninsula based upon coring and auguring programs. (Brown 1969b, and Sellmann and Brown 1965)



Figure 4. Vertical aerial view of frost-scarred, ice-wedge polygonal relief near Barrow CRREL study area.

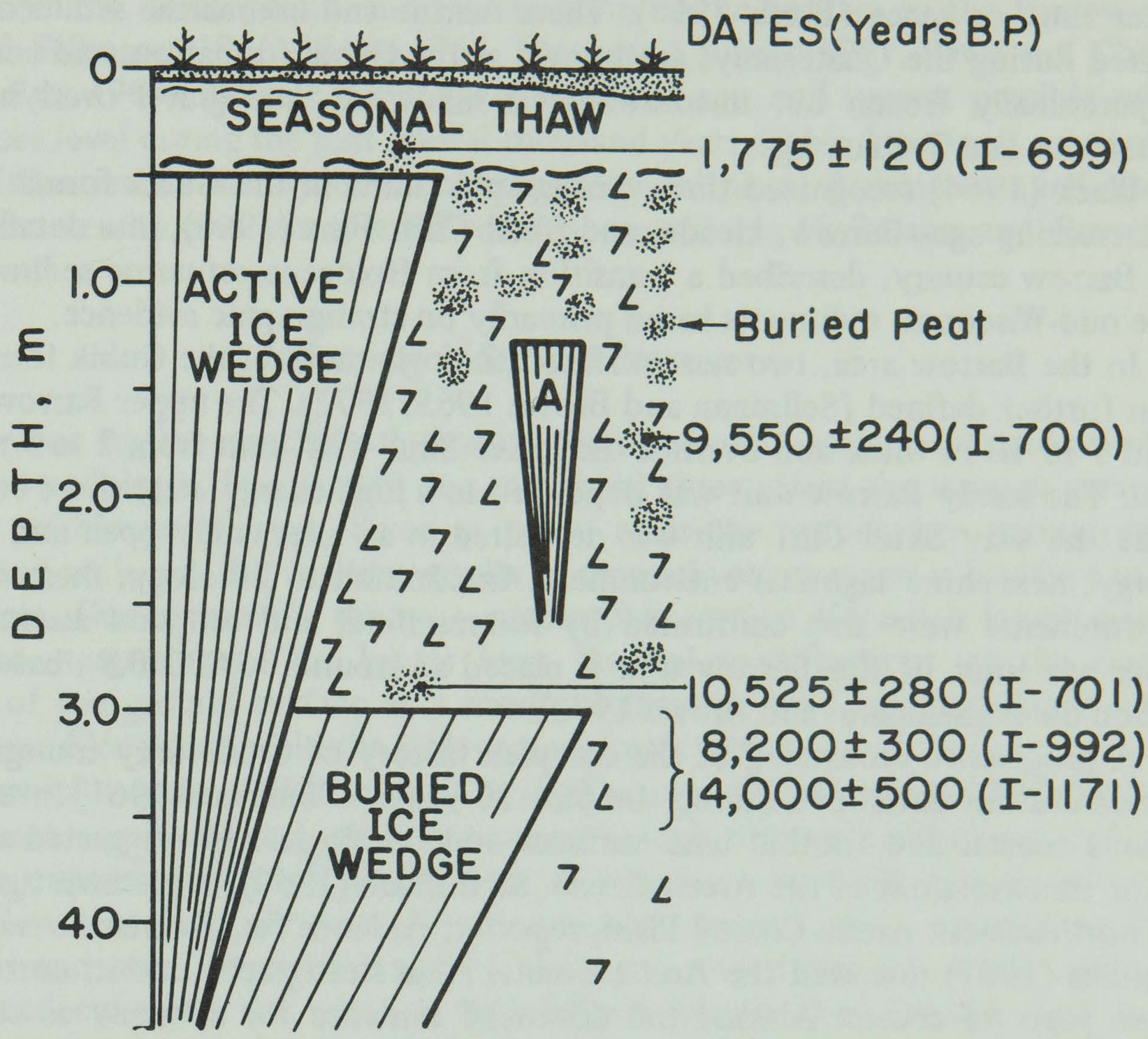


Figure 5. Idealized permafrost section from Barrow showing radiocarbon dates of buried organic matter and ice-wedge stratigraphy. (Brown 1967, 1969a,c)

Chemical. Chemical characteristics of perennially frozen sediment have been investigated only at Barrow (Brown 1969b, and O'Sullivan 1966). The primary objective of these studies has been to develop a technique whereby depositional environments could be chemically differentiated. The work was begun by O'Sullivan in the early 1960's and continued by the authors into the mid-1960's. As a result of these studies, it has been possible to classify chemically several different types of sedimentary environments and postdepositional modifications of the permafrost (Figure 6). The assumption is made that the soluble chemical constituents in the sediments remain essentially the same after freezing, particularly at lower concentrations. Therefore, the relative amount of soluble salts recovered from thawed samples gives an indication of the chemistry at the time the sediment or soil froze.

Sediments underlying freshwater lakes have relatively low salt concentrations, whereas recently uplifted or emergent land surfaces have high concentrations. Thus, the longer sediments remain unfrozen, the more opportunity for leaching. Chemical nonconformities in the frozen sediment generally correlate with other stratigraphic markers (such as truncation of ice wedges). Similar techniques have since been applied to the warmer permafrost conditions near Fairbanks (Brown 1969a, Péwé and Sellmann 1972, and Sellmann 1967).

Quaternary stratigraphy and depositional history. The Arctic Coastal Plain represents a series of depositional and erosional surfaces in which uplift has not been uniform in either time or space (Black 1964). These marine and nonmarine sediments were deposited during the Quaternary, are known as the Gubik formation, and consist largely of perennially frozen but unconsolidated sands, silt, and gravel overlying rocks of Cretaceous and Tertiary age.

Black (1964) recognized three stratigraphic units in the Gubik formation in order of increasing age—Barrow, Meade, and Skull Cliff. Faas (1966), in a detailed study of the Barrow estuary, described a transition from Holocene estuarine sediments to possible mid-Wisconsin sediments based primarily on stratigraphic evidence.

In the Barrow area, two near-surface lithologic units of the Gubik formation have been further defined (Sellmann and Brown 1965, 1972). The upper Barrow unit varies from 7 to 10 m thick and overlies the lower Skull Cliff unit from 2 to 7 m below sea level. The sandy Barrow unit was deposited in a high-energy, near-shore environment, while the silty Skull Cliff unit was deposited in an alternately open and closed low-energy, near-shore lagoonal environment. In addition to lithology, these depositional environments were also confirmed by foraminiferal and ostracod assemblages. The lower age limit of the Barrow unit is placed at around 36,000 B.P., based on radiocarbon dates (Sellmann and Brown 1972).

A progressive unraveling of the complex history of Quaternary transgressions and regressions has developed during the past 20 years. O'Sullivan (1961) investigated the various coastal and foothill land surfaces and lithologies. He suggested at least four major transgressions of the Arctic Ocean. McCulloch (1967), in his investigations along the northwestern Arctic Coastal Plain, reported evidence for five marine transgressions. Hopkins (1967) reviewed the Arctic Coastal Plain stratigraphy and its correlation with other parts of coastal Alaska, and advanced evidence for as many as seven marine transgressions during the Quaternary. Our investigations of the sediments in the Barrow area provide evidence for a late Pleistocene marine transgression and at least one

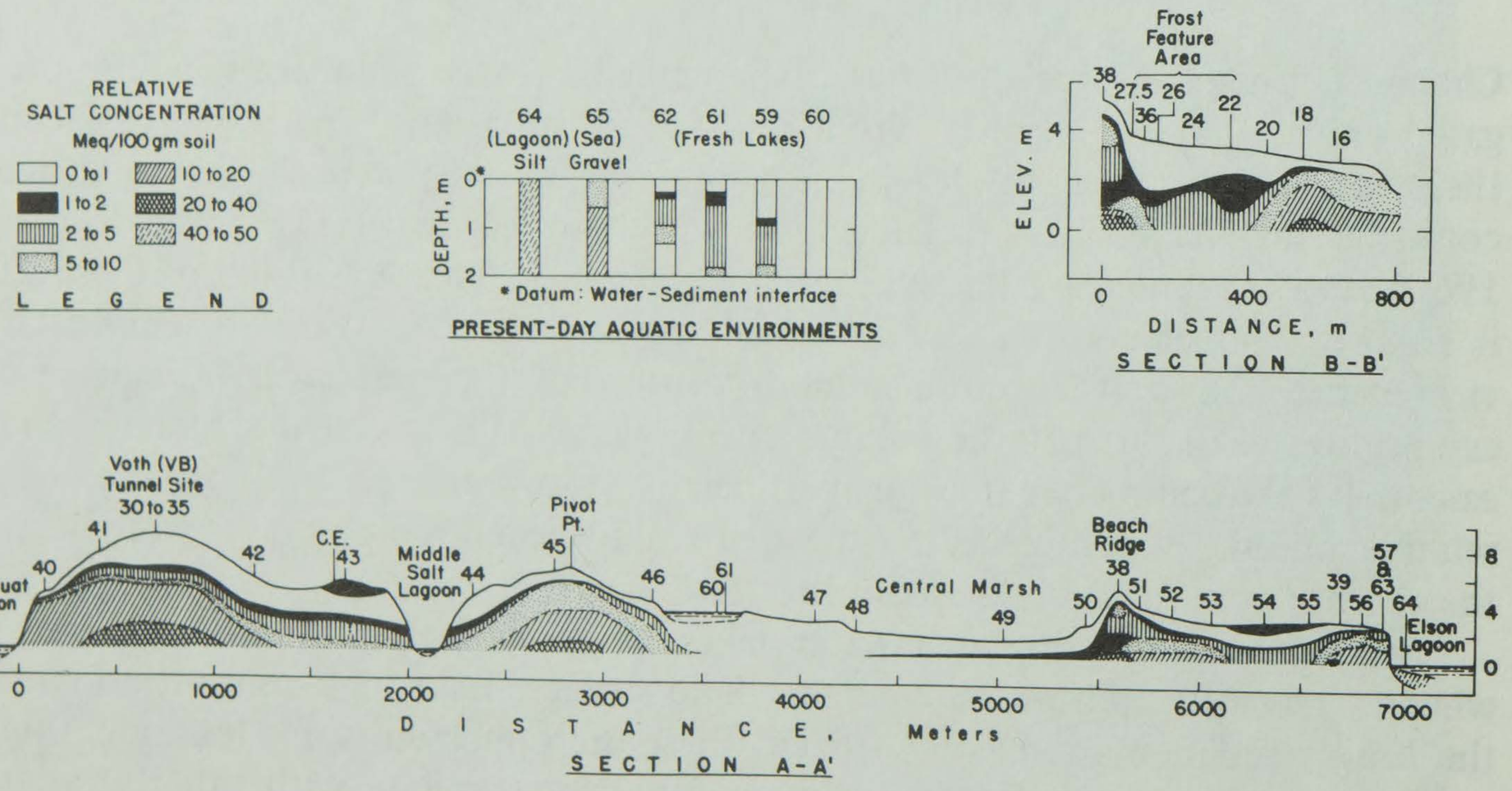


Figure 6. Cross sections of Barrow area showing ionic concentrations in soils, permafrost, and aquatic environments. (Brown 1969a,b)

earlier marine transgression. Our conclusions generally agree with those of earlier workers as well as with aspects of those proposed by Lewellen (1972).

Studies on the development and modification of the beaches in the Barrow area (Brown and Sellmann 1966, Hume 1965, Hume and Schalk 1967, Péwé and Church 1962, and Rex 1964) indicate a relatively youthful age, and suggest possible subtle changes in sea level during the past several thousand years. Table 1 presents a summary of the late Quaternary history of the northern coastal plain. A more detailed discussion of these results and interpretations is now available (Sellmann and Brown in press).

Influences of Surface Processes

Three major surface processes influence the uppermost permafrost: geomorphic, ecologic, and pedologic. In one way or another, all three affect the thaw or preservation of ice within permafrost. Since in many areas the near-surface permafrost is supersaturated with ice, any melting results in dramatic changes and subsidence in the surface terrain. One extreme is the near-catastrophic erosion of ice-rich frozen ground on gentle to steep slopes. The longer term thermal modifications are the gradual subsidence of the ground surface as a result of thawing over ice wedges and other forms of ground ice which yield the high-centered polygons.

The thaw lake cycle of Britton (1957, 1958) is a regional process which has been studied from a combined ecologic and geomorphologic approach. Briefly stated, this involves the expansion of small, shallow ponds which are generally found within the centers of low-centered polygons. As these centers expand, they coalesce to form larger ponds and lakes. In so doing, they thaw the underlying ice, which results in deepening and enlarging the lake. A well-defined lake is thus formed, and in the process the vegetation and soils which once occupied the surface are modified or removed. As the lake further expands, it coalesces with other lakes. Eventually, a breach occurs and the lake drains, exposing all or some of the silty, organic bottom sediments. In time, vegetation recolonizes the lake bottom and ice wedges form new polygons.

The lakes created by this process have been investigated in terms of unique morphologic characteristics by several generations of investigators (Black 1969a,b; Black and Barksdale 1949; Carson and Hussey 1959, 1960, 1962; Livingstone 1954; Rex 1961; and Tedrow 1969). These lakes are characteristically elongated with the major axis aligned 10° to 15° west of true north. This occurs due to differential erosion at the north and south ends of the lakes. This erosion, as measured from aerial photographs, averaged over 1 m per year, while virtually no erosion occurred along the sides of the lakes. These data are from Lewellen (1972), who has also conducted a similar photointerpretation and ground investigation of thermal erosion along beaded streams.

Carson and Hussey provide the most recent hypotheses and data on the origin of oriented lakes. Briefly, long-shore currents at right angles to the prevailing summer wind generate erosional forces at the ends of the lakes. Characteristic shallow shelves along the east and west shorelines tend to insulate and protect the permafrost. Warmer water during spring melting at the north and south ends of the lake also increases thermal erosion. Carson (1968) has attempted radiocarbon dating of events which lead to maximum development of the oriented lakes. Relict strand lines are generally less than 3,500 years old. Evidence suggests that maximum development of lacustrine expansion peaks near the end of the hypsithermal and that onset of posthypsithermal cooling correspond with the initial period of lake contraction.

Table 1. Summary of late Quaternary environments and events for Barrow area.

Time (yr)	Climate and permafrost	Vegetation[7/8/9]	Depositional	
			Marine	Lacustrine and terrestrial
Present	Mean annual ground temperature warming of 4°C in past 100 yr.[14] Continuous formation of ice wedges from at least 14,000 B.P.	Pollen predominantly grass, sedge, willow; no major changes in last 5,000 yr.	Active erosion along ocean and lagoonal coastlines (0.2-2.0 m/yr).[15] No major transgressions, only 1- to 2-m fluctuations in sea level resulting in formation and modifications of existing spit and drowning of Birnirk site.[5/11/13/18]	Thaw lake cycle active[2/3] but in contractive phase since hypsithermal expansion.[6] Burial of soil organic more or less continuous since at least 11,000 B.P.[4]
5,000	Postglacial thermal maximum but no major thaw of permafrost during past 10,000 yr.[7/12]	Significant alder pollen first appears.	Rapid deposition of estuary sediments.[10] Rising sea level from close of Wisconsin onward and continuing uplift totaling a minimum of 8 m since mid-Wisconsin.	Expansive phase of thaw lakes between 4,000 and 8,000 B.P.[6]
10,000	General warming from 14,000 B.P. onward.[7]	Willow, grasses, and sedges present; birch first appears.	– – – – – – – – – – –	– – – – – – – – – –
14,000 to 25,000	Colder and more severe than present.[7] Near-surface permafrost formation following emergence.	Grasses, sedges, mosses, and willows present by 14,000 B.P.	Post mid-Wisconsin uplift of central coastal plain. Recession of mid-Wisconsin seas and deposition of inland beach ridge provisionally about 25,000 B.P.	– – – – – – – – – –
35,000	Mid-Wisconsin warm period.	– – – – – – – – – –	Deposition of Barrow unit in shallow seas during mid-Wisconsin transgression. Ice-rafted boulders up to 7.5-m elevation.[16] Sea level near that of present.[17]	– – – – – – – – – –
100,000	Sangamon warm interval.	– – – – – – – – – –	Deposition of silty Skull Cliff unit during Illinoisan[1] or Pelukian transgression.[12]	– – – – – – – – – –

[1]Black (1964).
[2]Britton (1957).
[3]Brown (1965).
[4]Brown (1969a).
[5]Brown and Sellmann (1966).
[6]Carson (1968).
[7]Colinvaux (1964a).
[8]Colinvaux (1964b).
[9]Colinvaux (1967).
[10]Faas (1966).
[11]Ford (1959).
[12]Hopkins (1967).
[13]Hume (1965).
[14]Lachenbruch and Marshall (1969).
[15]Lewellen (1972)
[16]McCarthy (1958).
[17]McCulloch (1967).
[18]Péwé and Church (1962).

Finally, the pedologic aspects of permafrost have been approached both morphologically and thermally. Morphologically, Tedrow and others have noted and radiocarbon dated a buried organic layer within the uppermost permafrost throughout northern Alaska (Brown 1967, 1969c; Douglas and Tedrow 1960; and Tedrow 1965). The dates are within the 8,000- to 11,000-year bracket, which suggests a period when thawing may have been deeper and/or frost heaving greater. Other evidence indicates a continuous incorporation of surface peat into the soil and upper permafrost, particularly over ice wedges where dates between 2,000 and 5,000 years are common.

Future Research

Permafrost research in Alaska has been remarkably productive if you consider that only a few federal agencies and investigators have been involved in this emerging science. The opportunities offered at Barrow through the Naval Arctic Research Laboratory and ONR funding have been largely responsible for the current knowledge on arctic permafrost in the United States. More recently, the petroleum industry has conducted permafrost investigations related to technological problems. Also, both federal and state agencies are now involved in regulatory activities concerning the use of permafrost lands.

The need for coordinated, comprehensive, and sustained national programs for permafrost research should be the next step. We are at a point where cumulative biological, thermal, and physical knowledge available from the terrestrial arctic ecosystem can be applied to the construction and validation of environmental and permafrost terrain models. Ideally, these models will simulate natural phenomena which are principally controlled by climate and by man-made modifications to the arctic landscapes.

Our demands for more field and laboratory information concerning permafrost will increase. Our past data have come from too few locations. Additional terrestrial and near-offshore temperature profiles are required to determine heat flow from different physiographic provinces and to map the extent and existence of permafrost conditions. Also, additional geothermal data will permit further reconstruction of recent climatic changes and shoreline fluctuations. Observations on ice-wedge growth and distribution will provide the means for deciphering present and past geomorphologic events. Investigations are required to determine the rates at which thaw lakes, ponds, and pingos form and degrade. Further developments of geophysical techniques for mapping will provide data for construction purposes as well as for further definition of permafrost characteristics. The list for future research is a long one that encompasses both field observations and laboratory studies.

Finally, we are entering a new period of international cooperation with our Soviet colleagues. The forthcoming Second International Permafrost Conference in Yakutsk in July 1973 and renewed bilateral relations between the United States and the Soviet Union will undoubtedly enhance the current status of permafrost research in the Arctic.

Acknowledgments

This paper was prepared under auspices of the U.S. Army Cold Regions Research and Engineering Laboratory whose sponsors—Corps of Engineers and Army Materiel

Command–have supported a variety of in-house and cooperative basic permafrost research at Barrow over the past several decades.

The authors express their personal appreciation to the Naval Arctic Research Laboratory and its staff for the continuing support of Barrow-based projects. Finally, the authors recognize and acknowledge the assistance of the many scientists who have contributed to our better understanding of the Barrow permafrost environment.

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MORPHOLOGY OF THE NORTH SLOPE

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The North Slope is defined in this paper as that part of northern Alaska which drains to the Arctic Ocean, excluding the area south of Point Hope (Orth 1970). Unifying characteristics of the North Slope include: northerly exposure, continuous permafrost, a general lack of trees, a nearly complete snow cover for 7 to 9 months a year, the freezing of all surface water (river, lake, and ocean), and the cessation of flow of all rivers during winter. Nonetheless, within this 200,000-km^2 area occur a number of regionalizing characteristics, such as elevation, relief, structure, soils, drainage patterns, lakes, and glacial forms.

The most common characteristic for dividing Alaska is topographic variability. The latest refinement is a map by Wahrhaftig (1965). On the map, the North Slope includes all or part of three physiographic provinces of Alaska: the Arctic Coastal Plain (100 percent), the Arctic Foothills (94 percent), and the Arctic Mountains (30 percent), each of which has been further subdivided into sections. (See Figure 1 and Table 1.)

The North Slope portions of these physical divisions range from 2,300 km^2 for the De Long Mountains to 62,400 km^2 for the Northern Foothills. Although established because of structural unity and geologic and topographic similarity, these divisions do not separate particular forms or processes, nor were they intended to serve that purpose. Indeed, only rarely are individual forms or processes exclusive to one division. Thus, although these physiographic units are used as a basic areal framework, the discussion in this paper is more general in some cases, more specific in others.

Within the past few years, one periodical and numerous books have been produced which deal specifically with periglacial processes and forms [*Biuletyn Peryglacjalny*, NAS-NRC (1966), Hamelin and Cook (1967), Péwé (1969b), Tricart (1970), and Washburn (in press)]. In addition, *Arctic, Arctic and Alpine Research,* and *Quaternary Research,* although having a broader topical base, carry numerous pertinent articles. Also, the newer textbooks in geomorphology have chapters dealing with periglacial processes—a subject neither considered nor mentioned in most volumes a few years ago.

A sizable portion of these contributions have resulted from work conducted out of NARL, as is evidenced in the bibliography at the end of this paper and by documentation used herein. Many important articles have not been referenced, but most of these

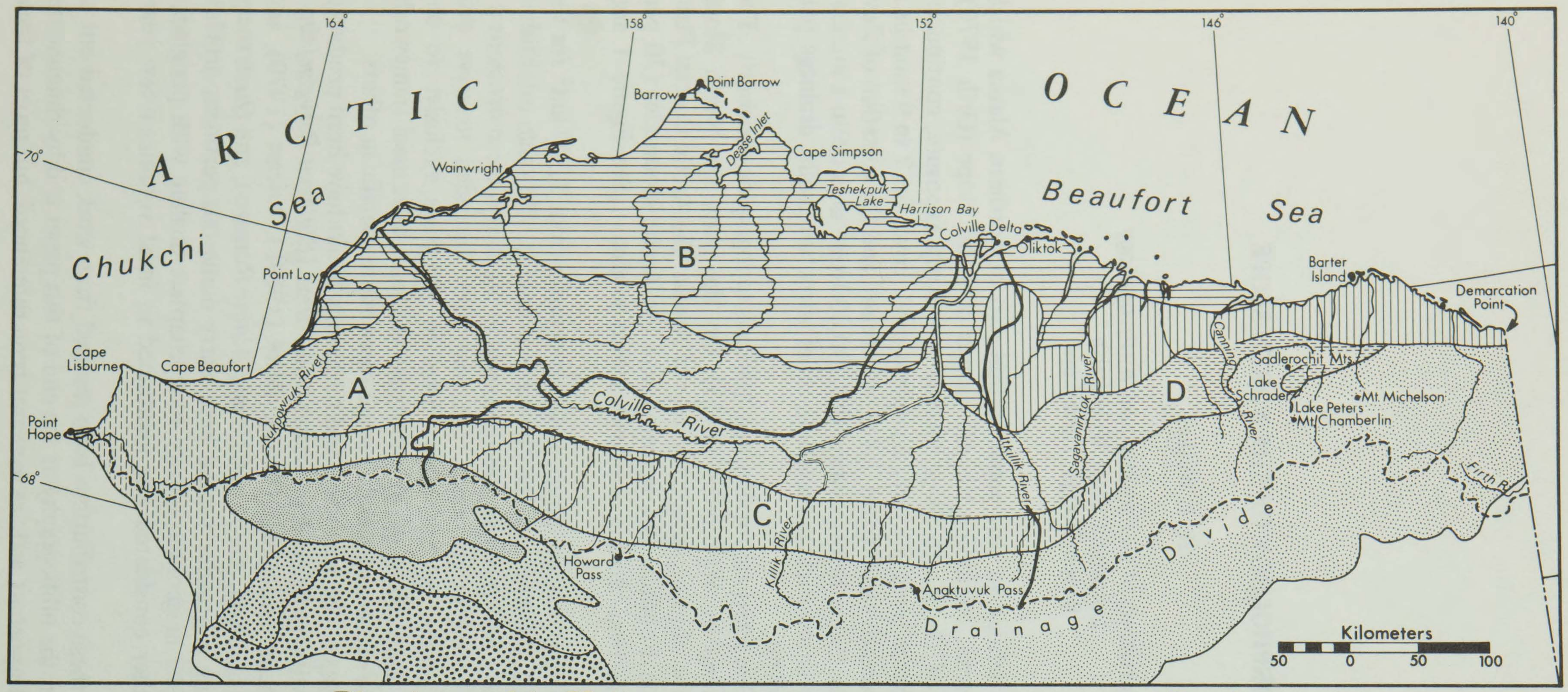


Figure 1. Physiographic provinces, drainage regions, and key locations of the North Slope.

will be included in the bibliography of NARL-sponsored research to be published soon by the Arctic Institute of North America. Also, additional references will be found in the excellent topical review on the geology and geomorphology of northern Alaska prepared by R. F. Black for the NARL Dedication Symposium (1969a).

Periglacial Morphology

Since late Pleistocene, the North Slope has had an annual temperature average well below freezing (winters are long and cold; summers are short and cool). Seasonal change is not from a long summer to a short winter or from a long period of unfrozen ground to a short period of frozen top soil, but the reverse. The change is not one where the temperature passes from above to below freezing with a short period of freeze-thaw cycles, but the reverse. It is this "unfamiliar" proportioning of the seasons that is the *sine qua non* of North Slope conditions in particular and periglacial conditions in general.

The study of the morphology of the North Slope is the study of periglacial geomorphology in an almost ideal setting. The Northern Foothills and Coastal Plain share with central Alaska and central Siberia the distinction of having been subjected to uninterrupted periglacial activity longer than anywhere on earth. Yet, there are also

Table 1. Physiographic units of northern Alaska.[1]

Area	Physiographic unit (km^2)			North Slope area	
	Division	Province	Section	Km^2	Percentage
Interior Plains	70,900	....	....	....	100
Arctic Coastal Plain	....	70,900	....	....	100
Teshekpuk	....	....	54,000	54,400	100
White Hills	....	....	16,500	16,500	100
Rocky Mountain System ...	237,000	....	....	....	57
Arctic Foothills	....	100,800	....	....	95
Northern Foothills	....	....	62,400	62,400	100
Southern Foothills	....	....	38,400	33,100	86
Arctic Mountains	....	136,200	....	....	30
De Long Mountains	....	....	11,100	2,300	21
Noatak Lowlands	....	....	11,100	....	0
Baird Mountains	....	....	13,000	....	0
Central and Eastern Brooks Range	....	....	90,600	[2]38,200	42
Ambler-Chandalar Ridge and Lowland	....	....	10,400	....	0
Totals	307,900	307,900	307,900	[2]206,900	67

[1] Northern Alaska in this table includes the Arctic Coastal Plain, the Arctic Foothills, and the Arctic Mountains.
[2] Includes the 250 km^2 of the Alaskan portion of the Firth River which, although draining into the Arctic Ocean, is in the Intermontane Plateaus Division.

parts of the North Slope where periglacial activity has only recently been reinitiated because of the retreat of the glaciers which formerly extended into the foothills from the Brooks Range.

Each form on the North Slope, whether large or small, permanent or ephemeral, stabilized or changing, results from one or more processes which have been operative at and across the air-ground interface for some period of time. Some of these processes are found only in periglacial environments and result from cold climate processes. Most also operate in other environments, but even these are affected to some degree by the relatively unique conditions over the North Slope.

Because many of the periglacial conditions, agents, and processes are treated in detail in other papers in this volume, I will discuss only the most important of these and then only to the extent needed to understand their role in the evolution of the forms found on the North Slope today. The section on periglacial processes and forms is followed by a discussion of the more familiar geomorphic parameters as they apply to the North Slope; namely, structure, topography, glaciation, drainage patterns, and eolian and coastal processes and forms.

Climatic factors. As in other regions of the earth, the weather and climate control the types of processes responsible for morphologic change on the North Slope. Further, they generally determine the rate of operation and the duration of effectiveness of these processes. The great seasonal variation of most climatic elements is responsible for the equally great variation in the effectiveness of most processes—biologic as well as morphologic.

The traditional concept of the seasons, especially their duration, has to be modified when applied to the North Slope. There is winter, but it lasts from 8 to 9 months of the year. There is summer (that is, the warmest part of the year), and there are two transition periods (spring and fall). All three of these periods combined are only about half as long as winter. Each period, in its own distinct way, is morphologically important.

Winter. The two most significant factors about winter are: (1) low temperatures which result in the freezing of all surface materials, and (2) the presence of a blanket of snow over nearly the entire surface of the North Slope. Winter might best be considered a period of dormancy during which little change occurs. There is, however, one important mechanical action occurring during winter which is morphologically significant. This is the formation of vertical fractures in the tundra caused by thermal contraction of the frozen ground. These eventually lead to the development of ice-wedge polygons, the most conspicuous form over much of the North Slope (Figure 2).

Low winter temperatures freeze the layer of soil which had thawed the previous summer as well as all surface water. During winter, then, there is no water movement on the North Slope, except beneath the ice in some lagoons and at the mouths of some of the rivers because of tidal action.

Snow is significant in several ways. Primarily, it serves as a cover during most of the year. Even though it is a thin cover, it protects all but the most angular surfaces from wind erosion. Only the steepest slopes and cliffs (primarily in the Brooks Range) have no snow cover (Figure 3) and are thus subjected to the erosive action of wind-carried snow. The hardness of snow grains increases with lowering temperature, causing them to be effective agents against all unprotected surfaces during most of the winter period.



Figure 2. Ice-wedge polygons of Colville River delta.



Figure 3. Northern front of Brooks Range in March showing snow-free areas. (Photograph by J. LaBelle)

Because snow is an insulator, its density and thickness affect the amount available for melting (Bilello 1969, and Williams 1970) as well as temperature extremes at snow-ground and snow-ice interfaces. Thus river, lake, or sea ice varies in thickness with the time of formation and the depth of the snow cover.

The winter surface is mainly a snowscape. The snow cover conforms generally to the landforms, although drifting and packing reduce both local relief and the angle of most slopes. It masks most small surface forms such as tussocks and smooths out irregular surfaces. At the same time, however, the snow develops its own surface characteristics, mainly in response to wind (Benson 1969, and Sellmann *et al.* 1972).

Spring. Although winter is a time of relatively little activity, the transition period from winter to summer is another story. Spring is considered the time when most of the snow that accumulated during the previous 9 months melts. All changes affecting snowmelt, breakup, and runoff are especially significant. This transition period is variable in time of onset and duration, and therefore in morphologic change.

Temperature in the spring is important in two ways: (1) the temperature rises above 0°C and initiates a period of thaw-freeze cycles which are probably the most important single factor in the breakdown of rock on the North Slope, and (2) spring temperature fluctuations are the primary control of snowmelt.

The process of freezing and thawing results in frost-shattering (frost-riving, frost-splitting, or congelifraction). It may affect parent material as in the case of exposed rocks in the Brooks Range, or it may affect previously shattered rocks which are part of the material in the annually thawed layer. The process is especially effective when moisture is plentiful and when temperatures frequently fluctuate across 0°C. Since the breakup of rocks usually requires repeated freezing and thawing, and/or contraction and expansion, the number of occurrences per season is significant.

The frequency of this process varies across the North Slope and is less common than generally expected. It has been calculated that it occurs about 15 times per year at Barrow (Conover 1960) and up to 30 times in the Brooks Range (Brown 1966, and MacNamara 1964). This process is more common on the steep slopes and cliffs in the Brooks Range than on surfaces at lower elevations, and it is more common on exposed rocks than on rocks buried in the soil. The most dramatic evidence of frost-shattering is in the talus found at the base of most cliffs. Felsenmeere (block fields) are found in more level locations in the Brooks Range. The degree of fineness characteristic of soils is partly a reflection of the frost-shattering process.

Much of the patterned ground is maintained by frost action even if not necessarily initiated by it (Schmertmann and Taylor 1965). Included are nonsorted as well as sorted forms. These range in size up to the large ice-wedge polygon and are variable in shape and composition (Brown and Johnson 1965). Nets, steps, circles, and stripes as well as polygons are found in many North Slope locations (Brown 1966, and Ferrians *et al.* 1969).

By controlling the rate at which snow melts, spring temperature affects the nature and timing of runoff and breakup. Once melting begins, the snow cover usually disappears rapidly from the tundra surface. The actual relationship between incident radiation, temperature, sublimation, and melting, however, is important to the dissipation of the snow cover and the formation of melt water, and thus the first stream erosion of the season. The effect of microrelief features such as tussocks on the melting rate may be great (Figure 4).

During the early part of the melt season, wind is frequently an important agent. Snow disappears from mudflats and sandbars earlier than from the tundra surfaces.

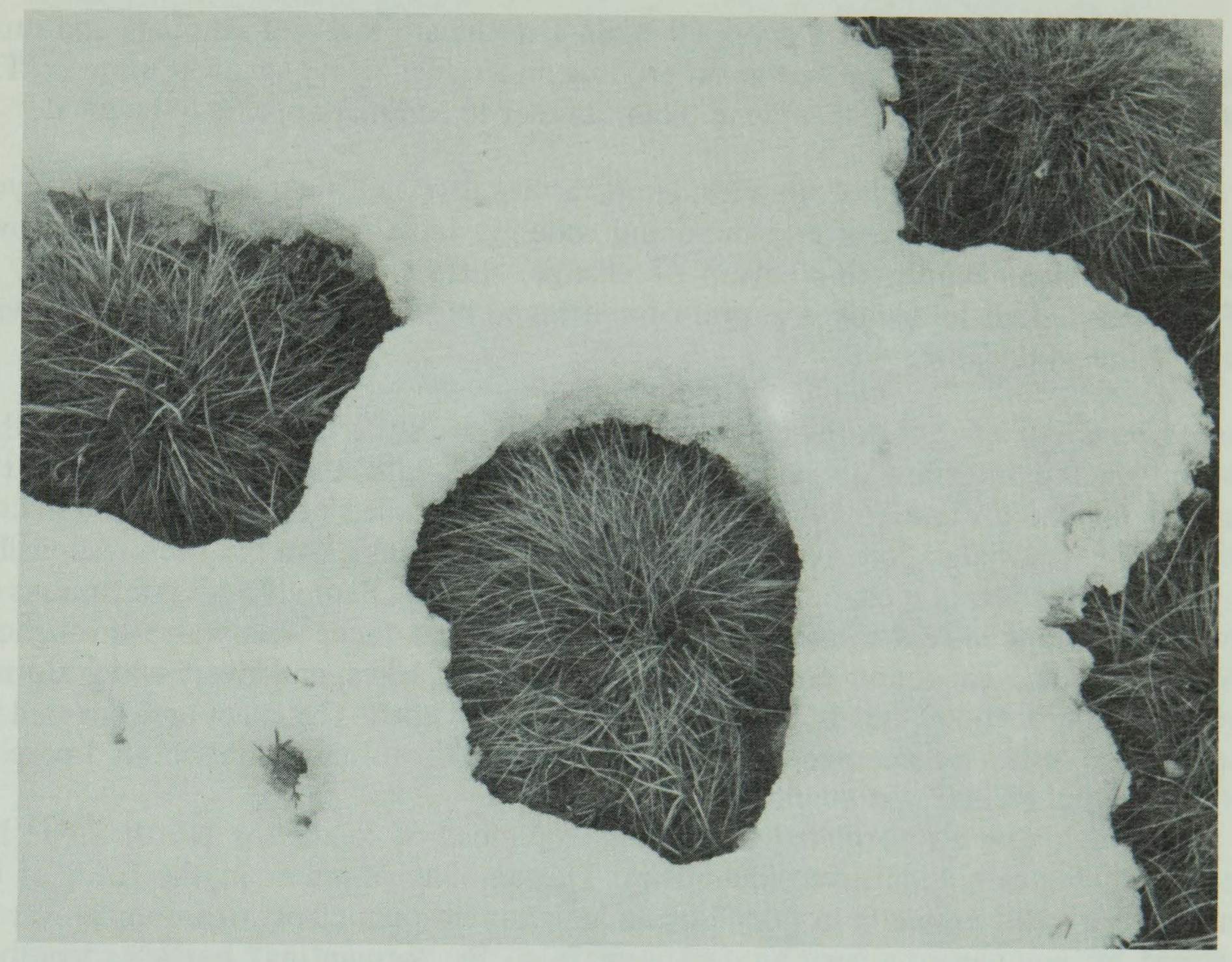


Figure 4. Snow melting from grass tussocks in late May.

There is usually a period of several days between the time the bars are snow free and melt water or floodwater begins to cover them. Winds during that period are especially effective on such exposed surfaces.

Summer. Summer might be considered as beginning after the snow from the general tundra surface is gone and the major floods—those which accompany the breakup of the rivers—are over. Temperatures, although low, rarely drop below freezing during the summer, and thus freeze-thaw activity is rare except at higher elevations in the Brooks Range. Summer temperatures are sufficiently warm to thaw surface materials and produce ground water which flows slowly from the tundra soil to the rivers. In some areas, deep snow drifts in sheltered ravines furnish melt water throughout much of the summer.

Semipermanent or permanent snowbanks are responsible for the protection of nivation hollows, especially at the base of north-facing slopes. These snowbanks prolong freezing and thawing, and therefore the production of finer materials which are moved by melt water. An associated form is the protalus rampart which results from weathered material rolling down the snow surface to pile up at the bottom.

During summer, precipitation is usually in the form of light rain. Although heavy showers can occur, especially in the mountains, they are rare. Generally, rainfall is not an effective eroding agent. After breakup flooding, stream flow is usually low and normally decreases as the summer progresses. By the end of summer many of the smaller streams are dry.

Wind, if it accompanies a dry spell when streams are low and sandbars and mudflats are dry, may be important as an eroding and transporting agent in summer. The variation in the effectiveness of wind from summer to summer appears to be great.

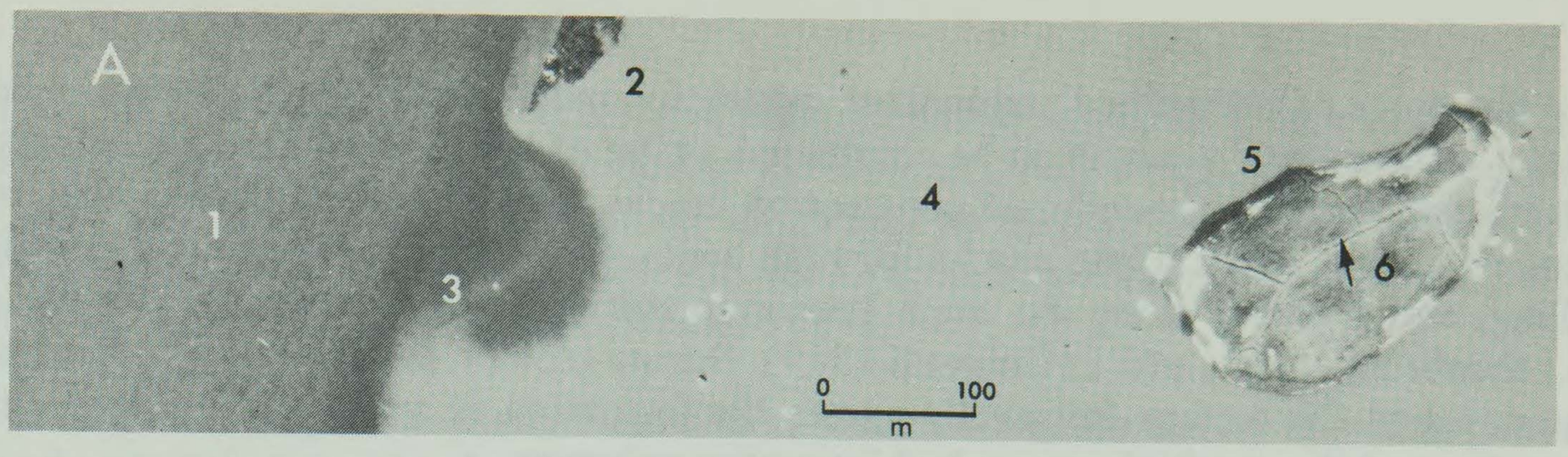
Fall. Toward the end of summer, temperatures drop and the fall freeze-thaw cycle is established. Soon thereafter ground and water surfaces freeze, and the snow cover begins to form. During this period of change, surface processes reduce rapidly in effectiveness. Fall is mainly a period of continued reduction in morphologic activity toward the winter low.

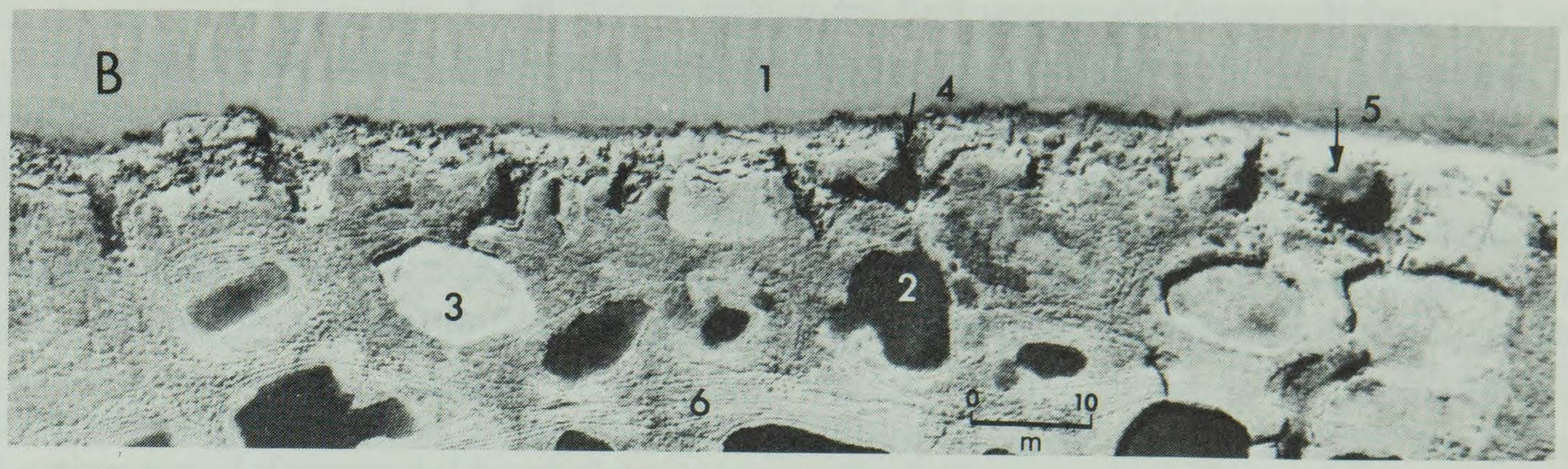
Permafrost. Air temperatures of the North Slope are sufficiently low to insure that the air-ground interface averages below 0°C. Thus, with the present climate, it is natural for the ground to be frozen. This condition, called permafrost, has affected weathering, transportation, and erosion of North Slope rocks, and has been responsible for the production of a characteristic type of topography. Permafrost is continuous on the North Slope except in areas where rock or soil interfaces with water throughout the year. Such year-round contact occurs in lagoons, lakes, and rivers which do not freeze to the bottom; that is, those 2 m or more in depth. The exact area covered by such water bodies is unknown; however, Brown (1967) estimated that about 5 percent of the Coastal Plain might qualify.

Although not all permafrost contains ice, most of it on the North Slope has geomorphologically significant quantities. The amount of water in the form of ice varies from small amounts in "dry" or undersaturated permafrost to amounts over 80 percent by volume in supersaturated permafrost. By "cementing" particles together, ice increases the stability of the ground and creates an impervious layer. But, equally important, supersaturated permafrost is responsible for volume change upon melting. Morphologically, permafrost differs in its role during the three distinct periods of its history; that is, during formation, existence, and decay.

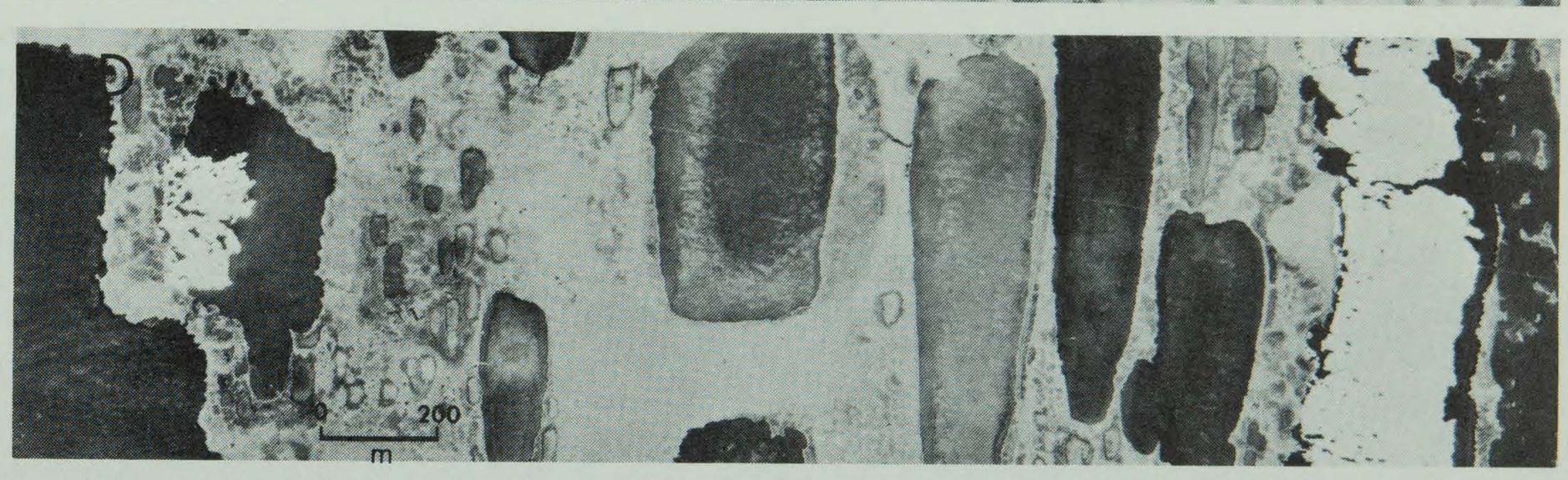
Formation. Since the climate across the entire North Slope insures permafrost under all exposed ground, regionally there must be a complete cover. Today, permafrost formation occurs only under special circumstances; that is, when new surfaces or formerly protected surfaces are subjected to the regional climate. There are several circumstances under which permafrost develops; for example, (1) when there is the conversion of the lower part of the active layer into permafrost at a rate about equal to the accumulation of new deposits in the surface, such as on alluviating mudflats or sandbars; (2) conversion of the lower part of the active layer to permafrost as a result of the insulation provided through revegetation of thermokarst; and (3) when a reduction of water level through lake drainage or river meandering allows below 0°C temperatures to come into existence and prevail at the water-ground or air-ground interface. When a lake is tapped by a meandering river, for example, drainage happens rapidly and sometimes produces one of the most striking forms of the Arctic, the pingo (Figure 5A).

Pingos are ice-cored mounds which result when permafrost advances into drained lake basins. Although best developed near the geometric center of former circular lakes, they also occur in narrow lakes such as abandoned river channels. Since pingos have received little study in Alaska, their number is unknown and little specifically is known about their dimensions. In some areas they are relatively numerous. From the roof of the NARL research cabin at the head of the Colville delta, 38 have been counted on a clear day.









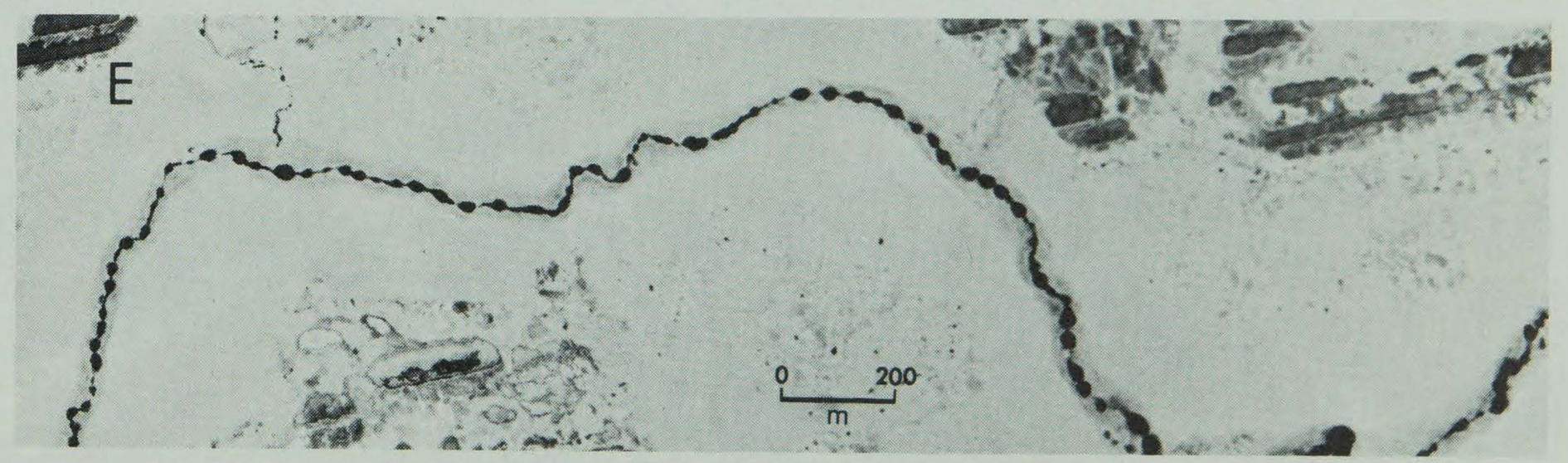


Figure 5. Permafrost forms. A. Pingos: 1. Colville River. 2. Riverbank remnant. 3. Lake entrance. 4. Flooded lake basin. 5. Pingo. 6. Summit rupture. B. Ice-wedge polygons: 1. Colville River. 2. Undrained low-centered polygon. 3. Drained low-centered polygon. 4. Ravine left by ice-wedge thaw. 5. Peat block isolated by ice-wedge thaw. 6. Caribou trails. C. Perched lakes: 1. Perched lake. 2. Sand dune. 3. Mudflat. 4. Colville River channel. D. Oriented lakes. E. Beaded Stream.

Existence. Undisturbed permafrost, which for most of the North Slope has been many thousands of years, must be considered a type of bedrock with special characteristics. The temperature-induced contraction cracks may be several meters deep and tens of meters apart. These cracks fill with water which freezes. Continued cracking, filling, and freezing along the same lines eventually creates a network of ice wedges (Lachenbruch 1962, and Leffingwell 1919). During growth, interaction with processes operating at the surface frequently causes the formation of troughs and ridges which have formed the much photographed ice-wedge polygons.

Generally, at least in the early stages, ridges separate troughs from the center of the form, resulting in low-centered polygons (Figure 5B). As they develop, especially as ice wedges thaw, they are converted to high-centered polygons (Sellmann *et al.* 1972). Despite the fact that most ice wedges probably have no surface expression (Lachenbruch 1970), the surface of the Coastal Plain is almost completely covered by polygonal ground features. Although local relief is low, surface irregularity is great (Figure 5B).

As ice wedges grow, there is an increase in the total volume of the substratum, accompanied by a disturbance of the frozen ground in which growth is occurring. Ice wedges may be large—up to 8 m wide in the Colville delta (Figure 6)—and may eventually occupy a large portion of the upper several meters of the ground.

Permafrost also serves as an impervious layer that limits infiltration to the zone above the permafrost table. In limiting percolation it influences runoff, much of which occurs as sheet wash. Because drainage is impeded, lakes are numerous. Poor drainage also is characteristic of many slopes. Since the permafrost table nearly parallels the



Figure 6. Ice wedge on Colville River delta.

surface, depressions fill with water and become ponds, most of which drain as the active layer develops or evaporate during the summer. This is especially true of ponds found in sand dunes near river channels which may be perched many meters above the flood plain (Figure 5C). Those studied in the Colville River basin are sufficiently well perched so that they are perennial (Walker 1967).

Decay. Although the present climate of the North Slope is one in which permafrost is normal, there are local circumstances in which it will decay. There are two ways in which this conversion from the frozen state to the thawed state may occur: by thermal erosion and by thermal melting (Mackay 1970). Thermal erosion involves the melting of the ice in a frozen layer by flowing water. Such a process occurs when water flows over frozen ground such as in the conversion of former ice wedges to ravines (Figure 5B), and when thermoerosional niches are created along bank faces (Walker and Arnborg 1966). Such niches may be deep; and, when banks (river, lake, or ocean) are undercut, collapse frequently results. This process is often rapid and accounts for great retreat of banks; for example, in the Gubik materials along the Colville River delta (Walker 1970). (See Figure 7.)

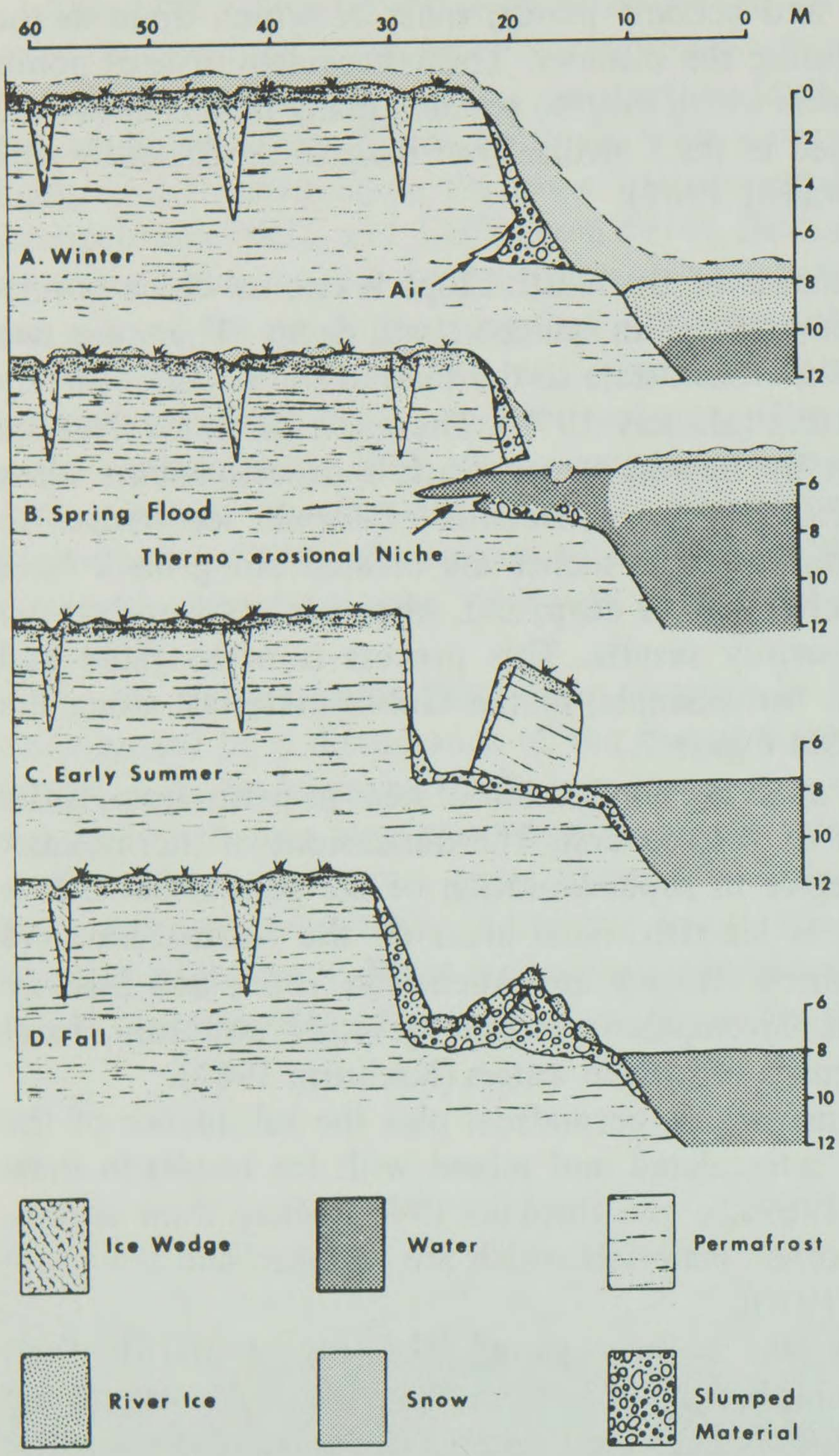
Thermal melting, which depends upon the conduction of heat to permafrost, is the process responsible for the creation of thermokarst. The dimensions of thermokarst forms depend primarily upon the degree of supersaturation of the permafrost that is being thawed. As most permafrost is ice rich, most areas on the North Slope are susceptible to thermokarst development (Hussey and Michelson 1966, and Mackay 1970). Other factors influencing its development include geologic structure, local topography, soil, vegetation, and drainage of surface waters (Kachurin 1962).

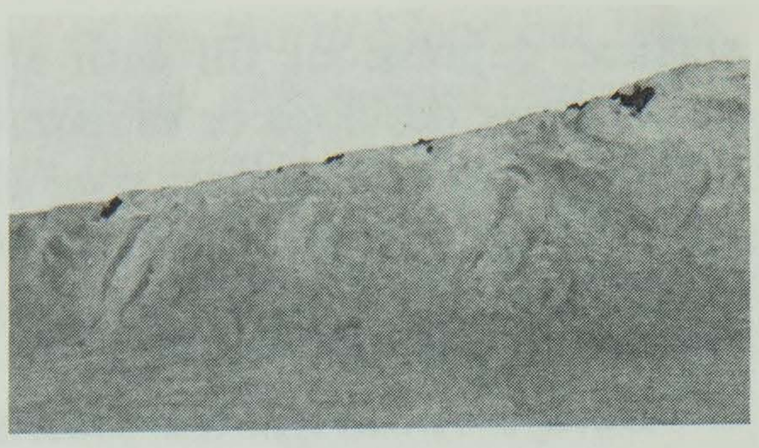
The loss of volume due to ice melting in permafrost plus the subsidence of the mineral or organic matter formerly intercalated and mixed with ice results in thaw depressions and thaw lakes (Black 1969a,b; and Hopkins 1949). Many thaw depressions eventually fill with peat and other materials which are refrozen and later subjected to renewed thawing (Williams 1970).

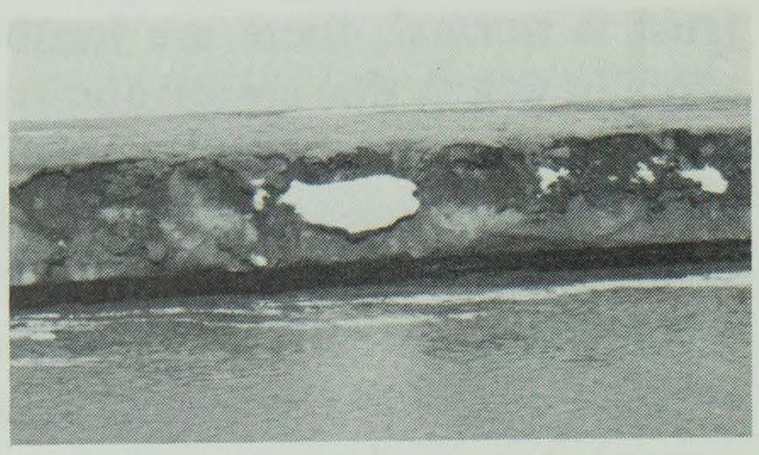
The most studied type of thaw lake is the oriented lake (Figure 5D). In fact, probably more papers have been published on this form than on any other on the North Slope. These lakes, while not limited to the Coastal Plain of northern Alaska, have their most extensive development there. They occur by the thousands and are aligned 10° to 15° west of true north. There are some regional differences. Those west of about 152°30′ west longitude are subelliptical to subrectangular in shape and are generally large (some are as much as 15 km long). Many of the basins have conspicuous shelves along the sides, and most range from 1 to 2 m in depth (Carson 1968, and Carson and Hussey 1962). The oriented lakes to the east of 152°30′ west longitude are generally smaller, shallower, and more rectangular.

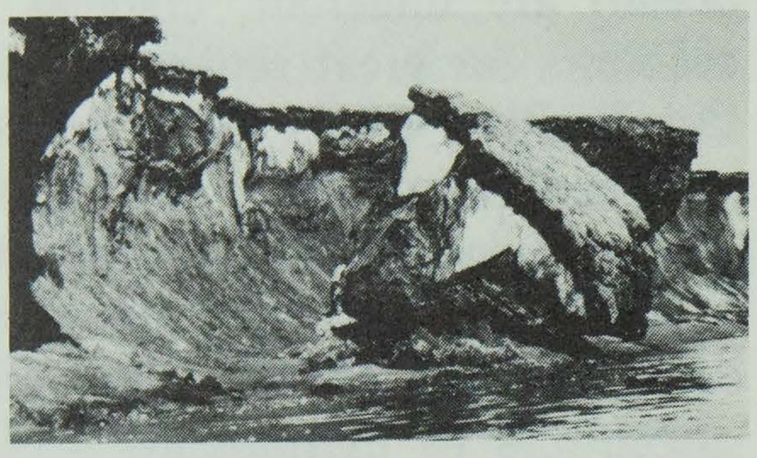
The cause of orientation, although much debated, is still unresolved. Serious explanations over the past 25 years have included either individually or in combination the following: (1) waves resulting from winds oriented parallel to the long axis (Black and Barksdale 1949, and Cabot 1947); (2) waves resulting from winds oriented perpendicular to the long axis (Livingstone 1954); (3) structural control (Rosenfeld and Hussey 1958); (4) angle of solar radiation; and (5) sediment distribution (Carson and Hussey 1959).

Whatever the reason for orientation, measurements show that it is proceeding today (Carson and Hussey 1960). Further, it is apparent that thaw lakes are continually being drained and reformed such that examples of almost any stage of development in the cycle can be found (Britton 1957).









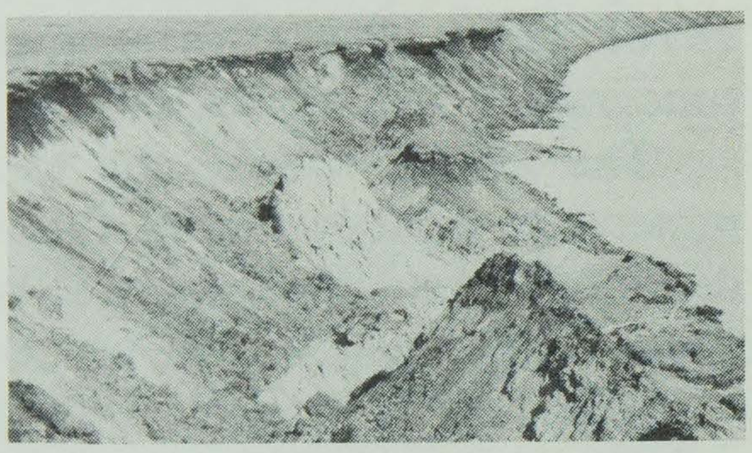


Figure 7. Riverbank erosion of Gubik formation in Colville River delta.

Thaw lakes, as represented by these oriented lakes, are most numerous on the Coastal Plain, but they are also found in favorable locations in other parts of the North Slope. For example, they are quite common in the loess which overlies the high, level terraces bordering the rivers in the Brooks Range and Southern Foothills (Detterman *et al.* 1963, and Tedrow 1969).

Although thermal erosion and thermal melting may work independently, they frequently accompany each other in landform modification. One of the best examples is in the modification of ice-wedge polygons. When an area of ice wedges is disturbed, such as by bank erosion, increased gradients result in thermal erosion along the ice-wedge system (Figure 5B). Thermal melting within the system results in ice-wedge ponds, especially at wedge junctions. An example of this type of combined activity is evidenced in the frequently encountered, sharply defined beaded stream (Figure 5E). Beaded drainage patterns consist of small pools connected by short, usually straight water courses which generally follow ice wedges (Hopkins *et al.* 1955).

Active layer. Permafrost, extending to depths of 700 m on the North Slope, is topped by an active layer which thaws in summer and freezes in winter. Its thickness varies from a few centimeters under dense vegetal mats to over 2 m in nonvegetated, coarse-textured, southerly exposed materials. Thickness often varies greatly over short distances but generally closely follows the contours of the surface. Numerous factors affect this thickness, including vegetation, microrelief (topographic variability), soil texture, ice (water) content, and drainage.

As in the case of permafrost, there are three significant periods in the seasonal cycle of active layer modification: (1) the period during which it is frozen, (2) the period dominated by thawing, which is unidirectional perpendicular to the surface, and (3) the period of freezing, which occurs both from above and below.

Although the depth of thaw may vary from year to year, there are probably no locations or situations on the North Slope where the layer thawed in the summer is not refrozen. A possible exception may occur at the base of large cliffs when thick snowdrifts form early in the season.

The active layer on the North Slope is generally close to or at saturation because percolation is limited in depth by the permafrost table. Dune areas, alluvial fans, and similar surfaces are exceptions. The closeness of this table to the surface and the melting of ground ice as the active layer develops help keep the soil supersaturated and the included rock fragments damp. According to MacNamara (1964), internal drainage is more dependent on depth to ground ice than on texture. The moistness at the base of the active layer provides a lubricated surface favoring movement.

A form which occurs in the active layer and related in genesis to the pingo is the frost mound (ice-cored mound). (See Figure 8.) Its maximum height is about 1.5 m and its diameter can be up to 5 m. Its core is ice and its cover may be either soil (soil mound) or peat (peat mound). These may be either annual or short-lived perennial features. Although some, especially the largest, have their cores situated in permafrost, most probably are restricted to the active layer. They are especially common in marsh areas (such as in low-centered polygons) and are frequently surrounded by a narrow, shallow moat. Upon thawing they often leave behind a small circular pond.

Changing depths of the active layer with time have a bearing on the effectiveness of periglacial processes. As pointed out by Holmes and Lewis (1965), "during warm periods the permafrost table would be deeper, and mass movement, frost churning, and stream action would be more effective than they are at present or were during the glacial advances."

Solifluction. Solifluction, the downslope movement of water-saturated sediments, is probably the most important mass-wasting process on the North Slope. It differs from most other types of mass movement in that there is actual flow instead of individual particle movement, as in creep and rockslides. Solifluction is the most distinctively periglacial of all of the types of mass movement. Its effectiveness depends mainly upon the degree of saturation, the depth of the active layer, and the slope. Slopes of less than 3° can have active solifluction. It is a condition caused primarily by the impermeability of the permafrost and by the low evaporation rate. Movement is slow and limited to the period of thaw; however, it is an effective instrument in the transport of great volumes of material. It accounts for the surface appearance of much of the North Slope.

Solifluction is responsible for such forms as solifluctional lobes, terracettes, and stripes (Figure 9). Although these are forms of visual relief, solifluction is significant in other ways. Possibly its most important action is the smoothing and rounding of hills.

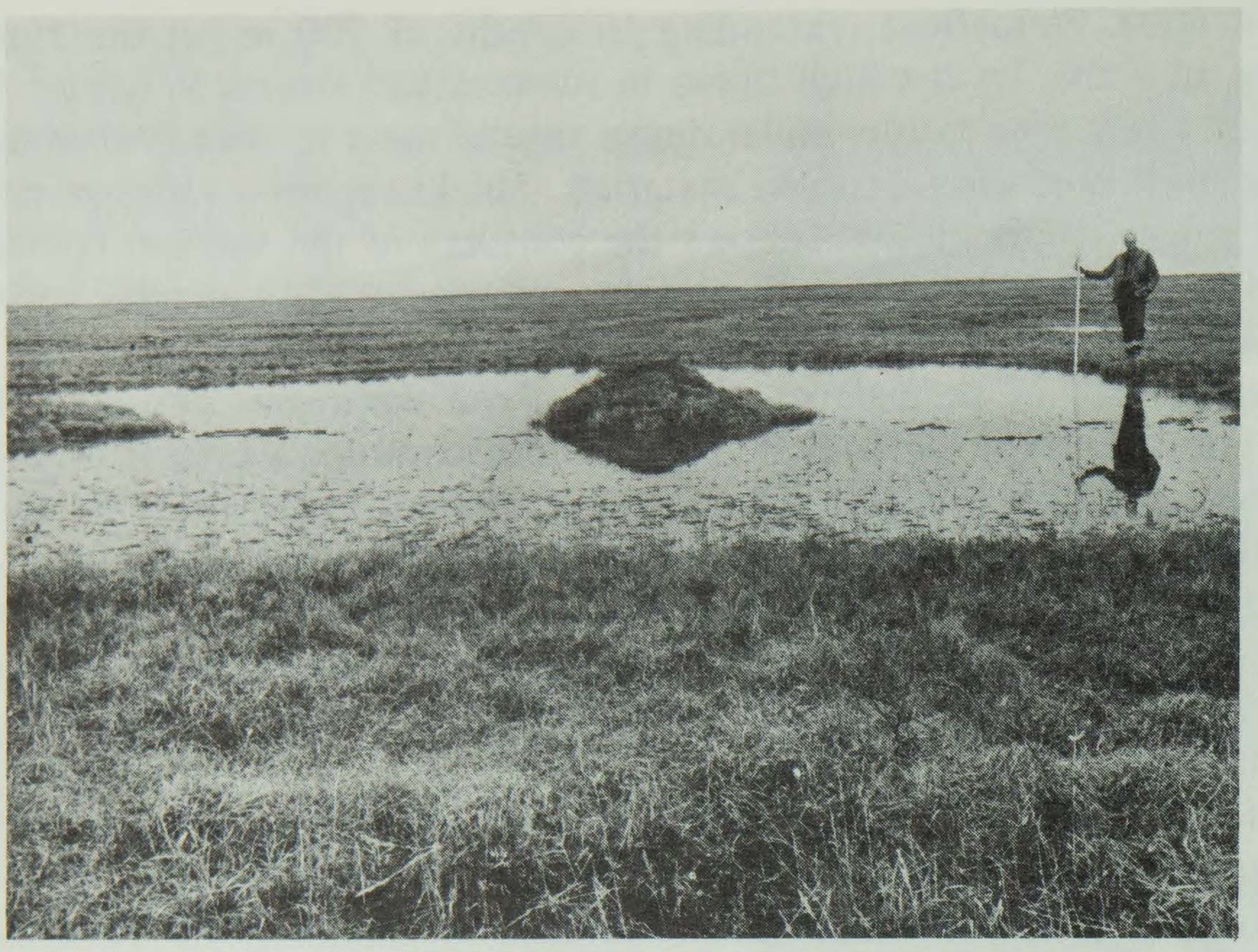


Figure 8. Frost mound.



Figure 9. Solifluctional stripes in Southern Foothills.

Because movement is slower near the base of the active layer, however, it tends to enfold and bury the surface vegetation.

Although solifluction is the most common type of mass movement related to the active layer, it is not the only one. Occasionally, the layer of thaw will deepen more than usual and mudflows will occur (Holmes and Lewis 1965).

Topographic History

Above, we considered those processes which rarely occur outside periglacial regions, and we discussed briefly the more or less unique forms for which they are responsible. These processes must operate within the topographic framework established by more universal activities. Whereas the relatively small forms discussed above develop over short periods of time (at most, a few thousand years), the lithology and structure of the North Slope are the result of millions, even hundreds of millions, of years of geologic activity. As pointed out by Wahrhaftig (1965), "any understanding of its [Alaska's] present topography depends . . . on some knowledge of its geologic history."

Two different but interrelated parts of geologic history are important in determining the present topography: depositional history and tectonic history. Deposition provides the sediments that eventually become rocks which are altered, uplifted, folded, faulted, and exposed to subaerial processes by tectonic activity. For the North Slope these histories have been summarized and updated in a number of articles in recent years; for example, Brosgé and Tailleur (1970), Gates and Gryc (1963), Gryc (1958), Gryc *et al.* (1969), Payne *et al.* (1951), Rickwood (1970), and Tailleur and Brosgé (1970).

During much of its history, the area now occupied by the North Slope was under water. It was a broad stable shelf bordered on the north by an extensive landmass and on the south by a geosyncline. The landmass to the north, probably a part of the Canadian Shield (Rickwood 1970), contributed clastic sediments in great quantities to the shelf and the geosyncline which extended south to central Alaska between at least middle Paleozoic and middle Mesozoic times. In the northern part of the geosyncline, igneous activity was rare. In the southern part, on the other hand, it was common and resulted in the addition of igneous rocks.

During the late Mesozoic two significant tectonic actions occurred. One was the separation of the coastal region of northern Alaska from its hinterland to the north (that is, the Canadian Shield) and its subsequent drift southward. The two major results of this rifting and drifting were the creation of the Arctic Ocean and the elimination of a northern source of sediments for Alaska. The other major late Mesozoic tectonic action was the uplift of the Brooks Range, an activity which has been more or less continuous to the present. Possibly the most significant result of this uplift was the creation of a new sediment source, one that was south instead of north of the North Slope receiving basin. These two generally concurrent tectonic activities established the basic framework of the North Slope as it exists today (Figures 10 and 11). The main structural features from south to north are: (1) the Brooks Range geanticline; (2) the asymmetrical Colville geosyncline; (3) the Barrow Arch; and (4) the continental slope.

The Colville geosyncline (Colville Basin) has an east-west axis across the area now occupied by the present Southern Foothills. Subsidence of the geosyncline just north of the Brooks Range resulted in a highly asymmetrical structure. Near the source

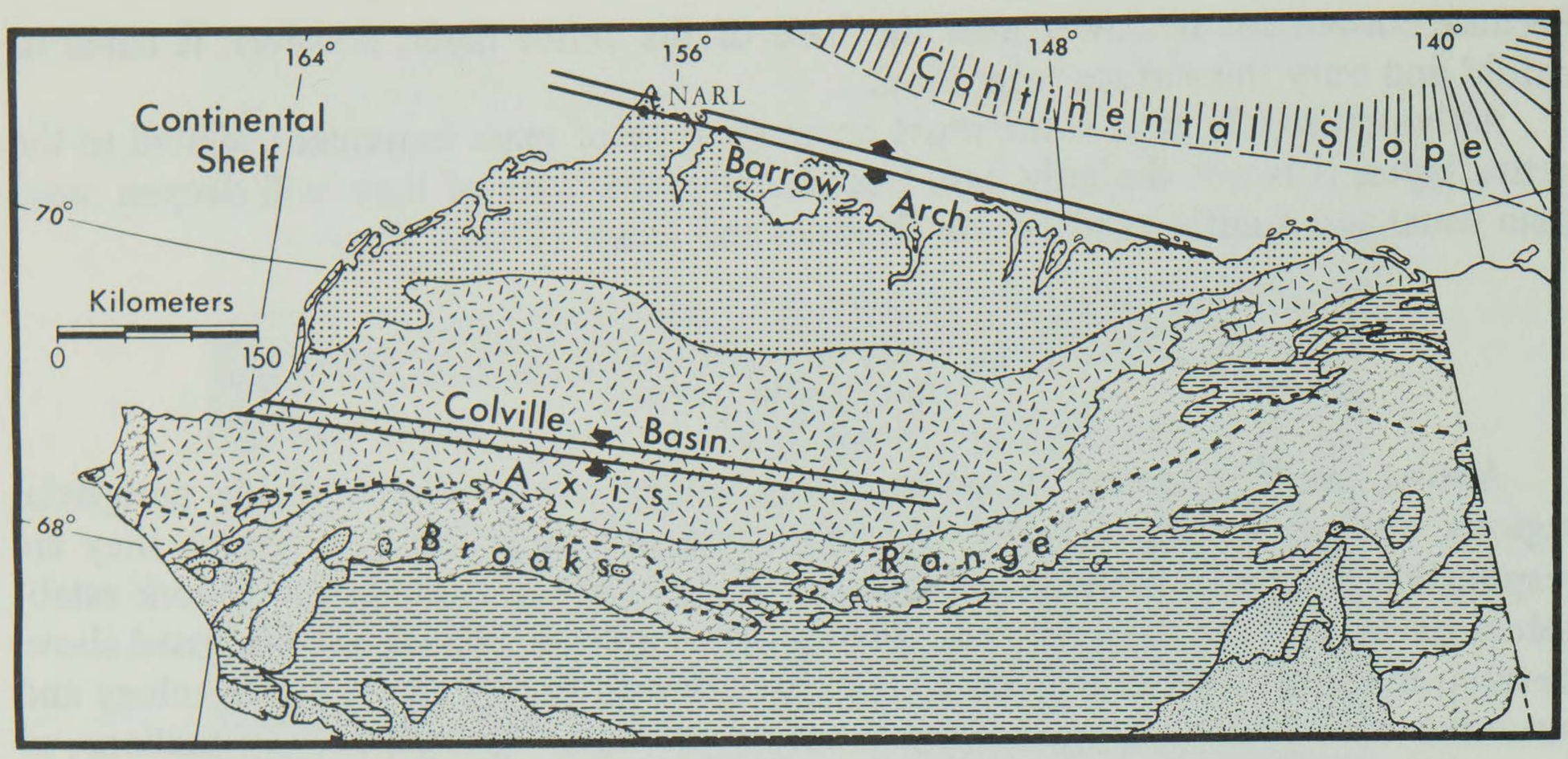


Figure 10. North Slope geology.

Figure 11. North Slope structure.

region, the Colville Basin, especially at first when subsidence was rapid, was steep sided, and turbidity currents were active. The materials were from the rapidly rising ancestral Brooks Range.

With basin infilling and continued uplifting, the sea was moved northward, and a series of successor basins were gradually filled (Figure 10). With continued erosion the rocks in the source region changed from the Mesozoic volcanics of the upper layer to the underlying Paleozoic limestones and quartzites. Further, the relief of the mountains decreased and the distance of sediment transport increased. As a result, the area of the Northern Foothills received sediments that were not only of a different composition but also better sorted than those deposited earlier in the Southern Foothills. As the uplift of the Brooks Range was intermittent, the strand line fluctuated back and forth across the Colville Basin (Chapman and Sable 1960).

The Barrow Arch, the southern flank of which is a continuation of the northern slope of the Colville Basin, was a stable shelf area with a gentle dip. Since the Barrow Arch was covered by shallow water for most of its history, it was far enough north of the Brooks Range source region so that it usually received only muds and silts. Occasionally, as the water of the Colville Sea became shallower and exposure occurred, river deltas would progress far enough north to contribute sands to the arch area.

During the late Mesozoic and early Cenozoic, the Brooks Range and the Southern Foothills were subjected to continued intense folding and faulting, and the Northern Foothills area underwent gentle folding. This activity intensified the long existent east-west structural grain (Figure 11). Northward from the central Brooks Range there is a general decrease in: (1) structural complexity, (2) relief, (3) rock resistance, and (4) the age of exposed rocks.

In the Brooks Range, intense deformation was accompanied by metamorphism and some intrusive activity. Most of the rocks are middle Paleozoic limestones, sandstones, and shales, and their metamorphic equivalents. Gryc wrote (in Williams 1958) that from "... a structural viewpoint, the range is an elevated geanticline squeezed into tight folds and sliced by faults into sheets that have been shuffled together like a deck of cards" (Figure 12).

In the Southern Foothills, rocks were not metamorphosed as much as those in the Brooks Range and include shale, sandstone, conglomerate, limestone, and chert. Nonetheless, this section is nearly as complex, structurally, as the Brooks Range. It includes reverse faults which are upthrust on the south and numerous complex folds, many of which are overturned to the north. Irregular ridges (Figure 13) and hills are generally separated by low areas of shale (Payne *et al.* 1951). Only the Lisburne Hills, with their northward structural trend, contrast with the general eastward trend throughout the rest of the slope (Campbell 1961). (See Figure 11.)

In contrast, the Northern Foothills section, where tectonic activities were not as intense, is structurally simple. Only a few thrust faults are known. Folds, however, are numerous and relatively simple, although most are asymmetrical with the north limb being steeper than the south. It is a section in which ridges, mesas, and hills are generally even crested.

The Arctic Coastal Plain is generally smooth with low local relief. Undeformed Mesozoic sediments underlie as much as 50 m of unconsolidated silt, sand, and gravel of Quaternary age–known as the Gubik formation (Black 1964a, and O'Sullivan 1961). The plain east of the Colville delta, however, contains Tertiary deposits as well.

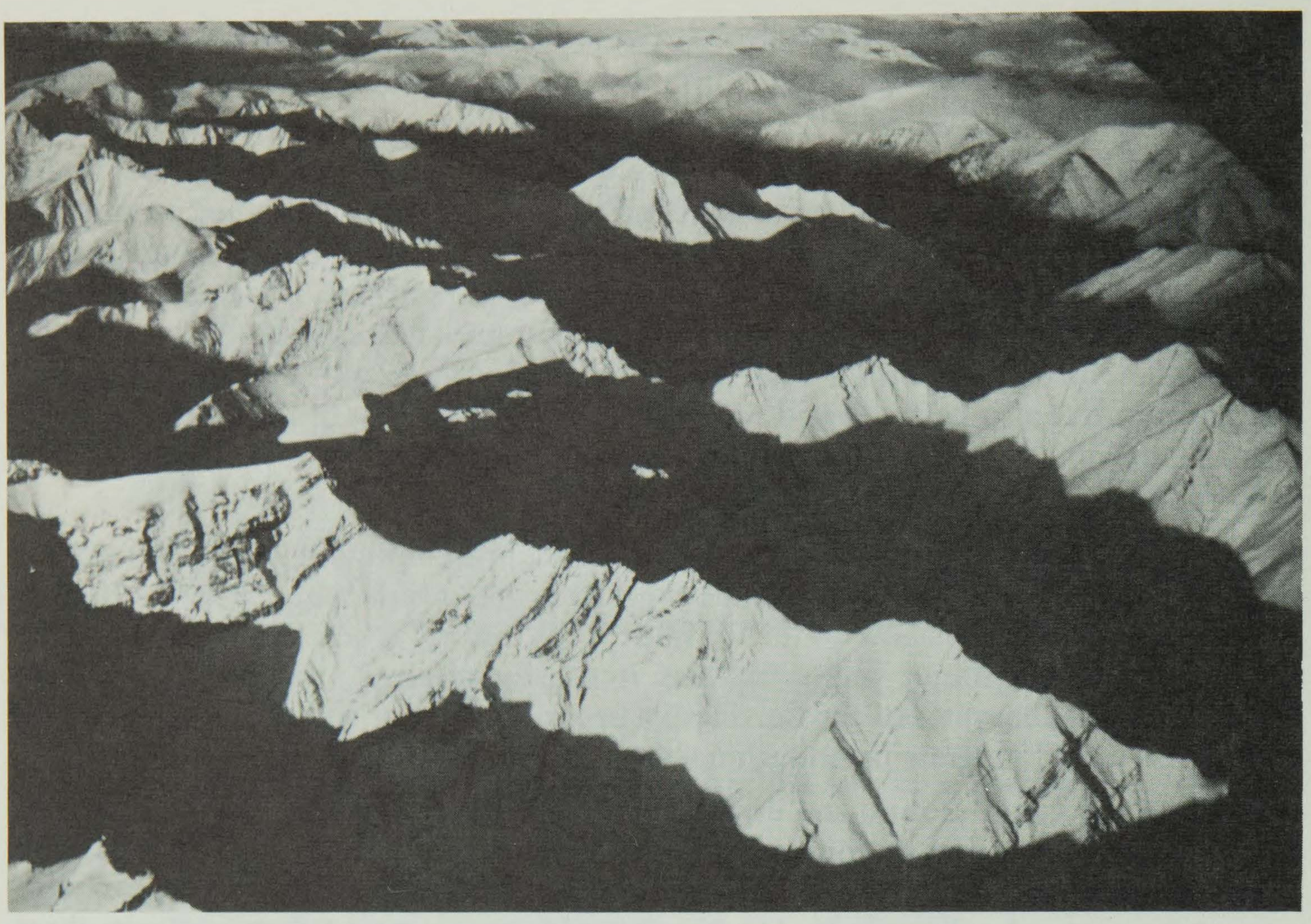


Figure 12. Brooks Range structure.



Figure 13. Irregular ridges of Northern Foothills. (Photograph by J. LaBelle)

Glacial Modification

The gross character of the landscape just discussed is mainly the result of Cenozoic or earlier activities. Many of the details seen today, however, were brought about by subsequent action. The uplift of the Cenozoic continued and probably accelerated in the Quaternary. It was accompanied by a changing climate, and the two in combination resulted in conditions which led to multiple glaciations in the Brooks Range.

The glacial history of the North Slope appears to be quite well deciphered, although its correlation with glacial histories outside the Brooks Range is still tenuous. Most of this history has been pieced together through examination of glacial forms found in the Brooks Range and foothills, especially in the Anaktuvuk Pass and Lake Peters areas. These studies have led to reliable relative dating of those advances whose records are still preserved.

All but the most recent forms upon which this history is based have been altered by periglacial processes. In general, there is a correlation of age with "freshness" of form. This generalization, while valid for determining relative age, must be used with caution when dealing with absolute age. As pointed out above, the effectiveness of periglacial processes varies with climatic conditions so that the degree of alteration of glacial forms depends partly on "the number, length and intensity of periods of warm climate" they have undergone as well as their absolute age (Holmes and Lewis 1965).

Major glaciations (that is, those where the ice advanced into the foothills north of the Brooks Range) occurred several times during the Pleistocene (Figure 14), with the

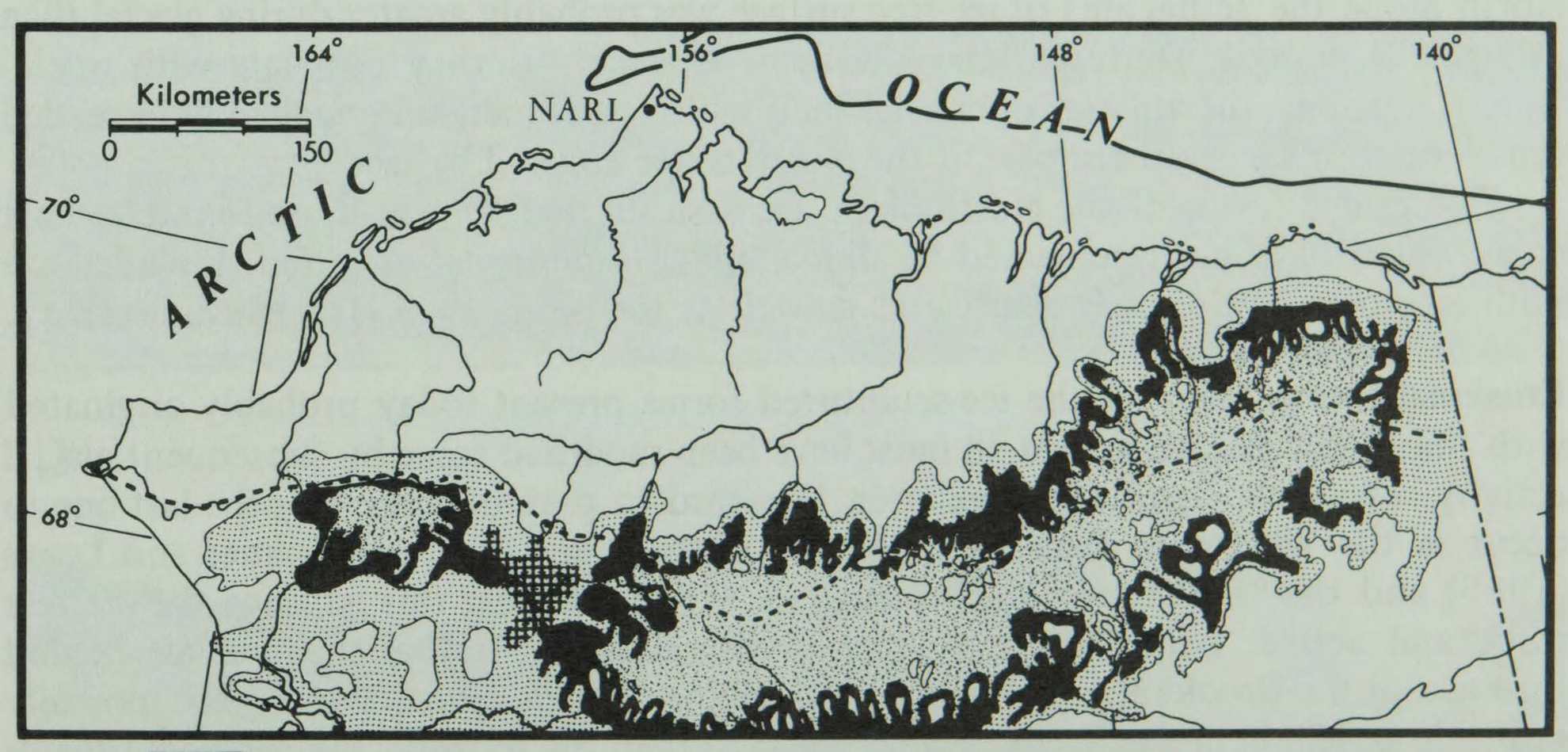


Figure 14. Extent of glaciation in northern Alaska.

last advance probably lasting into the early part of the Recent (Péwé *et al.* 1965). During the Recent (that is, the past 6,000 to 10,000 years), there have been several advances and retreats, but all have been confined to valleys within the Brooks Range. Today, glaciers are only present in north-facing, often oversized cirques in the higher parts of the Brooks Range and apparently all possess negative economies (Porter 1966, and Sable 1961). The largest ones, up to 5 km long, occur around Mt. Chamberlin where they are also most numerous. The number and size decrease westward such that there are only a few in the higher peaks around Anaktuvuk Pass. In the west, as in the De Long Mountains, they are absent.

The Brooks Range was sufficiently high during the Pleistocene so that its peaks protruded through the ice. These nunataks must have been quite numerous, especially to the east. Only a suggestion of the number can be obtained from the generalized glaciation map (Figure 14). On the other hand, ice was sufficiently thick during the major advances so that most of the lower peaks of the Brooks Range and many of the ridges of the Southern Foothills were covered.

Thus, while the higher portions of the peaks of the Brooks Range were subjected only to the periglacial activity which accompanies glaciation, lower peaks and ridges were directly altered by overriding glaciers. The ice which advanced northward down the valleys of the Brooks Range coalesced across divides and formed a series of piedmont lobes in the foothills. Coalescence resulted in a continuous band of ice across northern Alaska nearly to the west coast, at least during the earliest glaciation. During this time individual lobes extended as much as 70 km north of the Brooks Range.

Despite the enormity of this glacial band, never more than 15 percent of the North Slope was covered with ice. This proportion contrasts with the nearly 50-percent value that applies for the state as a whole (Péwé *et al.* 1965). From the standpoint of the North Slope the actual area of ice-free surface was probably greater during glacial than interglacial periods. During glacial advances, especially if they correlate with world-wide glaciations, the amount of coastal shelf which was emergent equalled or exceeded the amount of the southern part of the North Slope covered by ice.

The glacial forms of the North Slope are basically the same as those found in most areas which have been subjected to alpine and piedmont glacial action. Included are both erosional and depositional forms as well as the products of glaciofluvial activity.

Erosional forms. Many of the ice-sculptured forms present today probably originated with the oldest glaciation, but all must have been modified some by subsequent glacial activity. The most significant glaciation in regard to present forms was the last one to occur in the Wisconsin; that is, the Peters advance described by Holmes and Lewis (1965) and the Itkillik by Detterman *et al.* (1958). During this advance the ice was thick and active. Large U-shaped valleys with hanging tributaries were left behind throughout the Brooks Range (Figure 15A). Some of the deepening was great, possibly as much as 750 m in the Brooks Range and 350 m in the foothills (Patton and Tailleur 1964).

Valley side erosion was sufficient to produce truncated spurs which rise to 1,000 m above valley floors. The lowering and straightening of valleys in the Brooks Range such as at Howard Pass have had very important subsidiary effects. By reducing the effectiveness of the Brooks Range as a barrier, warm winds moving from the south cause relatively early melting of snow in such areas.

Irregular longitudinal profiles in these valleys resulted from glacial gouging, and many of the depressions now filled with water are glacial lakes. In other valleys gradients are steplike, a characteristic which is reflected especially in variable drainage

gradients. Those areas covered by the ice, such as the divides in the Southern Foothills, were rounded, smoothed, and lowered by the overriding ice. Melt water flowing along the sides of some of the glaciers eroded channels into the adjacent hillsides and across ridges. Such channels have been reported around Anaktuvuk Pass (Porter 1966).

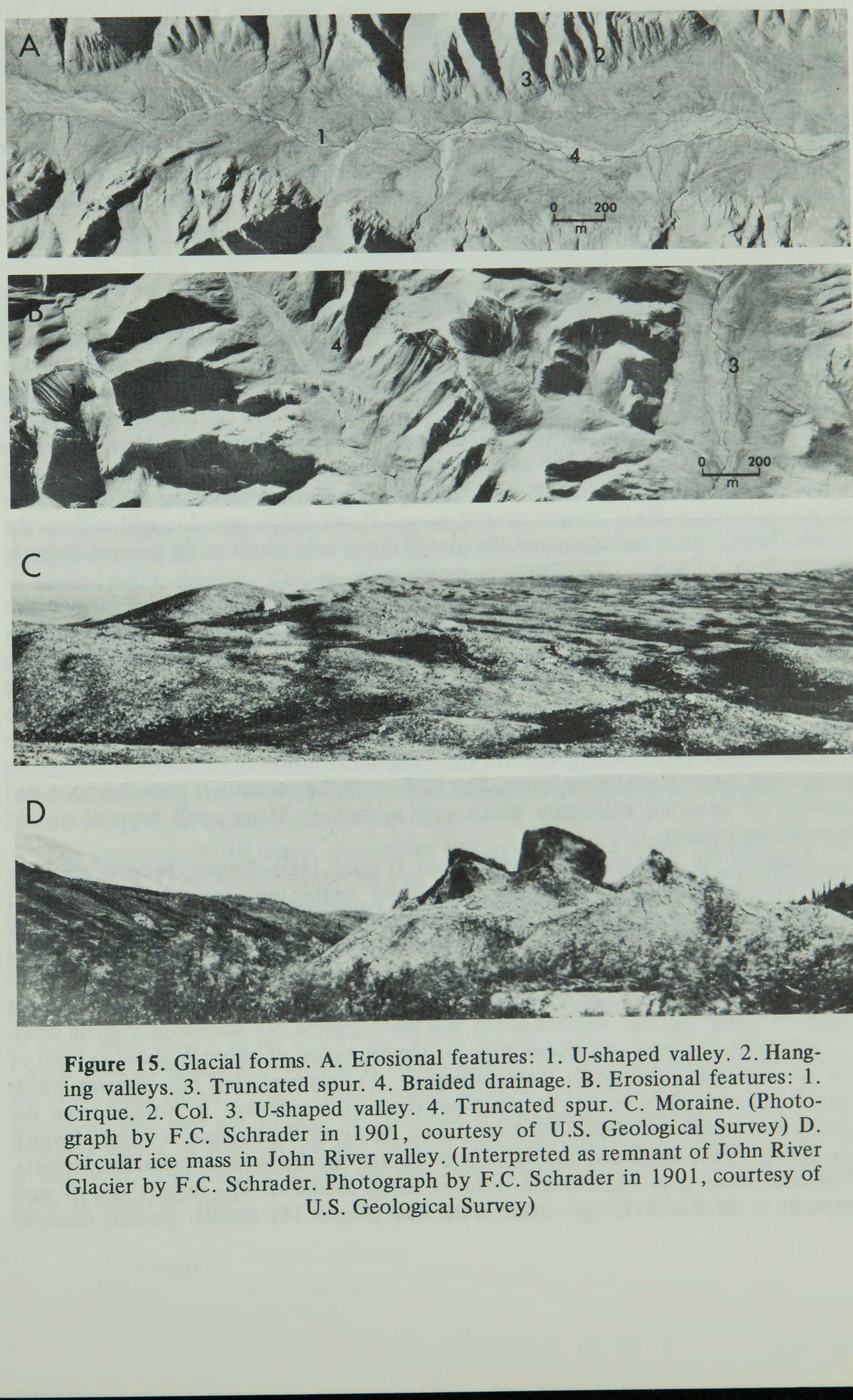


Figure 15. Glacial forms. A. Erosional features: 1. U-shaped valley. 2. Hanging valleys. 3. Truncated spur. 4. Braided drainage. B. Erosional features: 1. Cirque. 2. Col. 3. U-shaped valley. 4. Truncated spur. C. Moraine. (Photograph by F.C. Schrader in 1901, courtesy of U.S. Geological Survey) D. Circular ice mass in John River valley. (Interpreted as remnant of John River Glacier by F.C. Schrader. Photograph by F.C. Schrader in 1901, courtesy of U.S. Geological Survey)

The heads of the high valleys where glaciers originated were enlarged into cirques (Figure 15B), a few of which have glacier ice in them today. These steep-walled cirques are numerous throughout the Brooks Range, especially in the central and eastern parts. Tarns (water-filled rock basins) occupy the floors of many cirques.

As cirque glaciers quarried headward, mountain sides were rapidly steepened. This action, when combined with frost-wedging and gravity, produced arêtes (knife-edge ridges), cols, and horns. These sharp features, maintained today by continuing frost-shattering, give most of the Brooks Range a very ragged appearance (Figure 12). Because of the difference in elevation between east and west during glaciation, however, there is a difference in appearance today. In the central and eastern Brooks Range, where elevations rise between 2,000 and 3,000 m, the peaks and ridges are saw toothed; to the west, in the lower parts of the De Long Mountains, the surfaces are smoother and more subdued.

Depositional forms. Most forms deposited by alpine and piedmont glaciers are present north of the drainage divide of the Brooks Range. They are in various stages of alteration, ranging from the freshness of presently forming morainal deposits at the toe of the small cirque glaciers to the almost completely obliterated deposits farthest removed from glacial source areas.

The oldest depositional form recognizable today is the erratic. Many are quite large, with some over 3 m in diameter. They are found on mountains at levels above other evidence of glaciation and have served as a guide in establishing the outer limits of glacial activity. Many of the erratics around Howard Pass were brought in from the south. Their source indicates that the glacial divide was south of the present drainage divide.

Moraines, the most common glacial deposits, are especially abundant in that part of the Southern Foothills which was glaciated. Most of the valleys north of the Brooks Range have a series of recessional moraines up-valley from a terminal moraine. Some recent moraines may still be ice cored (Porter 1966). Within the confines of most valleys, lateral moraines are common and frequently are found on both sides of the valley. Ground moraine (Figure 15C) is quite thin where it only subdues slightly the original topography. Over much of the piedmont, however, it is thick enough to completely cover preexisting forms. The surface of the moraine is quite irregular and consists of unsorted sediments which vary in texture. Many small depressions and mounds are present.

Stagnant ice topography is widespread (Figure 15D). Kames, because they are deposited by running water, have a degree of sorting not present in the ground moraine. Nonetheless, since they are associated with stagnant and retreating glacial ice, they are highly varied in surface expression and distribution. Kame terraces (fluvial deposits between a retreating glacier and valley walls) are common. Individual kames occur as small hills over some morainal surfaces. Kettles, many of which are in various stages of filling through sedimentation and plant growth, are numerous in some areas.

Glacial melt water was responsible for the formation of outwash plains in front of the glacial lobes. Most melt water, however, was concentrated into streams which flowed through gaps in the terminal moraines. The sediment it brought from the glacier was sorted and deposited downstream. Many of these deposits, some of which are quite thick, are being re-eroded just as are the kame and morainal deposits. Proglacial lakes were formed and received much sediment. The largest area of such deposits in the Brooks Range occurs in the west (Figure 14). Smaller glacially dammed

lakes were present in the foothills and must have been quite numerous where individual valley glaciers coalesced around spurs in the foothills.

Remnant glacial lakes are numerous today in the formerly glaciated areas. Many of the largest are those which are partially or wholly the result of morainal damming. Lake Peters and Lake Schrader are two examples.

Rock glaciers. Rock glaciers are present at high elevations in the Brooks Range, but they are less common than in the Alaska Range. Apparently many of them are inactive (Porter 1966). The forms are characterized by masses of rocky rubble at high angles of repose. Some of them possess conspicuous ridges along their margins and have a variety of microrelief features on their surfaces.

Periglacial modification of glacial forms. The present appearance of North Slope glacial depositional forms might be best illustrated by considering two small areas which represent the results of glaciations of different ages. The two areas selected are part of a large region mapped by Holmes and Lewis (1965). One straddles the moraine separating Lake Peters and Lake Schrader; the other, 20 km to the north-northeast, lies just to the south of the Sadlerochit Mountains at the northern end of the foothills along the Sadlerochit River (Figure 16). The oldest glaciation (Weller) reached the Sadlerochit Mountains, but today it is represented only by some scattered erratics (1 to 2 m in diameter), by very subdued and rounded ridges which may have been lateral moraines, and by patches of drift which were probably kame terraces.

Few exposures of this material exist. Some of it has been covered by talus from the steep slopes of the Sadlerochit Mountains and some of it by more recent glaciofluvial and fluvial deposits (Figure 16). Most of it, however, has been covered by, or altered to, colluvium. This material, which is composed of drift, frost-shattered rock, alluvium, and often eolian deposits, is transported by solifluction. The colluvial sheets along the Sadlerochit River include ". . . lobes and terracettes, soil stripes, stone stripes, stone garlands, polygons, tussocks, and frost mounds" (Holmes and Lewis 1965).

Although these are not the only forms present on colluvial surfaces, they represent the majority and illustrate the variety of periglacial forms occurring on the oldest glaciated surfaces of the foothills and mountains of the North Slope. Colluvium tends to be thickest over the older, longer exposed surfaces, but a thin cover is present on all but the steepest slopes and youngest deposits.

The youngest of the major glaciations (Peters) extended down the valley to the north end of Lake Peters where its end moraine is only partially preserved today (Figure 16). Steep-sided, little-altered lateral moraines border each side of the lake. Since they were formed, they have been breached by mountain streams which are building alluvial fans into the lake.

Around the southern end of Lake Schrader is a morainal deposit from the next older (Schrader) glaciation. Schrader moraines have been smoothed slightly and altered in other ways but not to the extent where they are unrecognizable (Reed 1968). Other forms, such as knobs and kettles, although present are not as common as in many glaciated areas (Reed 1968). The moraines do have a well-developed system of patterned ground and are subject to earth-flows. Colluvium completely covers some Schrader slopes. In contrast, on the younger Peters moraines, colluvium is missing or is very thin. Also these moraines contain numerous unmodified knobs and kettles, some of which are large.

Hydrologic Factors

The most significant factors in the hydrology of North Slope rivers are the virtual cessation of water flow during winter; low annual precipitation; the concentration of most of the season's flow in a short period of time; the inclusion of vast amounts of river ice in the flow usually during peak discharge; the shallow or nonexistent active layer during initial flow; and the tundra vegetation (Brown *et al.* 1968, Cook 1967, and Walker 1970).

The nature of the flooding depends mainly on the amount and timing of snowmelt. The variability in both can be great. Normally, melt water begins to accumulate inland in early May and near the coast during middle to late May. The time between the appearance of melt water and the removal of ice from the river also varies greatly. Once breakup begins, virtually all of the ice is removed within 2 or 3 days, although the time of breakup may vary several weeks between the headwaters and the mouth of the major rivers.

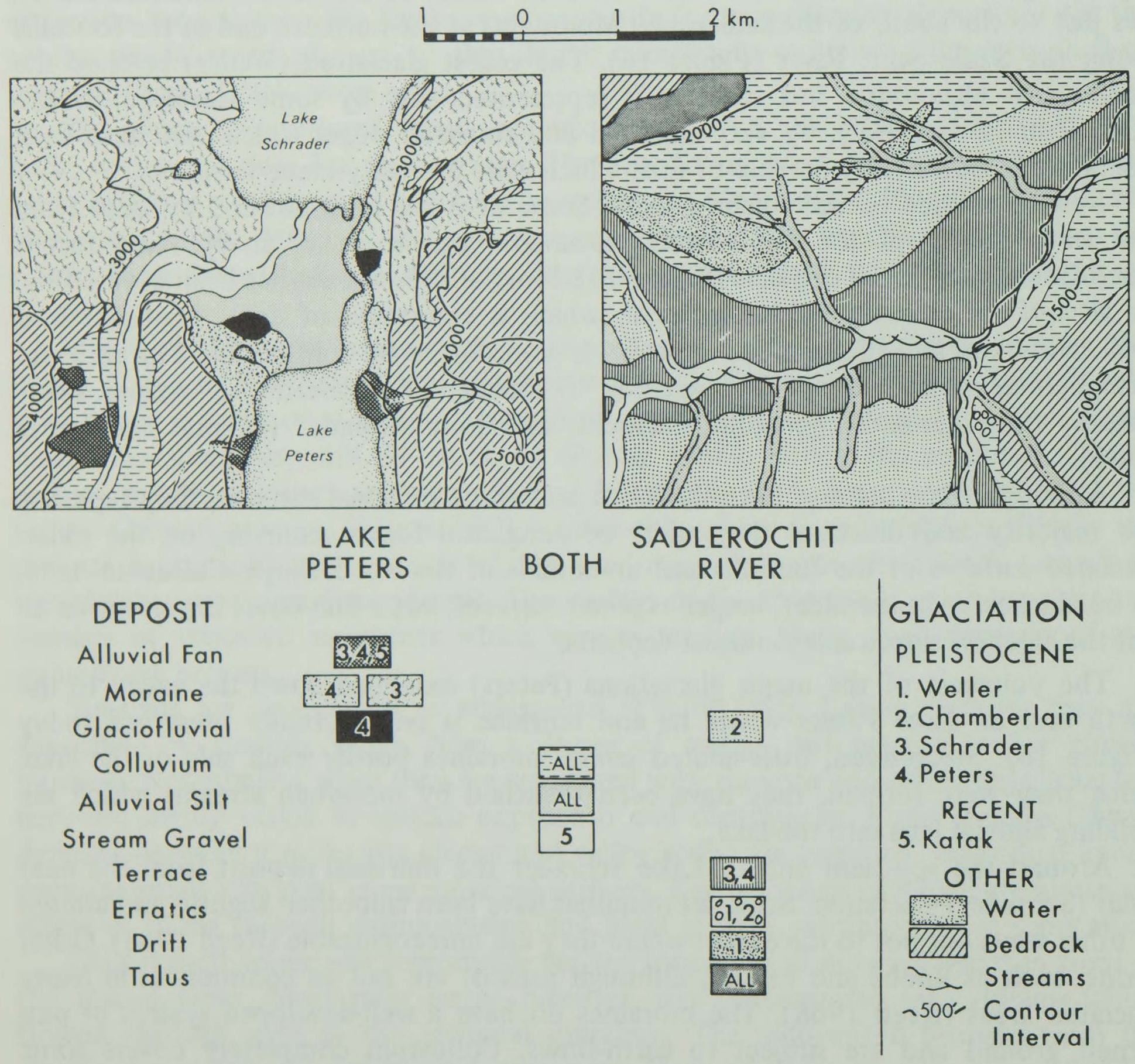


Figure 16. Glacial topography. (Holmes and Lewis 1965)

Although snow is the most important source of water for river runoff, it is not the only source. During summer, rain keeps many streams flowing. Rainfall on the North Slope seldom is responsible for flash flooding, although rapid fluctuations in level, even if small, reflect the timing of rainstorms. Other sources include ground water contributed by the thawing active layer and slow surface seepage through the tundra from the numerous lakes and ponds.

Some rivers, such as tributaries of the Sadlerochit River, are fed by deep lakes and continue to flow after freezeup (Lewis 1962). In the eastern Brooks Range a small amount of water is contributed by glaciers. Icings (aufeis fields) occur along many of the rivers of the North Slope and give evidence of springs, some of which are perennial (Williams 1970). Some icings last through the summer (Figure 17), while other are eliminated by thermal erosion and melting (Hopkins *et al.* 1955). Icing mounds are often associated with aufeis (Lewis 1962).

The materials (inorganic and organic) moved by the river in suspension, in solution, or as bedload vary greatly in quantity with season. The first melt water carries very little sediment, but as melting increases and the active layer begins to form, sediment from dunes, bars, and the tundra surface is transported by the rivers. Much of this sediment is deposited temporarily as fans on river ice, snowbanks, and sandbars (Figure 18). These are usually removed during flooding. Some deposits become thick enough to protect the snow and ice beneath them for some time.

During the flooding which precedes breakup, river-carried sediment may be deposited on the surfaces over which it flows, including bottom-fast ice in rivers, lakes, and the ocean (Walker and McCloy 1969). This ice breaks loose and floats to the surface during breakup (Figure 19). Ice in the river carries its sediment load seaward, while ice in the lakes melts in place and drops its load to the lake bottom. Some of the sediment deposited on the sea ice is lost to deltas, since it is carried away during sea ice breakup.

The bulk of the annual sediment load is transported during the short spring flooding. For example, in 1962 the Colville River moved 75 percent of its total load in a 3-week period in June (Arnborg *et al.* 1967).

The erosive effects of arctic rivers have been little studied. Because of permafrost, it is generally believed that bottom erosion is limited and that lateral erosion is especially important. In the major rivers there is no permafrost beneath the deep channels, although during flooding water extends over surfaces that are exposed for all but a couple of weeks per year and are indeed underlain by permafrost. Some surface erosion occurs in the many braided streams. In addition, lateral cutting is quite active.

Development of thermoerosional niches, especially common during flooding, also occures at lower stages when wind waves are active (Walker and Morgan 1964). Such active bank erosion helps bring about rapid shifting in river channel positions and is also responsible for other flood plain changes. Lakes of various types are numerous in flood plains, including deltas. These are continually being tapped by meandering river channels. In the Colville delta, at least four large lakes (several kilometers in area) were so tapped in the last 15 years. Lake levels are lowered and subsequently fluctuate with river level. Flood water sediments are trapped and lake deltas rapidly form.

A form frequently found on the North Slope and commonly ascribed to periglacial processes is the asymmetrical valley (Black 1964b). (See Figure 20.) To date, however, they have received little attention. Although asymmetry may develop in several ways, the type typical of periglacial regions theoretically results from an increased rate of solifluction on south-facing slopes because the insolation received there is greater than on north-facing slopes. A study in the Point Hope area shows that other, especially



Figure 17. Icing in Sagavanirktok River (August 1971).

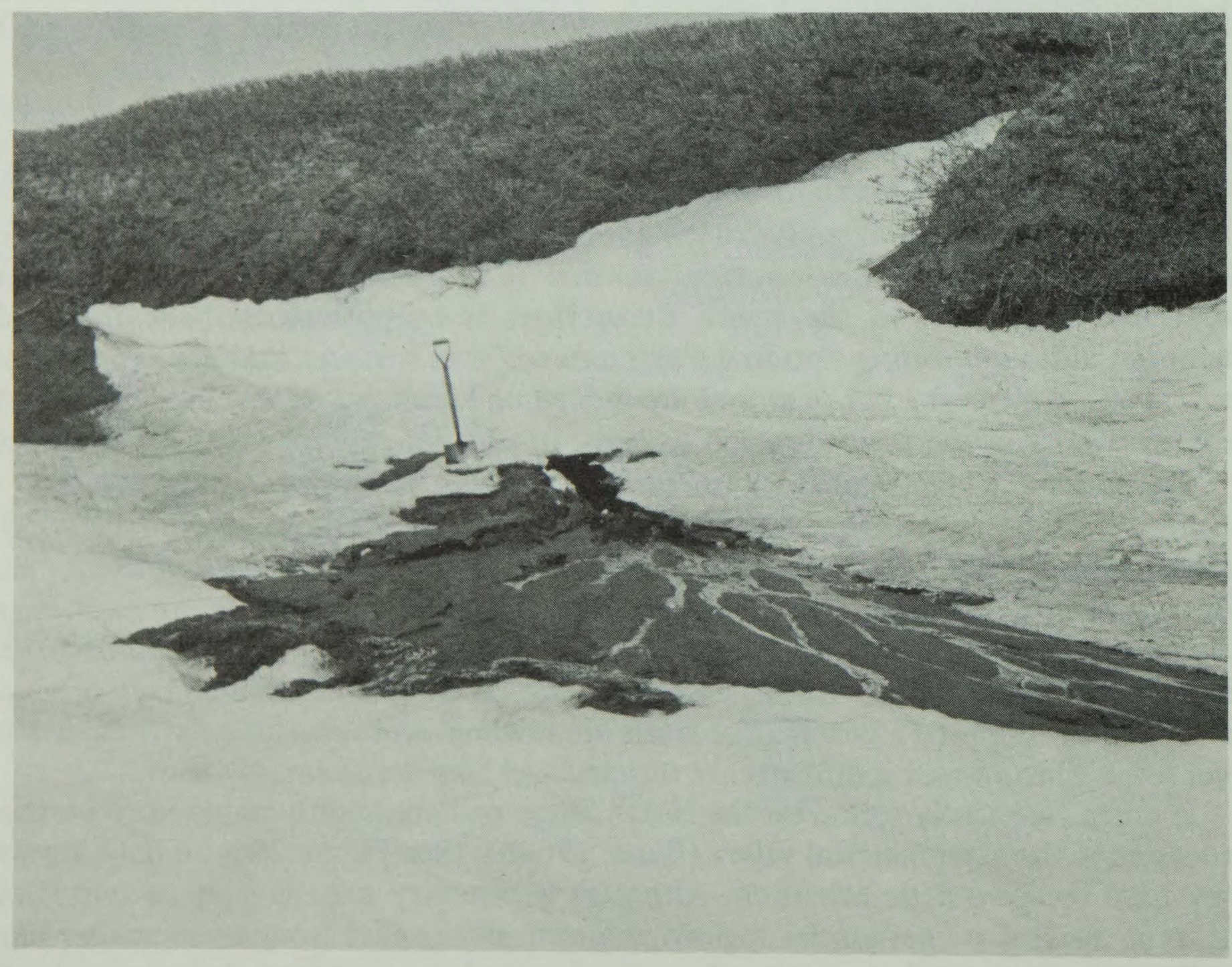


Figure 18. Deposition by snowmelt runoff on snow.



Figure 19. Sediment-covered river ice.

local, factors are very important in determining asymmetry (Currey 1964). More recently field work in northwestern Canada did not "... bear out the accepted hypothesis of 'periglacial' asymmetry in which permafrost and solifluction are the dominant factors" (Kennedy and Melton 1967).

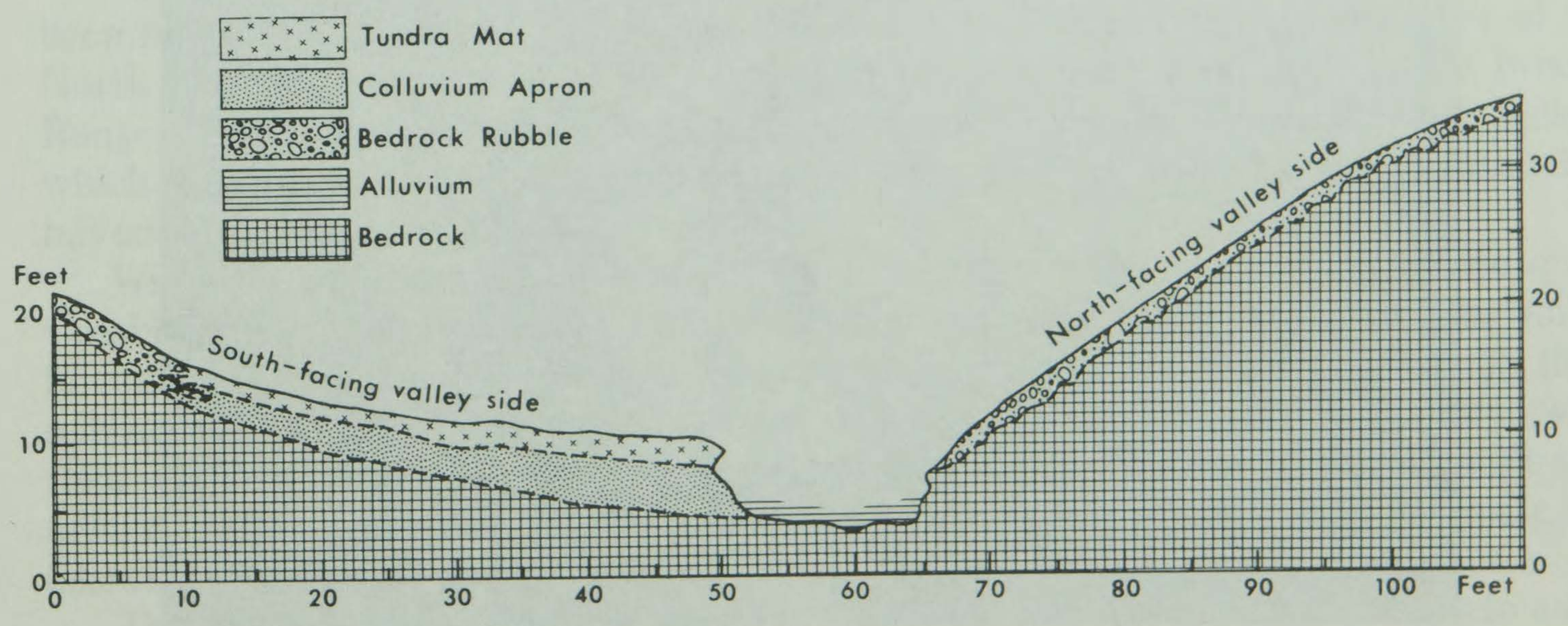


Figure 20. Idealized asymmetrical valley. (Currey 1964)

During prebreakup flooding, bottom-fast ice protects the bed from fluvial action. Once downstream movement of ice begins, it becomes an active agent. Its effectiveness depends upon several factors, including whether breakup occurs on a rising or falling stage (Walker 1970). When breakup is on a rising stage, ice is carried downstream with little chance of grounding. On a lowering stage, however, ice is likely to be stranded, thereby increasing the possibility of ice jams and bank erosion. Ice trails on sandbars (Figure 21) and ice gouges on riverbanks are numerous. Stranded river ice, which may last until late June on some of the North Slope riverbars, leaves the debris it has carried on the bar as it melts. The period of river-ice action is very short at any particular location—at most, a few days. The period of fluvial action, however, continues for several months although at a lower intensity after breakup.

Most river forms found elsewhere are present on the North Slope. Braided rivers are characterized by almost innumerable gravel and sand bars separated by a maze of continuously shifting channels (Figure 17). Such changes are often so great that when the floodwater ". . . recedes the new braided pattern is so different that the entire aspect of the river is changed" (Keller *et al.* 1961).

Meandering rivers are continuously shifting courses and creating oxbow lakes, point bars, and ridge-and-swale topography (Figure 22). In the process these cause continuous shifts in the position of the permafrost (Williams 1970). Natural levees are less well developed than in some other environments, but they are often conspicuous. Despite small relief differences, the polygons near the bank of a flooding river are usually well drained compared to those in the "backswamp" sector.



Figure 21. Ice trail.



Figure 22. Meandering river on Coastal Plain.

Drainage and Drainage Patterns

Since the uplift of the Brooks Range, the flow of water on the North Slope has been north into the Arctic Ocean. As this direction crosses the basic structure of the North Slope, tributaries generally paralleling the structure developed. In the Brooks Range, rivers, many of which head in relict cirques, have deeply incised their valleys which are V-shaped in their upper parts (Figure 15B). At lower elevations glaciation has converted them to a U-shape.

With the two contrasting types of origin of these valleys, the gradients are quite variable. In the unglaciated portions the gradients are generally steep and the valley bottoms quite narrow. Some are hanging valleys and have falls or rapids at their entrance to the glaciated portions of the drainage system. The glaciated valleys with their mixture of glacial and glaciofluvial deposits generally have gentle gradients and meandering streams. In many cases the rivers have been dammed by these deposits and lakes have formed.

The rivers draining northward seem to "burst abruptly from the mountains to enter the Arctic foothills" (Reed 1958). Their nature is quite different on either side of the boundary because of the heritage left by glaciation. For some distance north into the

foothills the major rivers flow across a succession of recessional moraines where rapids are common. Small streams flowing down the steep front of the Brooks Range, on the other hand, have gradients that decrease as they enter the foothills.

The main streams in the foothills cross structural trends and have tributaries which are mainly structurally controlled. Once past the glaciated area, the main valleys are generally broad and flat, and contain low-gradient rivers which are usually braided. A number of valleys in the Northern Foothills, however, are V-shaped. Their rivers flow in single channels and are actively cutting through resistant rocks. Some of the steep cliffs along the rivers are caused by lateral migration. Examples of such migration are the Colville Bluffs which extend from Umiat to Ocean Point (Figure 23) and the Franklin Bluffs on the Sagavanirktok River (Anderson and Hussey 1963).

Many of the river valleys in the foothills possess well-developed terraces. In the Killik River valley, as many as five distinct levels have been recognized (Detterman *et al.* 1963). Alluvial fans, often coalesced, occur at the base of bluffs or banks which have been abandoned by migrating rivers (Anderson and Hussey 1963).

A large proportion of the rivers originating in the Brooks Range continue directly to the Arctic Ocean (Figure 1 and Table 2). Those draining the middle portion of the Brooks Range and the Southern Foothills, however, are tributaries of the Colville River and represent some 29 percent of the North Slope area.

Rivers after they enter the Coastal Plain have reduced gradients. They are usually shallow and flow in meandering channels, especially west of the Colville River. East of the Colville River, however, braided patterns frequently persist to the ocean. Although most of the North Slope is drained by rivers which originate in the Brooks



Figure 23. Colville bluffs. (Photograph by F.C. Schrader in 1901, courtesy of U.S. Geological Survey)

Table 2. Drainage regions of north Slope.*

Region	North Slope area		No. basins over 5,000 km^2 in area
	Km^2	Percentage	
Western	30,000	14.5	4
Northern	59,000	28.5	3
Colville	60,000	29.0	3
Eastern	58,000	28.0	3
Totals	207,000	100.0	13

*See Figure 1.

Range, there is a large area (59,000 km^2) north of the Colville River system which is drained by streams forming in the Northern Foothills and on the Coastal Plain (Figure 1).

It is here that extensive swampy areas, ponds, lakes, and sluggish streams are numerous. Although poorly integrated drainage is most common on the Coastal Plain, it also occurs in lowlands between the ridges in both the Southern and Northern Foothills (Chapman and Sable 1960). Most of the rivers of the Coastal Plain flow in unconsolidated deposits and have numerous cutoff meanders and oxbow lakes (Figure 22). Some possess Yazoo-type tributaries. A few rivers on the Coastal Plain, especially those draining to the west coast such as the Kukpowruk, cut through bedrock nearly to the coast itself.

Many of the rivers are forming deltas where they flow into lagoons or directly into the Arctic Ocean. The largest of these deltas is the 600 km^2 Colville River delta (Figure 24A).

All major drainage patterns are represented on the North Slope. Dendritic patterns are most common and range downward in size from that of major systems such as the Kuk River. The control over drainage exerted by structures, especially in the foothills, has caused the development of trellis, parallel, and rectangular patterns. Radial drainage, although less common, occurs on some structural highs in the foothills and on a smaller scale on pingos.

In addition to these more general or more regional patterns, there are several types which develop in response to local conditions. These include thermokarst (Figure 24B) and horsetail drainage patterns (Figure 24C), both of which are common on the North Slope (Hussey and Reckendorf 1963). Thermokarst patterns are indicative of poor and discontinuous drainage and develop best on low slopes. This nonintegrated type of drainage occurs along ice wedges such that the over-all pattern takes the shape of the polygons around which the water flows. The horsetail type is composed of subparallel channels which converge into a single channel and, unlike thermokarst drainage, is integrated. Other distinctive patterns on the North Slope include those which are fanlike and featherlike (Figure 24D).

Eolian Forms

Erosional aspects. Although fairly persistent throughout the year, wind, as an erosional and deflational agent, can only be effective against unprotected areas. Thus, it has

little effect during most of the year because of snow cover. Even during the short time the snow cover is absent, however, most of the North Slope is protected from wind attack by its lush tundra vegetation. At present, only a few types of surfaces are subjected to wind erosion. One is the hillside or summit where the ground surface is exposed. Such a surface is most common in the mountains and the Southern Foothills.

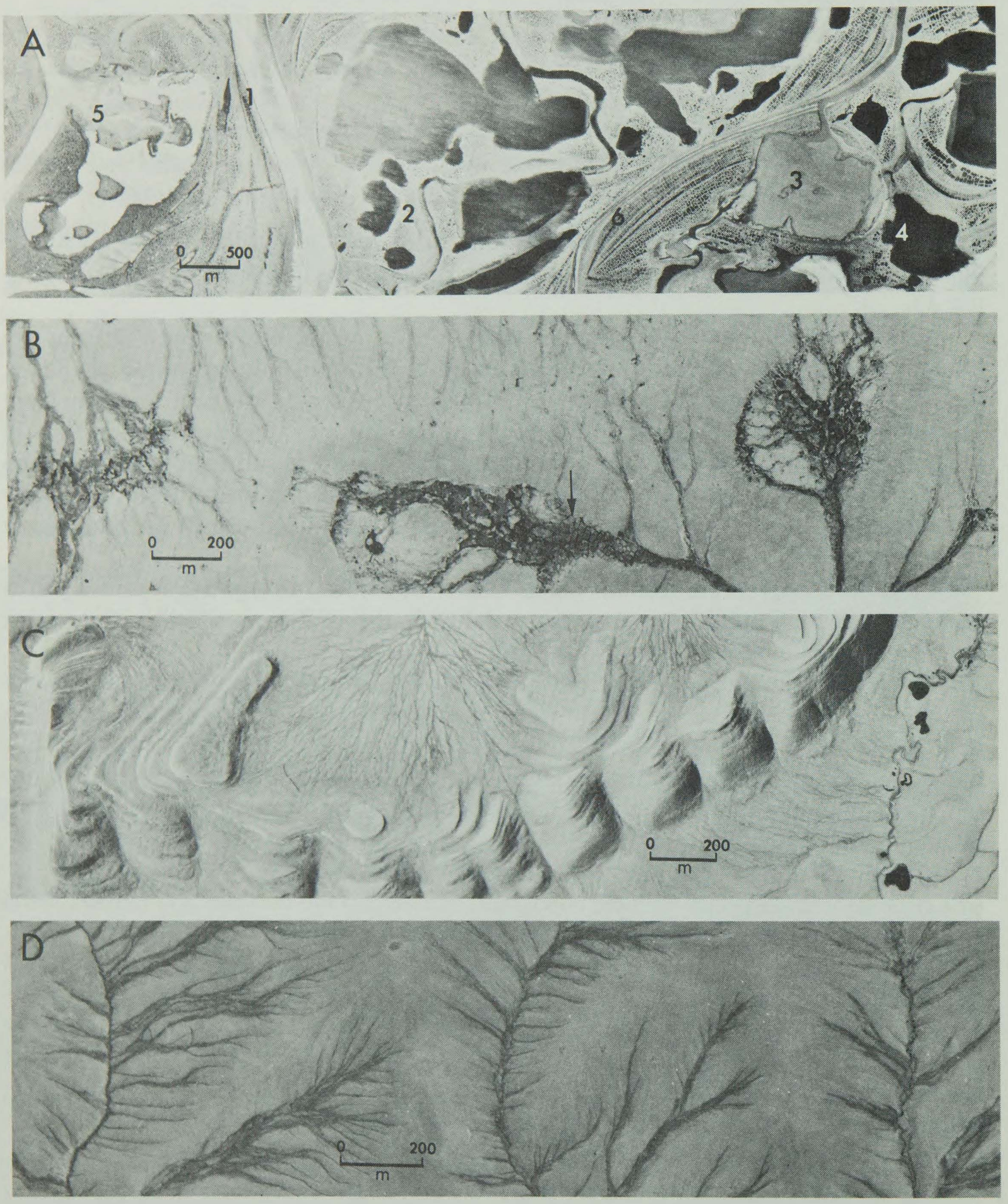


Figure 24. Drainage patterns. A. Deltaic drainage: 1. Active distributary. 2. Abandoned distributary. 3. Tapped lake. 4. Untapped lake. 5. Lake delta. 6. Ice-wedge polygons. B. Thermokarst drainage. C. Horsetail drainage. D. Featherlike drainage.

Abrasion in sandstone, for example, produces some fluting and rock pedestals, but generally these forms are rare (Chapman and Sable 1960). On a smaller scale, the edges of polygons, especially during dry periods, may be subjected to wind erosion. Another is the surface which for some reason has had its protective cover removed. Animals (squirrels or grizzly bears after squirrels, for example) often destroy the vegetal cover and expose the surface to wind action. Many of the active blowouts on the Coastal Plain are started in this fashion.

A third source region is the coast. Barrier islands, although mostly unprotected by vegetation, usually are a limited source of sand because of a gravel pavement which mantles their surfaces. Also much of the coast is formed of low cliffs of peat and has narrow strand lines. Sand beaches, although present, are not common. The most important source region on the North Slope is the flood plain. Since flood plains are mostly exposed during the snow-free period, they are potential source regions for several months (Smith and Mertie 1930).

Depositional forms. Black (1951) noted that eolian materials are present over most of northern Alaska. These include loessial blanket deposits as well as several types of stabilized and active dunes. In the Brooks Range and Southern Foothills, the major river valley terraces are topped with loessial deposits. Although 10 m or more thick near rivers, these deposits thin rapidly away from the river (Péwé 1969a). Possibly, much of the loess was transported during glacial maxima when strong katabatic winds would have prevailed and much silt was being produced (Determan *et al.* 1963).

The largest area of dunes on the North Slope is a band extending west from the Colville River to the Meade River, although they also occur elsewhere on the Coastal Plain and in the foothills (Rickert and Tedrow 1967). Most dunes are stabilized. The majority are parabolic or longitudinal, some of which may be as much as 3 km long (Black 1951).

Active dunes are common on the lee side of river bars and large lakes. In the Colville River delta, Walker (1967) found that the size of dunes correlated closely with exposure and the size of adjacent bars. At the front of deltas, dune fields have low, irregular, and rounded forms; blowouts are numerous and active. The other location with active dunes is adjacent to and southwest of river channels. Along these banks dune ridges several kilometers long and several hundred meters wide have formed. Such dune ridges are usually deeply furrowed by wind action (Figure 25). Blowouts cause the crest of dune ridges to be uneven and sinuous.

The effectiveness of the wind as a transporting and depositing agent is obvious when a windstorm occurs after source regions (sandbars and mudflats) are free of snow but before the snow has disappeared from the tundra surface. The areas downwind from the source regions become discolored, indicating the nature and extent of transport. The area of deposition is triangular, with the degree of discoloration decreasing downwind from the base of the triangle. After one such storm (48 hours of northeast winds at an average of 20 mph), triangular apexes were conspicuous for more than 5 km from the source (Walker 1967).

Small and ephemeral forms are also present. Clumps of vegetation or other small irregularities on bars are usually backed by wind-deposited sediment. In winter, it may be snow; in summer, sand. Such deposits are numerous on the inner edges of bars and frequently represent the beginning of new riverbank dune ridges.

Sediment movement by wind is a highly variable phenomenon on the North Slope; however, when a dry period is accompanied by moderate to strong winds (a frequent

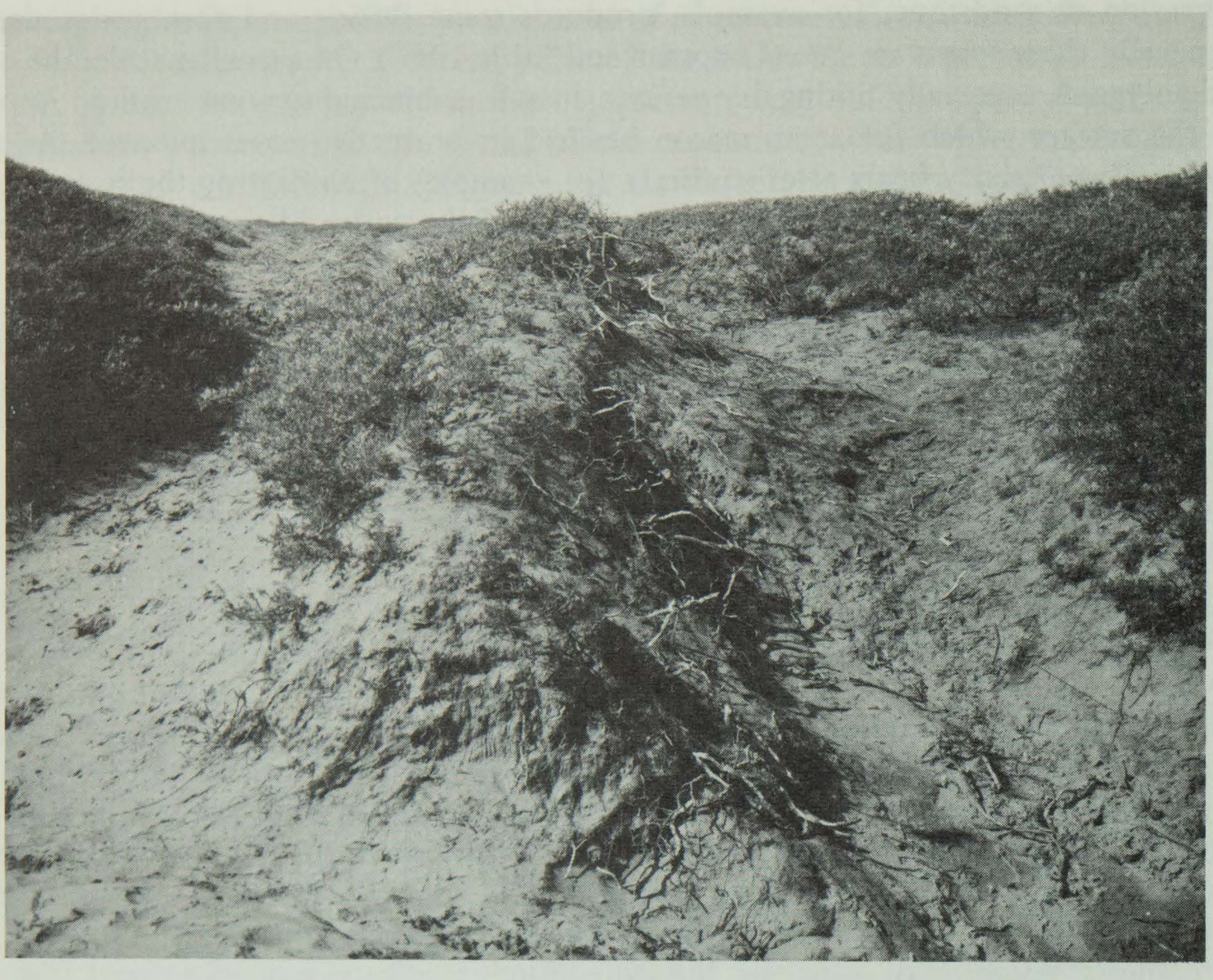


Figure 25. Wind-eroded sand dune.

occurrence during summer), much sand is moved. On larger bars ephemeral forms are common, such as the highly mobile barchans observed in 1971 (Figure 26).

The Coast

The interface between the land and the sea in northern Alaska is complex. It possesses a variety of erosional and depositional forms, and is being modified by a number of processes. The coast extends from Point Hope on the southwest to Demarcation Point at Alaska's border with Canada on the east (Figure 1). Its reported length of 1,750 km varies, depending on the amount of smoothing used in its calculation. At present, values ranging from 1,475 km (CSI 1972*) to 2,100 km (CRREL 1972**) are being used.

From Point Hope to Point Barrow (about 40 percent of thc total length), the coast generally faces northwestward and fronts the Chukchi Sea. At Point Barrow the coastal trend swings about 55° such that the coast, with a slightly east of north orientation, fronts on the Beaufort Sea. The coast is backed by the Coastal Plain except in the west where the Arctic Foothills Province reaches the shore (Figure 1).

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*CSI–Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana.

**CRREL–U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Point Hope, a large cuspate barrier system backed by numerous lagoons, gives way to high steep cliffs which extend north and northeastward to Cape Beaufort (Figure 27A). Although beaches occur along much of this coast, they are generally narrow and coarse textured. The few small barrier bars and lagoons which are present are backed by cliffs (Figure 27B). Stream channels are numerous along the coast and account for beaches and fans where they debouch from the cliffs.

A few kilometers northeast of Cape Beaufort, the shoreline changes to one in which barrier bars and lagoons are the predominant forms. These barrier bars are relatively straight, and the lagoons are generally narrow and shallow. Kasegaluk Lagoon, nearly 200 km long, is joined to the sea by numerous inlets which are normally narrow. The lagoon is backed by a tundra scarp that varies up to 20 m in height.

The section from Icy Cape to Point Barrow consists of two long concave arcs with maximum curvature occurring at their southwesterly ends. This portion of each arc is enclosed by barrier bars that result in broad lagoons which gradually narrow and eventually terminate northward. The nearly straight (northeastern) portion of each arc is backed by low bluffs ranging in height up to 10 m near Wainwright and 25 m southwest of Barrow. These bluffs contain numerous hanging gullies that result in a highly



Figure 26. Barchans on Colville River bar.

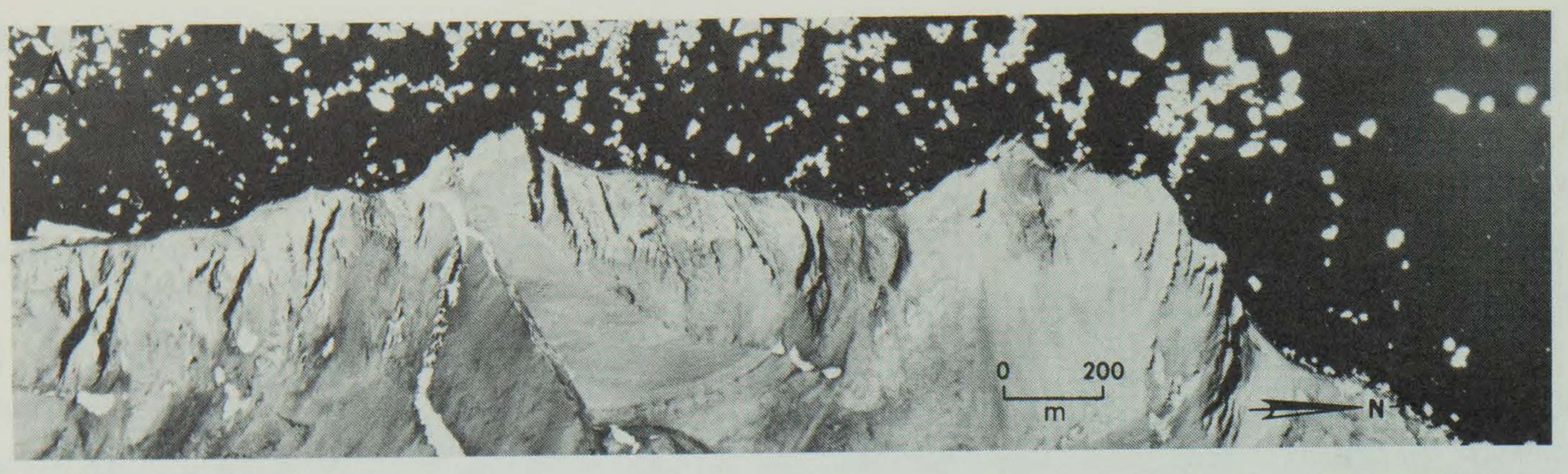


Figure 27. Coastal forms. A. Coastal cliffs at Cape Lisburne. B. Barrier bars near Cape Beaufort: 1. Sea ice. 2. Bar. 3. Lagoonal delta. 4. Tidal inlet. 5. Snow ramp. 6. Gully with remnant snow. C. Oriented lake shoreline: 1. Arctic Ocean. 2. Sea ice. 3. Snow ramp at base of former oriented lake bluff. 4. Drained oriented lake. D. Deltaic coast: 1. Arctic Ocean. 2. Mudflat. 3. Delta distributary. E. Offshore barrier bar: 1. Sea ice. 2. Bar pond.

serrated crest (MacCarthy 1953, and Potter 1971). The beaches along this coast are composed mainly of fine, well-rounded gravel (O'Sullivan *et al.* 1958). (See Figure 28.)

The coastline east of Barrow does not possess the symmetry evident to the southwest. It is characterized by a number of large bays and lagoons. Some have their long axis perpendicular to the coast, whereas others are oriented parallel to the coast. A number of deltas, especially eastward from the Colville River, are also present. Some of the bays and deltas are open to the sea, some are separated from the sea by widely spaced barriers or off-shore islands, and some have rather continuous barrier bars.

From Barrow a series of barrier bars extend southeast to Cape Simpson, separating Elson Lagoon and Dease Inlet from the sea. The lagoon shoreline is quite irregular with bluffs up to 3 m in height. Between Cape Simpson and the Colville delta, the coast is highly indented with bluffs similar to those behind Elson Lagoon. Many of the irregularities are the remnants of truncated oriented lakes (Figure 27C). The Colville delta, a multidistributary delta, is a result of deposition by the largest river of the North Slope (Figure 27D). The seaward edge of the delta consists of broad mudflats upon which algal growth is common (Figure 29).

Eastward from the Colville River to the Canning River, broken barrier bars are present at various distances from the shore (Figure 27E). From the Canning River to Demarcation Point barriers are also present, but they are generally more continuous and closer to shore. All along this coast the rivers are building deltas at their mouths.

Although there is variation in the height of the sea cliff along the coast of the North Slope, 74 percent of the coast has sea cliffs less than 5 m high, with the other 26 percent being less than 2 m (Sellmann *et al.* 1972).

Coastal processes and forms. In the general description of the coastline presented above, the major coastal forms were emphasized. Accompanying these forms are a number of smaller features, some of which are ephemeral. Both types reflect a number of processes and conditions, some of which are unique. Included are relief, structure and permafrost, sediment type, supply and distribution, waves, tides and currents, river discharge, and sea ice.

Ice. The ocean near the coast, like the rest of the water of the North Slope, supports a layer of ice during most of the year. Near shore this ice is bottom-fast and effectively isolates the beach from the sea. Shore modification is minimal for 6 to 9 months of the year. The length of time varies with location and from year to year. Sea ice remains in the Barter Island area about 3 months longer than at Point Hope. Although the immediate shore is protected, the ocean floor seaward of the bottom-fast ice can be modified by pack ice and the keels of associated pressure ridges to depths of over 30 m (Rex 1955). Reimnitz (Personal Communication) reports that side-scan radar records show ice-caused gouges on the sea floor in water depths to at least 60 m.

Sea ice, during the short period of time it is active, operates in several ways to modify the coastline. During the fall, washup from waves freezes as it mixes with beach sediments, and produces ice and gravel ramparts or kaimoo (Greene 1970, and Moore 1966). The spray itself freezes and produces a glaze over the surface (Rex 1964). As freezing continues, sea water freezes to the bottom and produces an ice foot. During this period of freezeup, wave action may be great, and parts of the developing ice foot are frequently broken off and washed up on the beach. Duguid (1971) reports that such an action occasionally produces an ice ramp at the base of shore cliffs up which storm waves can move gravel to heights as much as 10 m.

Some ice shove and transport of sediment by ice thus can occur in the fall (Rex 1964), but it is during and subsequent to the breakup of the shore-fast ice that most

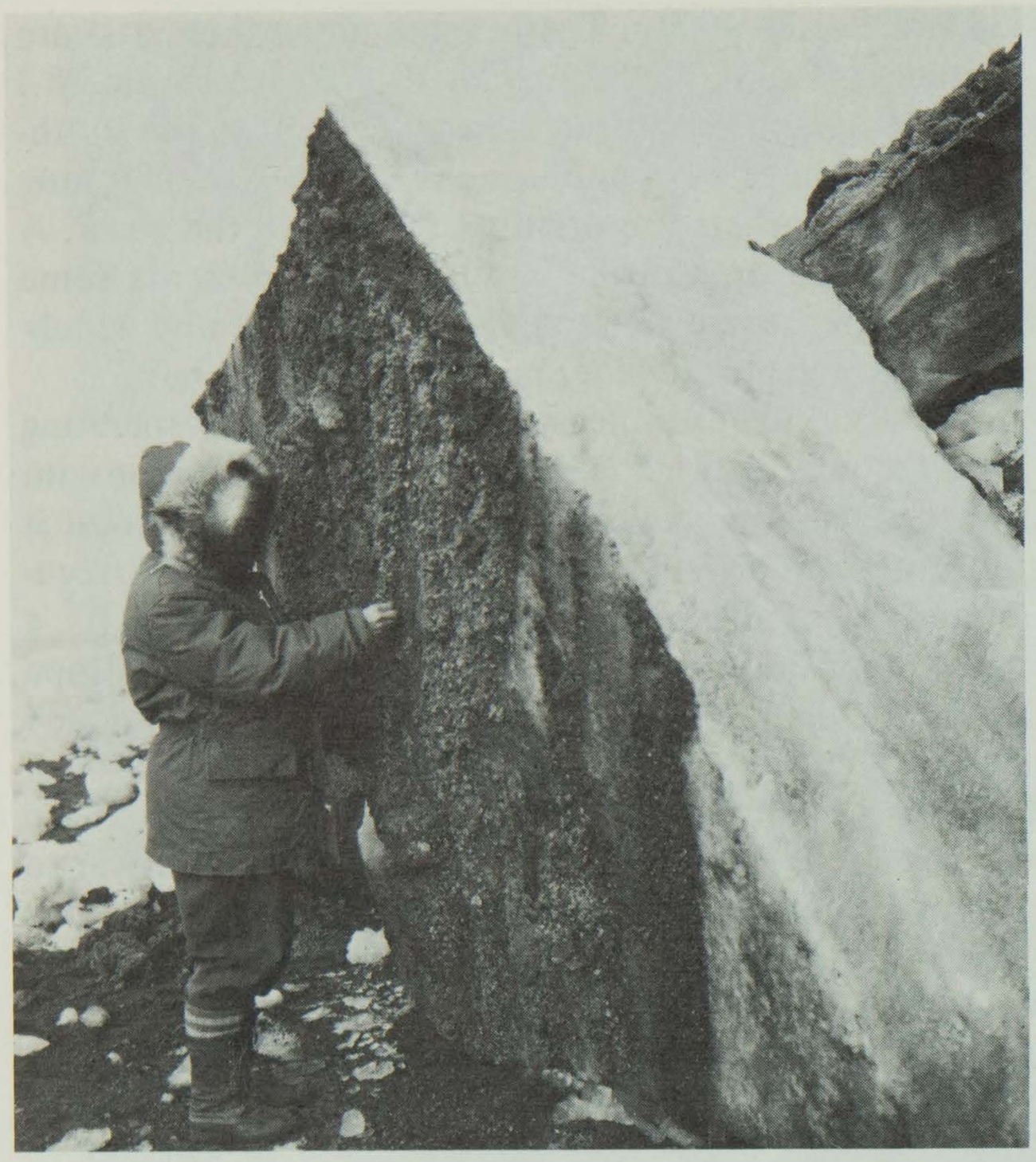


Figure 28. Ice lens along ocean cliff near barrow.



Figure 29. Algal flat on Colville River delta.

ice action occurs. Ice gouges, scrapes, and pushes as it moves onshore. Under the right wind and ice conditions, ice-pushed ridges may be 10 to 12 km long and 4 to 5 m high (Hume and Schalk 1964). Almost all of the coast is subject to ice action throughout the summer, for the pack ice will move to the shore under certain wind regimes. In addition, gravel or other materials frozen to the bottom of the ice may be rafted away (Nichols 1961).

Waves. Ice has other important, although indirect, roles in the morphologic modification of the coast. The presence of ice dampens wave action and alters current direction and force. The farther offshore the pack, the less coastal currents will be modified, but the greater the potential for significant wave action due to increased fetch. In general, the pack remains farther out from the southwest coast than it does from the northeast coast, thus wave action is normally more intense southwest of Barrow.

The significance of storms on beach morphology and beach transport was demonstrated at Barrow on October 3, 1963. It was calculated that this ". . . single storm moved more sediment in a few hours than would normally be transported in 20 years" (Hume and Schalk 1967).

Waves are not only transporting and depositing agents but also are responsible for erosion. Sellmann *et al.* (1972) found that 37.5 percent of the coast could be classified as a wave-erosion coast. These are open-ocean coasts which are in general retreat. They include cliffs in bedrock along the Cape Lisburne coast (Figure 27A) and in unconsolidated permafrost materials along most of the rest of the coast. It is especially in the latter where the most rapid erosion occurs. Wave action at the base of coastal cliffs produces niches comparable to those seen in riverbanks, and collapse associated with ice wedges is common. Such retreat in favored locations may be as much as 10 m a year (Leffingwell 1919, and Lewellen 1970). Even the landward shores of narrow, shallow lagoons are experiencing retreat because of the combination of wave action and thermal erosion (MacCarthy 1953).

Deposition. Sediment transport and deposition result from waves, currents, ice, and river discharge. When rivers carry sediment to the sea, it is either deposited within the area adjacent to the river mouth or transported away. If sediment is not removed as fast at it is supplied, a delta forms. There are a number of deltas along the coast of the North Slope, and they range in size up to 600 km^2 for the Colville River. Many of the deltas are growing rapidly. Most of the annual sediment load is carried seaward during flooding that accompanies river breakup. At the time this flooding occurs, the sea ice is still shore-fast and floodwaters flow out over the ice. Sediment as thick as 15 cm was deposited on the sea ice at the front of the Colville River in 1971. Some of this sediment is removed from the delta during breakup of the sea ice.

How important such loss is to delta growth has yet to be determined (Reimnitz and Bruder 1972, Walker 1970, and Wold *et al.* 1970). Nonetheless, sufficient sediment is deposited at the front of the Colville delta to make it the only section of the coast with a convex offshore profile as indicated by its large hypsometric integral (CSI 1972).

Many rivers and streams drain into lagoons which are generally shallow (Figure 27B). Most lagoons, especially those with few tidal inlets, appear to be filling quite rapidly. Some of these streams are close enough together so that coalescing fans are present at the base of coastal cliffs.

Sedimentation in many lagoons is also caused by oceanic waves and tidal action. Since many barrier bars are quite low, washover is fairly common along some sections

of the coast. Washover fans are conspicuous features on the lagoonal side of barrier bars. In addition, inlets are frequently bordered by spits which recurve into the lagoon and are the focal point for tidal deltas.

The beaches along much of the coast are usually narrow. Many of them consist mainly of gravel, although coarser and finer materials do occur (Rex 1964) and many are well sorted. Moore (1961) found that this sorting occurs primarily during the brief time when waves are changing character. Most of the deposits are derived from the Gubik formation, which fronts the ocean along most of the coast. This heterogeneous formation contains sufficient coarse materials to insure at least a veneer of gravel over most beaches (Black 1964a).

All beaches contain a number of microrelief features. Often, the beach has a rough and hummocky microtopography (Greene 1970) and in some cases is pitted (Nichols 1961). In addition to the ice-push forms mentioned above, sea ice kettles are common as are berms and ridge-and-runnel topographies found elsewhere. Another form observed in great numbers along the Point Lay coast are large (3 m in diameter) holes which are formed by grizzly bears.

Although most barriers are quite low and narrow, some rise above 7 m and extend to 1 km or more in width. Even at the highest levels, which are usually vegetated, there is evidence of storm action. Stranded berms frequently separate the crest from the shoreline (CSI 1972). The largest of these barriers support small sand dunes.

Summary and Conclusions

The landforms of the North Slope are the product of a number of processes operating singly or in combination over varying lengths of time. The time period extends back at least to the Mesozoic when the basic east-west trending structure and the north-facing exposure of the North Slope were established. Subsequent events, especially recent geological glaciation, altered the original surfaces. Erosion and deposition by ice in the southern mountainous portions were accompanied by alternating retreat and advance of the sea over the northern Coastal Plain. Both left their heritage on the landscape.

Today, with North Slope glaciers virtually nonexistent, processes are a mixture of those common to temperate regions, such as running water and wind, and those unique to cold climates. The more universal processes are responsible for major forms; for example, rivers produce flood plains and deltas, wind produces dunes, and ocean waves produce offshore bars and coastal cliffs. These forms, however, usually possess distinctive characteristics because of the short period of time their agents are operative and because of the modifications introduced by cold climate processes.

Until recently such unique forms as ice-wedge polygons, pingos, solifluctional lobes, and thermoerosional niches were considered little more than scientific curiosities. As a result of the recent intensification of interest and activity in the North, knowledge about both form and process has taken on a practical importance little dreamed of before the 1960's.

Although general statements are possible, only in rare instances can details be provided. Some of the details inevitably will be supplied by trial and error in the near future. More important, though, we are on the threshold of a new era, an era in which our knowledge about the morphology of the North Slope will rapidly increase. Indeed, the expansion of the scientific research needed to bring about such an increase in knowledge has already begun.

Acknowledgments

I thank the Arctic Institute of North America for providing me the opportunity of participating in the Symposium at Fairbanks, Alaska in honor of the 25 years that NARL has been involved in improving our understanding of the Arctic. Thanks are also extended to the many scientists whose published research about the North Slope made possible this paper and the summary presented at the Symposium. An attempt was made to interweave descriptions, analyses, and conclusions from these works into the over-all paper without distortion. Apologies are offered for any failure in this regard.

Lastly, I acknowledge with a deep sense of gratitude the faith, encouragement, and support supplied my own field work on the North Slope by many individuals and organizations, especially the Arctic and Geography Programs of the Office of Naval Research, the Naval Arctic Research Laboratory, the Arctic Institute of North America, and at Louisiana State University the College of Arts and Sciences, the Department of Geography and Anthropology, the Coastal Studies Institute, the School of Geoscience, and the Graduate School.

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PEDOLOGIC INVESTIGATIONS IN NORTHERN ALASKA

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Studies relating to the formation, characterization, and distribution of arctic soils were slow to develop in North America. Prior to World War II, there was not a single report on the soils of the North Slope of Alaska, as was largely the case in northern Canada. Studies on soils and related terrain features of northern Alaska were initiated through Boston University during the years 1951-1953. Since 1955, the Office of Naval Research and the Arctic Institute of North America have sponsored pedologic investigations in many sectors of the Alaskan Arctic Slope and the islands of the Canadian Arctic. This report summarizes the main findings of Rutgers University soil investigators since 1953.

Pedologic investigations have been aimed at the problem of processes, characteristics, taxonomy, and distribution of soils. In carrying out these investigations, it has been essential to consider not only conditions in northern Alaska but also those of other polar sectors, particularly northern Canada, Greenland, and northern Eurasia.

The tundra of northern Alaska, if viewed casually, appears as a monotonously wet area in the Arctic Foothills and on the Coastal Plain, with shallow, rocky conditions in the mountains. Closer examination, however, shows a variety of soils in each physiographic province. This report will consider the major soils found in northern Alaska.

Soils of Impeded Drainage

Tundra soil. This is the most common soil of northern Alaska. It tends to mantle most of the flat to undulating landscape north of the Brooks Range. During the period of vital activity, which is about 3 months, the soil thaws to a depth of about 30 cm (Drew *et al.* 1958). The wet conditions, which persist throughout the summer, are produced primarily by seasonal thawing of the soil on the underlying frozen material. Most Tundra soils are silty, with acid conditions predominating. In the areas of limestone rock, however, Tundra soils may be alkaline (Brown and Tedrow 1960, Douglas and Tedrow 1960, and Tedrow *et al.* 1958). It was found that drainage waters from limestone areas have a much higher mineral content than the acid rock areas (Brown *et al.* 1962).

Four major horizons are generally recognized in Tundra soil: the surface organic horizon, the upper mineral soil, the buried organic horizon, and the frozen substrate (Figure 1). Processes in the Tundra soil are qualitatively similar to those found in Gley soils of the northern forests (Tedrow 1970). On sloping ground, however, solifluctional processes are quite active (Figure 2). It became apparent during our investigations that the term *Tundra soil* covered a wide range of conditions and that it might be advisable to recognize an Upland Tundra soil (a Gley soil but usually on sloping land) and a Meadow Tundra soil (a Gley soil usually on areas having flat relief and basins) (Tedrow *et al.* 1958).

In addition to the low-temperature gley process operating in Tundra soil, the origin of the buried organic horizon has been of special interest. The ages of the buried organic matter in northern Alaska cluster around 8,000 to 11,000 B.P. (Douglas 1961; Douglas and Tedrow 1960; Tedrow 1962, 1965, 1966a, 1969, 1972b; and Tedrow and Douglas 1958), but there are exceptions to the above range of dates, especially on the younger landforms where carbon 14 dates are most recent. It is well known that frost action plays an important role in altering the original morphology of the soil, and undoubtedly some of the buried organic matter may have reached its present position through frost action. If this were the case, there would be a suggestion of a past thicker, active layer, which would have necessitated a warmer climate. Pollen spectra of the buried organic material (most of which was identified by Professor P. A. Colinvaux of Ohio Wesleyan University) showed major elements to consist of *Betula, Ericaceae,* and *Cyperceae,* which do not support a major climatic shift.

Frost action in Tundra soil involves displacement and deformation of both mineral and organic horizons (Tedrow 1962). Frost boils and other frost features commonly signify complete disruption of the acquired morphology. When raw mineral material is exposed, as in the case of frost boils (Figure 3), there is greater evaporation from the nonvegetated surface that results in the development of alkaline/saline conditions, including the formation of thenardite (Na_2SO_4) and other salts (Douglas and Tedrow 1960).

Bog soil. The Coastal Plain of Alaska is extensively covered with Bog soils (Tedrow and Brown 1968). In the Arctic Foothills, the Bog soils are confined to stream courses and positions of negative relief. They are as much as 9 m thick, and there may be instances of greater thicknesses. The Bog soil usually consists of a slightly decomposed fibrous peat of mixed plant composition. Most of the peat fabric retains its original identity, but there has been little work done on discovering the actual composition of the peats. Some of the peats are detrital slumps in the narrow valleys of the foothills where they are mixed with silts. Peats are nearly always acid in reaction, but there may be some alkaline conditions in the vicinity of the limestone outcrops and the eastern section of the Coastal Plain where carbonate-bearing eolian material is presently settling out over the landscape. Permafrost is shallow, usually within 30 cm or so of the surface. Where the peats are well drained by headward erosion or in the case of ice mounds or high-centered polygons, the permafrost will be much closer to the surface.

In the case of shallow peats where the thickness ranges from 30 to 60 cm, we have used the term *Half-bog* to describe the soil. Because of the difficulty of making a large number of borings in the frozen material, the accuracy in delineating the Half-bog soils in northern Alaska is uncertain.

Well-drained soils. Prior to the 1950's, the well-drained soils of the Arctic were largely unknown. This was especially true for the North American Arctic. The literature of

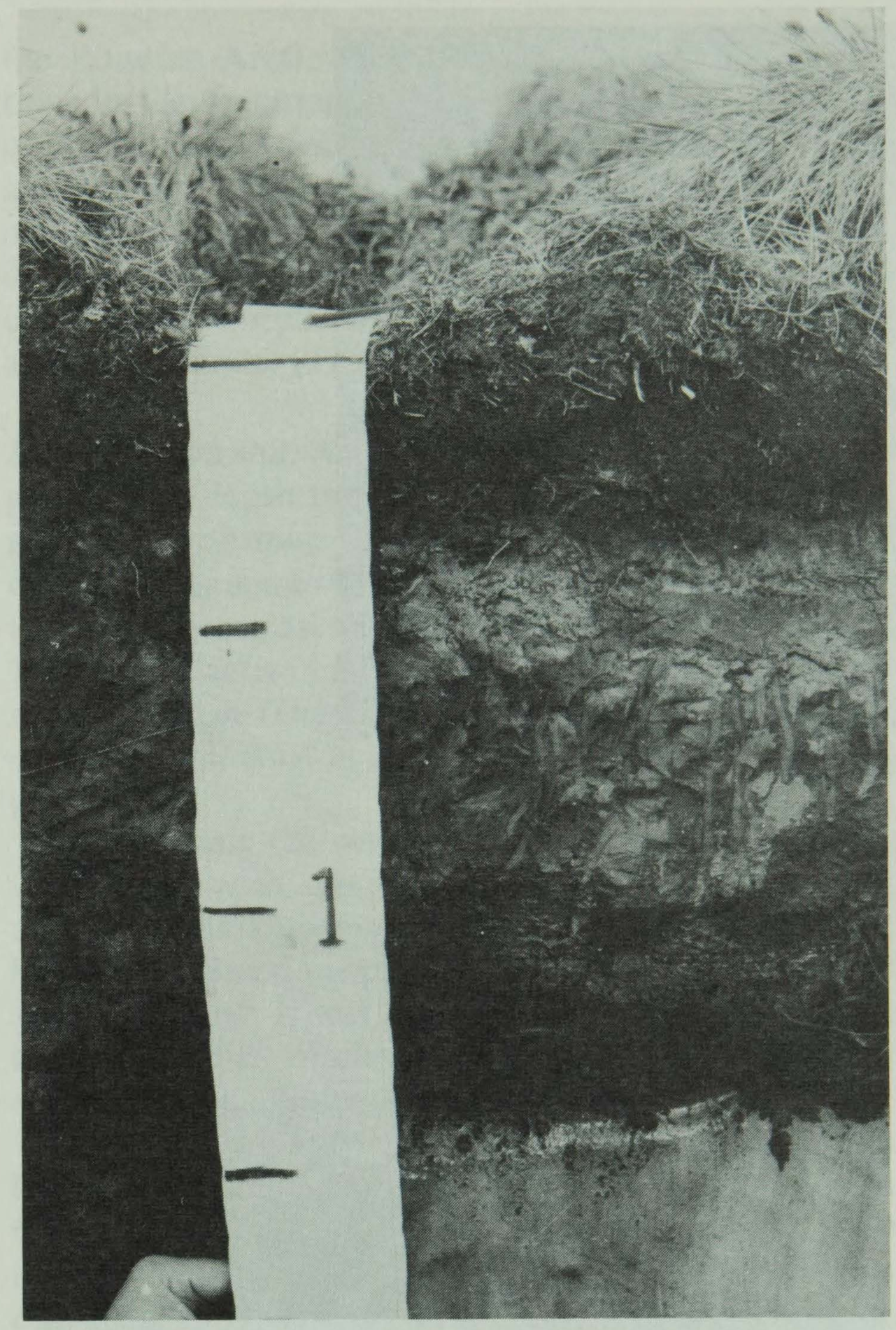


Figure 1. Tundra soil near Umiat Lakes. (The 10- to 15-cm-thick mat is underlain by a silt loam horizon which, in turn, is underlain by a horizon high in organic matter. The lower portion of soil is perennially frozen.)



Figure 2. Solifluctional lobes near Jago River.



Figure 3. Frost boil near Howard Pass. (Salts commonly effloresce on the surface of raw material, but they are not present in the adjacent turf.)

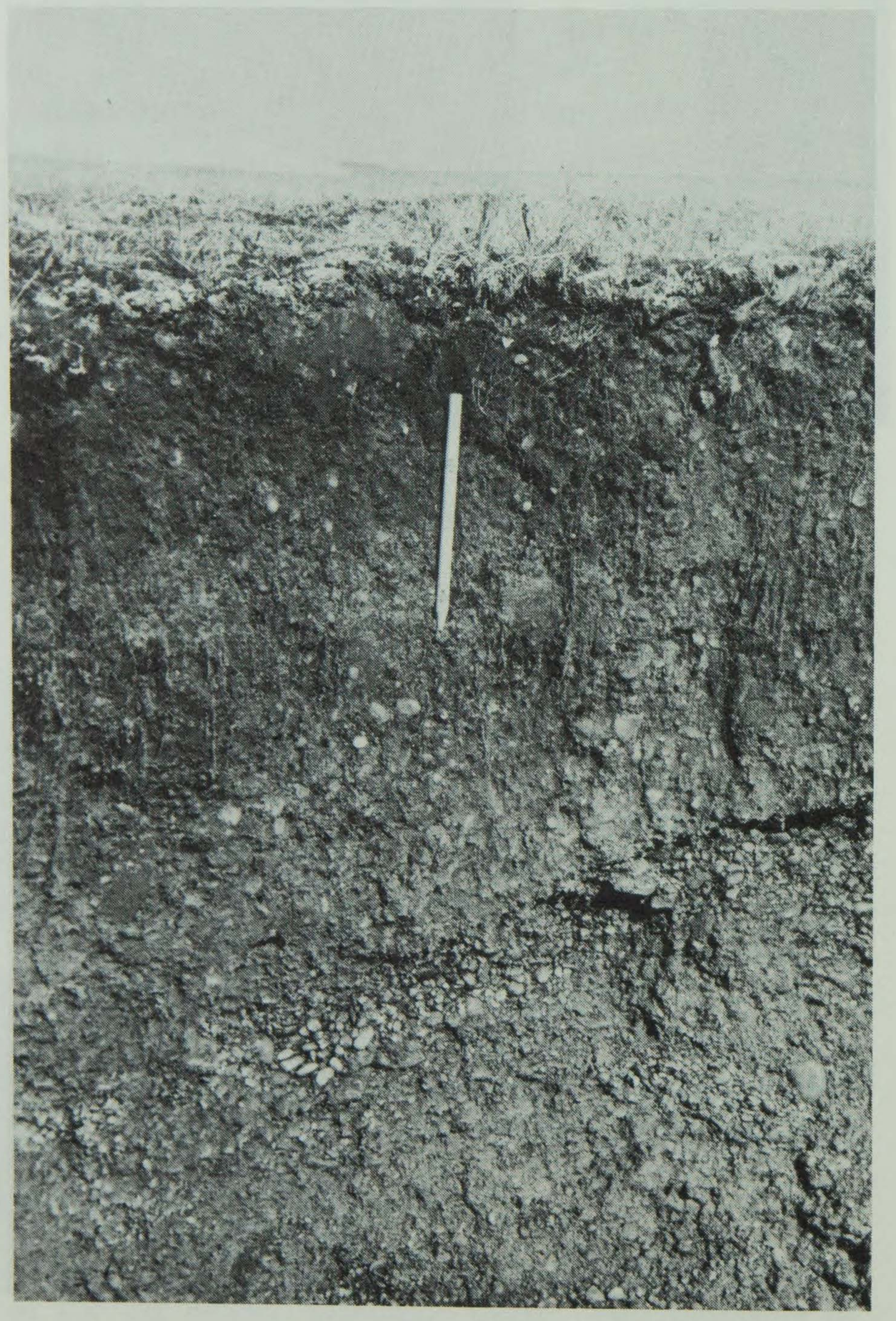


Figure 4. Arctic Brown soil near Point Barrow.

the Eurasian Arctic seldom mentioned well-drained soils, except the skeletal conditions in the mountains and the polar deserts of the High Arctic. With the recognition of Arctic Brown soil in Alaska (Drew 1957, Drew and Tedrow 1957, Hill 1957, Hill and Tedrow 1961, and Tedrow and Hill 1955), a concept was developed whereby one could make comparisons of pedogenic processes between the well-drained and poorly drained sites on a local basis (Tedrow *et al.* 1958) as well as study the problem of comparative morphology between the well-drained sites of the Arctic, the High Arctic, and the Subarctic (Tedrow 1968, and Tedrow and Thompson 1969).

Arctic Brown soil. Arctic Brown soil consists of dark brown loam to sandy loam which grades with depth to a dark yellow-brown color in the B-horizon and finally to a dark gray to gray-brown silt loam in the C-horizon (Figure 4). Arctic Brown soil can be considered as somewhat similar to the well-drained brown-colored soils of the northern forested sectors as well as the alpine regions to the south (Retzer 1965, and Rieger 1966). The active layer is thick in this soil, and summer temperatures of the soil are relatively high (Drew *et al.* 1958). While ice-wedge polygons are usually associated with this soil, frost action does not generally appear to be as active as with most other polar soils.

In studying the pedogenic processes of Arctic Brown soil, a low order of leaching was found, with the surface horizon being quite acid but with alkaline conditions commonly persisting at depth (Drew and Tedrow 1957, Hill 1957, and Tedrow and Hill 1955). Based on pH values, on base saturation, and on the status of reducible iron and manganese, it was concluded that an embryonic podzolic process was operative in this soil. Studies of clay mineralogy showed a 2:1 layer of silicate minerals, with small quantities of kaolinite also being present.

In order to provide some additional information on weathering within Arctic Brown soil, Hill and Tedrow (1961) showed there was iron staining along the fractures and cleavage planes of sand grains, formation of goethite, and alteration of mica minerals in the surface horizons. Also of interest is that feldspar persisted in the clay-size fraction to a size range of about 1 micron. Mikhailov (1961) objectively reviewed our studies but questioned whether Arctic Brown soil could be considered podzolic in character. This will probably be discussed for some time.

Pedologists have long recognized the phenomenon that conditions change with altitude. Termed the *Laws of Vertical Zonality*, the principle was established by V. V. Dokuchaev in Russia in 1899. It is based on the idea that with higher elevations in mountainous country there is a vertical zonality of soils, just as there are changes in climate and biotic spectra. A number of altitudinal traverses were made in the arctic mountains. In the valleys of the Brooks Range, Arctic Brown soil developed a solum up to 46 to 51 cm thick. As temperatures decreased with increasing altitude, there was a gradual decrease in solum thickness. At 1,670 to 1,830 m, there was no longer a developed solum (Tedrow and Brown 1962).

Podzol soils. A latitudinal "gradient of processes" was exemplified in the well-drained terrestrial soils of the North (Tedrow *et al.* 1958). One of the critical zones of the gradient is in the valleys of the Brooks Range, where the well-drained soils show a thin, discontinuous bleached horizon (Figure 5). These soils have been identified from Kurupa Lakes eastward to the Jago River and as far north as the Kogosukruk River.

This problem was studied in depth by Brown (1962, 1966) who found a translocation of iron and manganese within the soil which favored a low-order podzolic process. The problem of correlating degree of soil development with the age of the glacial

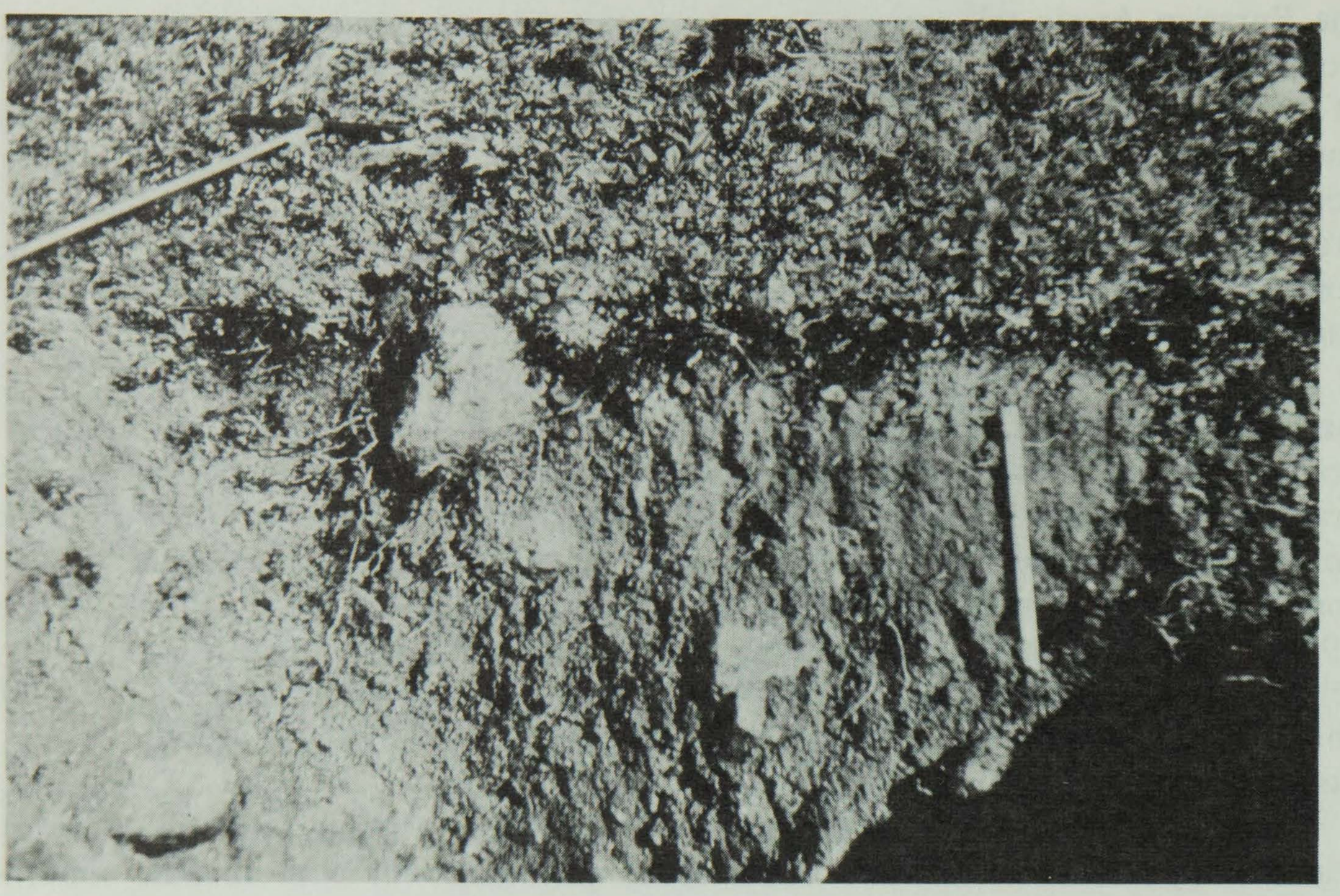


Figure 5. Podzol soil near Jago River. (Photograph by J. Brown)

deposits was also pursued, and it was concluded that within the area studied the nature of the mineral material was more of a controlling factor in soil development than was the age of the glacial deposit (Brown and Tedrow 1964).

Rendzina soils. Rendzina is a well-drained humus carbonate soil whose main distribution is in central, eastern, and southern Europe. Ugolini and Tedrow (1963) found that Rendzina soil forms on the limestone deposits of the Brooks Range. This marks the northernmost point of its known distribution. This soil is alkaline in reaction and is shallow, with limestone fragments usually scattered throughout the profile. Organic matter may reach the 50-percent level. Rendzina soil has now been identified from the eastern Brooks Range to Cape Lisburne and, as would be expected, is associated with Lisburne limestone (Holowaychuck *et al.* 1966, MacNamara 1964, and Ugolini and Tedrow 1963).

Shungite soil. The term *Shungite* comes from Karelia and is used to depict certain geologic as well as pedologic conditions. Shungite denotes a carbonaceous rock as well as an organic-rich soil in which much of the organic matter has been derived from the weathered rock (Toikka 1957). Shungite soils have been identified in a few valleys of the eastern Brooks Range where they consist of well-drained, alkaline peatlike material with poor horizon differentiation (Ugolini *et al.* 1963). The black shale contains about 5-percent organic matter, but the soil itself may have as much as 30- to 40-percent organic matter. By differential thermal techniques it was possible to approximate the source of the organic carbon in the soil.

Grumusol. In the Arctic Foothills are isolated soils formed on bentonite which have been identified as Grumusol (MacNamara and Tedrow 1966). Grumusol is a strongly acid, heavy clay soil rich in montmorillonite which, due to alternating wetting and drying, undergoes considerable mixing. The soil generally consists of a moist, gray plastic clay. Because of the great amount of physical mixing, it does not form well-defined horizons (Figure 6). Recognition of Grumusol in northern Alaska marks the northernmost known extension of this soil.

Ranker. Ranker (carpet) soils consist of a thick fibrous mat over shattered bedrock or boulders (Kubiëna 1952). Virtually no fines are present, and the tough organic mat can be peeled back to expose the underlying network of stones. This condition is commonly found on the steep slopes of the Brooks Range, but it is also present elsewhere, particularly in areas of stone stripes and rock polygons. Conditions are nearly always acid.

Soil and the Landscape

Figure 7 shows the general pattern of soils in relation to landscape elements and depicts the typical site locations in which the more common soils occur. The higher positions, which have good to excessive drainage, generally show a Lithosol-Ranker-Arctic Brown soil complex. In these locations the permafrost is usually deep and of the dry type. In the lower positions permafrost is massive and, being ice cemented, inhibits downward movement of drainage water. This results in great expanses of poor drainage, and accordingly Tundra and Bog soils are present.



Figure 6. Grumusol near Umiat.

lemmings and their occurrence in all habitats not temporarily under melt water; (2) extensive evidence of winter cutting (meaning virtually 100 percent by any sampling procedure which checks for presence or absence of cutting on plots of, say, 0.1 m^2); and (3) presence of predators, including jaegers at ceiling or near-ceiling breeding densities, breeding owls, and weasels.

Basically, several unusual weather events appear to have triggered and sustained the observed sequence and to have acted in concert in setting back the normal timing of cyclic events. For example, a persistent regional storm in June 1965 lasted, with some fluctuations, from the 5th to the 19th. Some fresh snow combined with blown drift snow coated the tundra, and radiation near and at the ground turned this snow cover locally into a thin ice shelf over the vegetation that lasted for days. For 10 of the 14 days, persistent easterly winds averaged more than 15 mph, and for 2 days more than 25 mph (U.S. Weather Service 1965). As late as the 18th, pilots reported continuous snow cover up to 95 km south of Barrow. Lemmings were abundant but mostly inaccessible to avian predators. The result was a chaotic interval for jaegers, since the breeding population would normally have stabilized and nesting would have been well under way. Pairs which settled before the storm gave up territories by the 9th, and significant resettlement did not begin until the 17th. The result was densities of nesting jaegers below earlier peak years, with only local areas reaching the 20-pair-per-1.6-km^2 ceiling. Nests failed progressively through July, and by late August only a few young fledged. Production of fledged young from eggs laid was not the virtual total failure of 1956, but it was certainly less than 10 percent. Snowy owl production (in terms of young fledged per nest started) was also poor, but nevertheless it was better than that of jaegers. Least weasels were present during the summer and into the postpeak winter.

One general point, then, is that the impact of avian predators on the lemming population was not the organized, progressive exploitation of normal peak summers. In the latter, even if exploitation weakens slightly or slowly as scattered pairs fail and desert, there remains an over-all pattern of more or less consistently dispersed pairs expanding hunting areas as neighbors desert. In 1965, the dispersion was irregular. The result, I believe, is that the lemming population survived in local patches or pockets, and then entered the postpeak winter in higher densities than in more normal peaks.

In 1966, the number of lemmings was low (Table 1), but not so low as in normal posthigh years. Moreover, lemmings were dispersed through favorable habitat (polygonal areas), and at the end of summer there was even a suggestion of a slight recovery in numbers. No weasels were seen. In 1967 and 1968, lemming numbers were up, and both species of weasels were present. In 1967, least weasels in some local areas were encountered with surprising frequency. In 1969, both weasel species were present in exceptional numbers, and there was abundant evidence of heavy overwinter predation on lemmings.

By the end of the 1968 summer, the number of lemmings caught had increased, but not to the degree typical of prehigh summers. Still, it appeared the increase would continue. Of 15 juvenile and subadult females from the mid-August run of traplines, 13 were pregnant; and a large sample taken near Barrow on September 18-19 was heavily dominated by juveniles born in late August and early September (106 in a sample of 142). As shown in Figure 3, and based on evidence just mentioned and on the incidence of winter nests in June 1969, the population began an increase in the 1968-69 winter, but to what level it progressed is not known. A peculiar freezeup condition apparently occurred. Some sort of ice mesh at the ground surface forced lemmings to forage along runway edges rather than feed laterally at will under a snow

years observed in 1968 were noted above. Then, in winter 1968-69, there occurred a numerical blip of unknown magnitude. Neither body growth nor reproductive rates were typical of peak years. Because of sustained predation by weasels and because of reduced access to winter food by undersnow conditions, any potential for a high was expressed neither in numbers nor in other characteristics correlated with conditions of peak winters. Consequently, to call 1968-1969 a peak year requires that one redefine peak year with criteria other than those given above. From the standpoint of impact on tundra vegetation and all related consequences of lemming grazing, 1968-1969 was not a peak year.

As though the exceptional sequence through 1970 were not enough of a lesson, the 1971 summer exploded with vegetation still in superb condition, but with brown lemming numbers as high as in the best peak years and with collared lemmings more numerous than ever before experienced at NARL. First we have the fact of scarcity of brown lemmings throughout the 1970 summer. Then, in June 1971, we observe the good condition of overwintering vegetation, the scarcity of winter nests, the paucity of young brown lemmings, and the low incidence of recent reproduction in females. All these facts in combination indicate that the bulk of the brown lemmings present near Barrow in June had immigrated. From where we do not know. Avian predators nested in densities below peak summers, but above the highest known in a prepeak summer (1952). Prey numbers were markedly depressed by midsummer, and many jaegers deserted. Cover for lemmings was excellent continually.

By late summer a recovery in the brown lemming population had begun. Throughout this time no weasels were seen, though in July a single sign of recent weasel predation was reported from the drained bed of Footprint Lake. By the end of the summer, the overall grazing impact on vegetation was not at all what early numbers of trapped lemmings might have promised, and indeed the excellent condition of the standing crop (and especially the extent of flowering of various grasses and forbs in August) indicated that the overwinter vegetation matrix would again be favorable for lemmings.

Notwithstanding this state of affairs at the close of the 1971 summer, the population in June 1972 was no more than about one-sixth to one-seventh that of the prior June. In fact, it was lower than that of late August 1971. At least two factors for this decline can be recognized. First, the snow cover in the 1971-72 winter was about two-thirds of average (Lewellen, Personal Communication); the pattern of overwinter cutting of vegetation observed in the 1972 summer reflected the effect of a subaverage snow mantle by patchy and localized lemming foraging and by the low number of winter nests. Second, arctic foxes were common in the fall and early winter of 1971 (Underwood, Personal Communication). Prior to the onset of trapping by Eskimos on December 1, foxes no doubt preyed on lemmings (see also Mullen and Pitelka 1972). Weasels, the other important winter predator, were absent.

Since 1965, then, the Barrow population of brown lemmings has not repeated the generally consistent sequence of cyclic events witnessed from 1949 to 1965. Indeed, the population has fluctuated at low density levels for 7 years, except for the high numbers present in 1971, which does not constitute a cyclic peak in the strict sense for reasons already summarized above. By 1972, 7 years had elapsed since the combination of features typical of cyclic highs had last been witnessed; and more particularly, it had been 7 years since the last strong pulse of dead plant matter was added to top soil by lemming grazing.

The recent experience at Barrow clearly raises questions as to whether the nutrient-recovery hypothesis (Pitelka 1964, and Schultz 1964) adequately explains



Figure 8. Bog soil in a water-saturated environment near Umiat Lakes.



Figure 9. Bog soil near Okpilak River. (Ice wedges have thawed, leaving organic pillars in well-drained condition.)

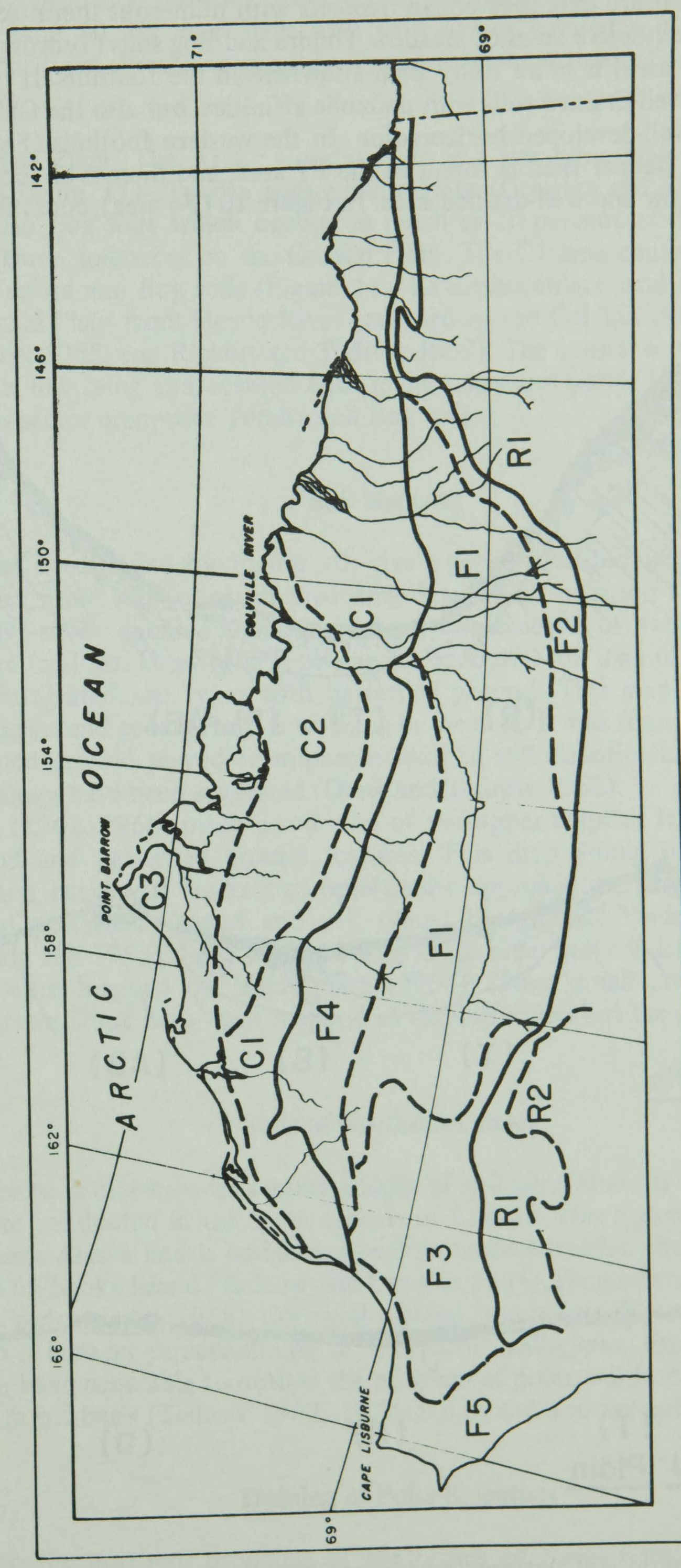


Figure 10. Map of northern Alaska showing regional soil patterns.

Just south of Umiat are extensive eolian deposits with numerous thermokarst depressions, resulting in extensive areas of Meadow Tundra and Bog soils (Tedrow 1969).

Figure 10 (F2 area) is more stony than elsewhere in the foothills. It is characterized not only by well-drained soils with podzolic affinities, but also the Gley soils here frequently show well-developed horizonation. In the western foothills (Figure 10, F3 area), the relief is steeper than is found in the F1 area, and there is an increase in the percentage of shallow and well-drained soils. In Figure 10 (F4 area), conditions become

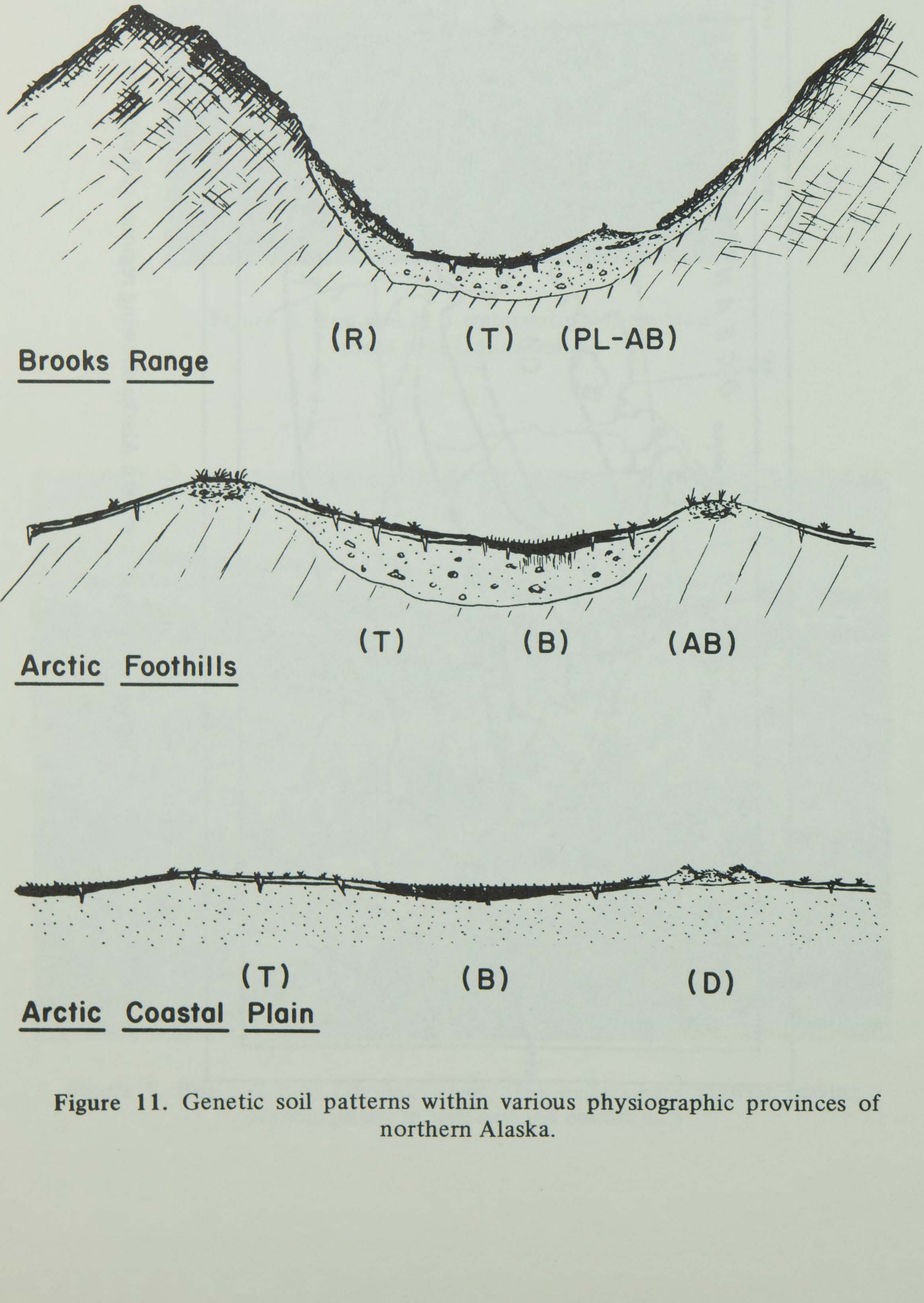


Figure 11. Genetic soil patterns within various physiographic provinces of northern Alaska.

more sandy, probably resulting from eolian deposits. The western margins of the foothills (Figure 10, F5 area) have soils with darker colored sola which may result from the maritime climate or possibly from greater quantities of montmorillonite in the soil clays.

Arctic Coastal Plain. The Arctic Coastal Plain is a low-lying area of unconsolidated sediments (Figure 11). Tundra soils predominate (Douglas and Tedrow 1960), but there are also Bog soils which occupy as much as 20 percent of the area. Figure 10 shows the three soil areas on the Coastal Plain. The C1 area contains fine sands and silts with Tundra and Bog soils (Figure 11). Extensive eolian sand deposits are found on the Coastal Plain from Meade River eastward to the Colville delta (Figure 10, C2 area) (Rickert 1965, and Rickert and Tedrow 1967). The coastal section in the vicinity of Barrow is low lying and covered with many lakes and ponds (Figure 10, C3 area). Most of this sector comprises Tundra and Bog soils.

Soil Mapping

Maps, as exemplified by Figure 10, give a generalized picture of soil conditions, but they are more important for recording detailed information in certain localities. Accordingly, more detailed maps have been constructed of various sectors of the Alaskan Arctic Slope. Drew (1957) prepared a 1:20,000 soil map of the Barrow area in which he integrated soil types with patterned ground. This map has been useful to many biologists and geocryologists working in the area. It was found that the nature of the patterned ground played an important part in soil classification, and accordingly some guidelines have been suggested (Drew and Tedrow 1962).

Brown (1962, 1966) made a soil map of the upper Okpilak River area which also showed soil and patterned ground features. This map should receive much future consideration because it marks a comprehensive approach at tying together the complexities of patterned ground and soil types. The Special Umiat Quadrangle Map (Tedrow and Hill 1954) shows some 10 soils in the area. Soil conditions in the Howard Pass area were mapped by MacNamara (1964). Other small areas throughout the Alaskan Arctic Slope have been mapped at varying scales, but the maps have not been published.

Soils of Northern Canada

In order to gain a broader understanding of soil conditions in other polar regions, studies were conducted in the arctic islands of Canada. This region is cooler and drier than northern Alaska and is designated as a polar desert rather than a tundra. Studies were made on Banks Island (Tedrow and Douglas 1964), Prince Patrick Island (Tedrow 1966, and Tedrow *et al.* 1968), Cornwallis Island, and others. These studies enabled us to develop a broader understanding of the arctic landscapes. From these and other studies, we have been able to outline the problem of polar soil formation and distribution on a global basis (Tedrow 1968, 1972a,b,c,d; and Tedrow and Thompson 1969).

Training of Polar Scientists

Prior to the northern programs of the Office of Naval Research and the Arctic Institute of North America, there probably was not a single pedologist in the United

States who considered himself as having a working knowledge of polar soils. It has been my good fortune to work with a dedicated group of young men at Rutgers University over the years in the problems of the Arctic and, later, of the Antarctic. Some of these men have continued in polar investigations and are now directing their own programs. I refer to J. V. Drew (Ph.D. 1957); D. E. Hill (Ph.D 1957); L. A. Douglas (Ph.D. 1961); J. Brown (Ph.D. 1962); E. E. MacNamara (Ph.D. 1964); H. Harries (Ph.D. 1965); D. A. Rickert (M.Sc. 1965); F. C. Ugolini (post doctoral 1961-1962); and G. F. Walton (Ph.D. 1972).

Other Pedologic Studies in Northern Alaska

This short review highlights the Alaskan soil work carried out by Rutgers University investigators. It is important to note that other pedologic investigations have been conducted in northern Alaska. I refer specifically to the activities of Holowaychuk *et al.* (1966) of Ohio State University who worked at Cape Thompson. Also, J. Brown of the Cold Regions Research and Engineering Laboratory at Hanover, New Hampshire has been working in northern Alaska for many years and has established an outstanding record of achievement in pedologic studies.

Acknowledgments

This work was sponsored by the Arctic Institute of North America with the approval and financial support of the Office of Naval Research under Contract N00014-70-A-0219-0001 (Subcontract ONR-402).

This is a paper of the Journal Series of the New Jersey Agricultural Experiment Station, Rutgers University, New Brunswick, New Jersey 08903.

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MICROMETEOROLOGICAL INVESTIGATIONS NEAR THE TUNDRA SURFACE

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Micrometeorology and microclimatology are concerned with the surface boundary layer of the atmosphere that extends from the ground to about 50 m (Munn 1966). This layer interacts dynamically with the underlying surface and with the atmosphere above. The terms micrometeorology and microclimatology have been applied synonymously to research carried out in arctic regions, where problems of heat transfer, energy, momentum, and mass have been cast almost simultaneously with questions concerning temporal and secular changes in the local climatology.

In commemoration of the 25th Anniversary of the Naval Arctic Research Laboratory, this paper documents the micrometeorological research carried out in cooperation with the Laboratory under the support of various agencies and institutions. The discussion pertains only to research accomplished on the tundra, its lakes, and its estuaries. The air-sea ice interface is not considered; it is, however, a subject of special interest to many meteorologists (Fletcher 1966, Hare 1968, and Untersteiner 1964).

Until the establishment of NARL, little was known about the microclimate of the tundra. In fact, only within the past two decades has a general understanding of polar meteorology and atmospheric circulation come into existence (Hare 1968, and Reed and Kunkel 1960).

Early projects at NARL set the stage for an investigation into the nature of the arctic climate near the ground, where most biological and geomorphic processes take place. There was not much existing knowledge to draw upon, since previous explorations were made primarily from ships whose personnel kept infrequent records of the near-surface polar maritime climate. The observations of U.S. Army Lt. P. H. Ray (1885) from 1881 to 1883 during the International Polar Year are probably the only readily available weather records of that century for Barrow. Until the 1950's, most meteorological investigations were routine weather observations used for general forecasting. Any information on the far northern latitudes is nonetheless valuable for long-term comparison.

Not until the 1950's was an organized attempt made to investigate the near-ground atmospheric environment over the Alaskan North Slope. This interest was undoubtedly stimulated by earlier U.S. Naval Petroleum Reserve (PET 4) explorations and by U.S. Air Force Distant Early Warning station activities.

During 1952, general climatological investigations were begun near Umiat on the Colville River. Similar studies were started the following year near Barrow. These studies were conducted by the Boston University Physical Research Laboratories under contract with the U.S. Air Force (Conover 1960). The quantitative results concerning a little-known part of the Arctic were published as part of the U.S. Army Quartermaster Research and Engineering Command series in microclimatology for use by scientists throughout the Department of Defense. Measurements of windspeeds, temperatures above and below the ground surface, and depth of thaw profiles were made near the Arctic Ocean coast, on Colville River valley slopes, and in the Brooks Range foothills. These measurements were aided by automatic recording equipment more advanced than any previously used in the field.

The Laboratory for Climatology of the Drexel Institute of Technology had been engaged for many years in a basic study of heat and moisture exchange between the earth and the atmosphere. Investigations included microclimatic observations of temperature, moisture, and wind at various levels in the air layer near the ground; precipitation; heat and moisture distribution in the soil; evapotranspiration from the soil; and solar and net radiation. These studies constituted two related programs of work. First, it was necessary to design or adapt instruments to measure the small differences in climatic factors that exist within short vertical or horizontal distances. Most meteorological instruments at that time did not possess sufficient precision. Second, once the observations were made, it was necessary to analyze the data to determine the microclimatic conditions and the reasons for their fluctuation.

Although these studies were conducted in temperate climates, their application was extended to other regions. Work in arctic climates began at NARL on June 19, 1956, with support from the Arctic Institute of North America and the Office of Naval Research (Mather and Thornthwaite 1958). Field observations were terminated in 1958. From detailed monitoring over 24-hour periods and from routine observations, it was possible to estimate the daily and seasonal microprocesses of heat balance under arctic conditions. Much work remained, however, on improving instrumentation, on recording data over longer periods, and on extending observations to other arctic locations.

By the end of 1958, several long-term micrometeorological programs for arctic regions were being planned. In 1957, the U.S. Atomic Energy Commission had established the Plowshare Program at Cape Thompson (Wilimovsky and Wolfe 1966). Included was a meteorological project set up during August 1959 in the Ogotoruk Valley at Cape Thompson to evaluate ecological differences and changes in terms of meteorological variables and to discern annual climatological variations. Observations continued for 2 years and provided baseline information on ridge and valley microclimates.

At about the same time, the Department of Meteorology at the University of Washington began a program at Barrow that came to encompass perhaps the longest period of meteorological research on the tundra. Department Chairman Dr. P. E. Church (Personal Communication) and his staff were interested in lower layer interactions between the ground surface and the atmosphere. By 1953, the Department was studying the meteorology of glaciers. During the International Geophysical Year (1958), the Department was investigating the meteorology of sea ice, and the Geography Branch of ONR continued to support this program for several years after the IGY. In fact, the Director of NARL (Dr. Max Brewer) requested that micrometeorological work be extended to the Alaskan Arctic, and in 1959 ONR responded by supporting a program at Barrow for the investigation of thermal gradients and solar radiation.

Meanwhile, the University of Washington's study at Barrow continued to expand, and in 1961 it included work in atmospheric chemistry. During IGY, the importance of carbon dioxide to the atmospheric heat budget led to the suspicion that this gas was increasing in the atmosphere and that possibly a "greenhouse" effect was operating (Callendar 1941) due to an increase in consumption of fossil fuels. In 1962, a chemical micrometeorological program was begun to obtain an accurate documentation of atmospheric carbon dioxide content and its variations (Kelley 1969). This program was associated with two other programs—one at Mauna Loa, Hawaii and the other at Amundsen-Scott Station, Antarctica (Brown and Keeling 1965, and Pales and Keeling 1965). In 1965, a long-term investigation of near-surface ozone was established (Kelley 1970).

During the early 1960's, the character and emphasis of micrometeorological investigations changed from routine measurements of a few meteorological parameters in isolated areas to cooperative interdisciplinary research of the general environment. Research thus focused on understanding the effect of the microclimate on the near-surface environment. By 1962, the U.S. Army Cold Regions Research and Engineering Laboratory had established an intense, long-term microenvironmental investigation at Barrow (Brown and Johnson 1965).

As the scope of work at NARL expanded, scientists needed more microclimatic information. Investigations into photosynthesis and respiration demanded accurate data on solar radiative components. Evaluation of mass exchanges, such as carbon dioxide, water vapor, and momentum transfer, required high-precision wind and temperature gradient measurements. Investigators in nearly all disciplines desired information not only on the near-surface climate but also on the subnivean microclimate (Benson 1969, Trabant *et al.* 1970, and Weller and Cubley 1972).

With the advent of the International Biological Program (IBP), a tundra biome project was planned in late 1968 with support from the National Science Foundation, from the Department of Defense, and from private industry. For the first time in NARL's history, many disciplines were represented in a coordinated experimental program. Micrometeorological investigations were represented in the abiotic part of the program (Trabant *et al.* 1970, and Weller and Cubley 1972).

Beginning in 1969, NARL provided logistic support for the heat and mass balance study of an NSF-funded program on McCall Glacier by the Geophysical Institute of the University of Alaska (Benson *et al.* 1970). McCall Glacier forms the northern terminus of the north-south chain of International Hydrological Decade glaciers, and it is the only arctic ice field under study in the United States.

Future micrometeorological research at sites on the tundra and taiga may not require large integrated programs. Present information on the near-surface microclimate, however, is still sparse despite the efforts of IBP and previous research projects. Most research on tundra microclimate has been accomplished within only a few kilometers of the coastline of the Arctic Ocean. This region, under the influence of polar maritime conditions, may not adequately reflect the near-surface climate of the Alaskan North Slope in general.

Much of the early near-surface meteorological data for the Alaskan North Slope provides a useful archive of various meteorological phenomena. During 1957 and 1958, the Drexel Institute of Technology program successfully estimated the components of heat flux in the Barrow vicinity (Mather and Thornthwaite 1958). Characteristic of the Arctic, the number of days suitable for instrumental observations varied from month to month, resulting in certain deviations from a smooth seasonal pattern of change that might be expected (Table 1). In both years of the study, the convective heat flux

reached an average maximum of 592 J per cm^2 per day in July; the minimum convective heat flux was −159 J per cm^2 per day in January. From October through February, generally negative values of convective heat flux occurred, due to a lack of solar radiation and to cold surface temperatures.

Instrumental difficulties associated with moisture measurements interfered with the winter efforts of the Drexel group, and no measurements of evaporative heat flux were recorded for this period. The soil heat flux was small and ranged from 184 J per cm^2 per day in June to −105 J per cm^2 per day in November. A positive flow from late April through August indicated a downward flux of heat into the soil, while an upward flow of heat from the soil to the air occurred from September through late April.

During its program at NARL, the Department of Meteorology of the University of Washington investigated micrometeorological phenomena over the sea ice of Elson Lagoon. Freely connected to the Arctic Ocean, this lagoon covers 250 km^2 and has an

Table 1. Average daily heat balance near Point Barrow for 1957-1958 (calories* cm^{-2} day^{-1}).[1]

1957	June	July	Aug	Sept	Oct	Nov	Dec
Convective heat flux	100	141	84	27	−5	−16	−22
	(14)	(31)	(30)	(28)	(23)	(15)	(16)
Evaporative heat flux	56	110	92	37	4	0	[2]0
	(8)	(22)	(23)	(23)	(22)	(12)	
Soil heat flux	14	4	2	−6	−19	−25	−24
	(3)	(31)	(31)	(30)	(31)	(27)	(16)
Total flux[3]	212	268	183	59	−19	−35	−40
	(3)	(22)	(23)	(23)	(21)	(16)	(9)
Net radiation	285	275	166	37	−8	−68	−62
	(6)	(29)	(31)	(30)	(31)	(30)	(31)

1958	Jan	Feb	Mar	Apr	May	June	July	Aug
Convective heat flux	−38	−13	16	32	33	70	158	96
	(2)	(10)	(23)	(17)	(16)	(27)	(29)	(28)
Evaporative heat flux	[2]0	[2]0	[2]0	[2]0	3	35	56	51
					(3)	(10)	(25)	(22)
Soil heat flux	....	−7	−4	0	8	44	40	30
		(28)	(31)	(23)	(31)	(28)	(28)	(24)
Total flux[3]	....	−20	10	41	41	192	260	174
		(10)	(23)	(14)	(16)	(10)	(21)	(19)
Net radiation	−45	−72	−45	−41	64	294	300	150
	(31)	(18)	(27)	(27)	(29)	(6)	(30)	(28)

*1 Joule/cm^2 = 0.239 cal cm^{-2}

[1] Mather and Thornthwaite (1958).

[2] Estimated.

[3] Total daily flux is the sum of the convective, evaporative, and soil heat flux averaged only for those days on which observations of all three fluxes were obtained. It is not the sum of the average of the three fluxes given above.

( ) Number of observations.

average depth of 2 to 3 m. Observations were first made at Eluitkak Pass and later at Niksiruk (Figure 1), where a small gravel spit juts into the lagoon. Studies at this location lasted until the station was destroyed by a storm in October 1963 (Kelley *et al.* 1964, and Lieske 1965).

During this period continuous climatological data were collected for global short-wave radiation, for reflected short-wave radiation over sea and land, for net radiation over sea and land, and for albedo over sea and land. Measurements of net radiation with an accuracy of 6 percent were made by means of a frequently calibrated Suomi ventilated radiometer (Kelley *et al.* 1964). A time cross section of thermocouple ice temperature data from March to June showed the ice at the 50-cm depth reached -10°C about mid-March, with warming of the ice occurring chiefly during May. Since the entire ice mass was near the melting point by June 1, the high values of net total radiation in June (14.85 kJ per cm^2 in 1962, and 17.57 kJ per cm^2 in 1963) were available for phase transformation.

In a series of experiments conducted on the coastal sea ice near Niksiruk (Badgley 1966), measurements were made of the heat and moisture picked up by air flowing over an open water surface. A semicircular artificial pond of continuously replaced salt water was constructed. Air flowed in a trajectory of 20 m over the -1.7°C water, and was warmed and moistened to a height of 2 to 4 m. The temperature varied from 27°C at the surface to 0°C at the top of the modified layer. The average temperature during the test period indicated a heat flux of 76.2 kJ per cm^2 per month. The average moisture flux was equivalent to a latent heat flux of 12.6 kJ per cm^2 per month.

After a storm in 1963 destroyed the Niksiruk site, all micrometeorological activities were moved inland from the Arctic Ocean to North Meadow Lake (Figure 2), where measurements were made until termination of the program in October 1967. Studies included an investigation of the vertical flux divergence of net long-wave radiation in the atmosphere (Lieske and Stroschein 1967). Radiative divergence in the atmosphere had been identified as a causative factor in temperature changes and fog (Fleagle 1953) as well as in stratus formation (Koshelenko 1960). If clouds and aerosols are absent, radiative divergence can be calculated by several methods, provided the air temperature profile, surface temperature, optical depths of the principal radiating gases (CO_2 and H_2O), and the flux emissivities of these gases are known. Measurements at North Meadow Lake were made from a moored Kytoon containing a gimbal-mounted net radiometer which monitored to 250 m above the tundra surface and from an adjustable boom tower that could be automatically adjusted to pause for 2-minute intervals at each of the first 5 m above the snow surface. Six Kytoon flights, each lasting from 2 to 3 hours, were made in temperatures from -5° to 5°C, and about 80 hours of data in the -4° to -30°C range were recorded by the boom tower.

Net radiation profiles over snow through the first 5 m of the surface inversion indicated that radiative convergence was a usual condition leading to radiative warming. Heating rates of 5°C per hour were obtained, and radiative divergences noted between 20 and 200 m were smaller than those measured between 1 and 5 m. A certain disparity between calculated and measured values was evident, but the calculated divergences tended to indicate radiative cooling whereas actual measurements showed radiative warming. Refinement of humidity measurements would then be necessary to confirm any real disparity between calculated and observed divergences.

During the research at North Meadow Lake, physical processes of the near-surface microenvironment were investigated. During 1965 and 1966, tundra and atmospheric surface temperatures were monitored hourly at 16 cm below the tundra surface, within the layer of vegetation and snow, and at 300 cm above the ground (Table 2).

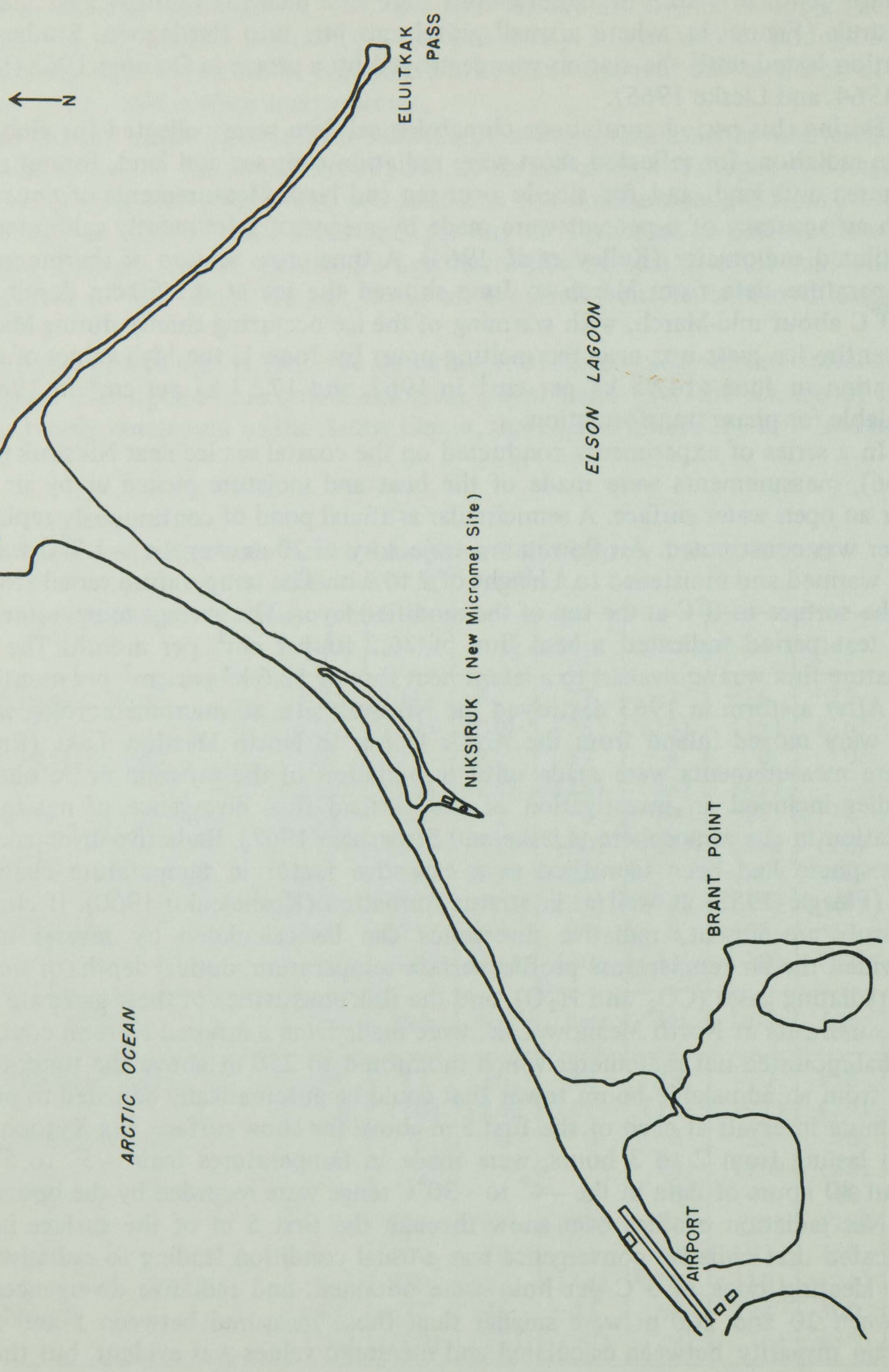


Figure 1. Map showing University of Washington's micrometeorological research sites for 1959-1963.

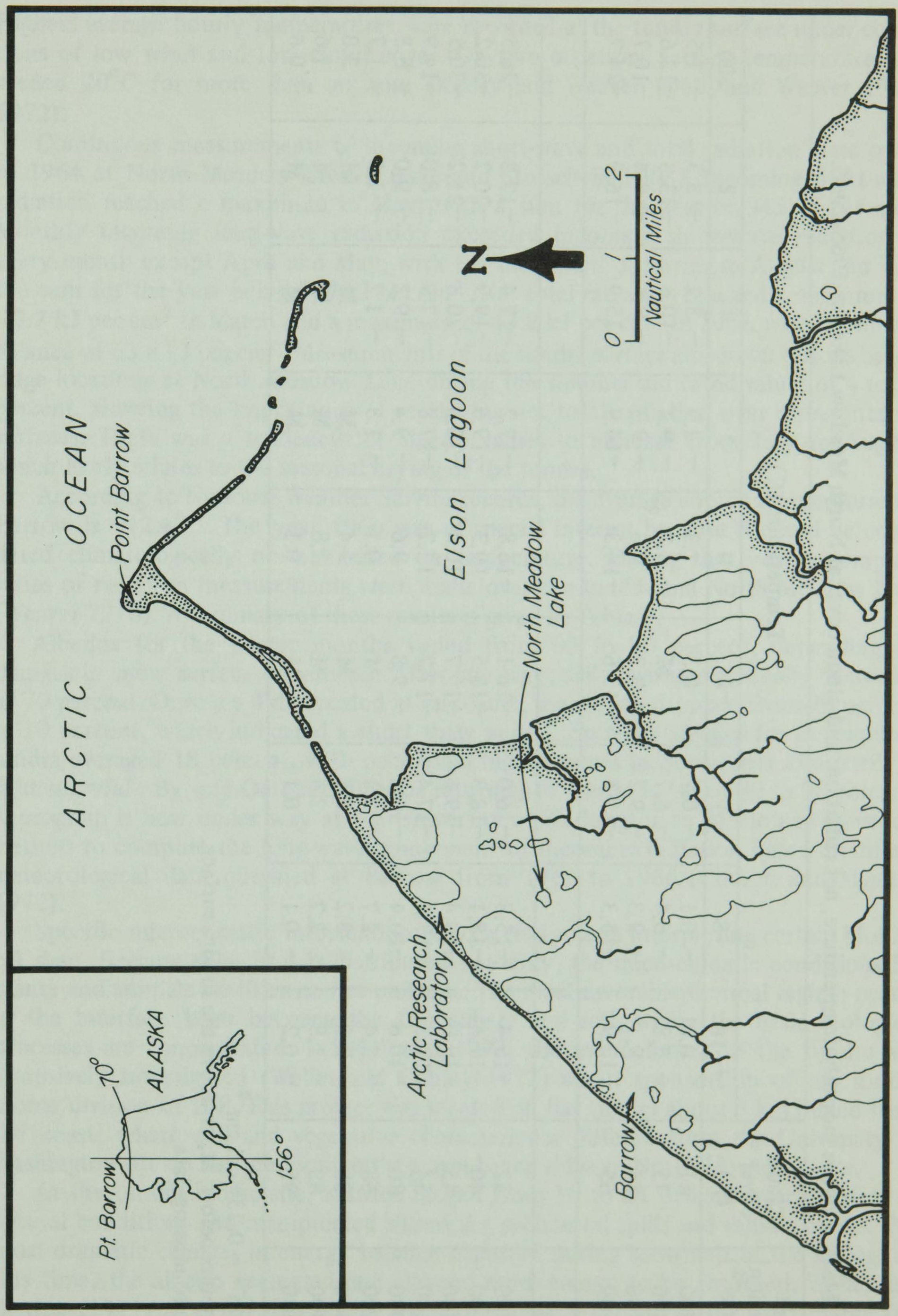


Figure 2. Map showing University of Washington's North Meadow Lake field site.

Table 2. Average monthly temperature, net radiation, and cloud cover at North Meadow Lake for 1965-1966.

1965	Net Radiation[1] (cal cm^{-2})	Cloud cover (%)	Temperature (C)								
			[2]−16	−8	−4	−2	0	2	4	8	300
Sept	−4,900	81	0.0	− 0.1	− 0.2	− 0.3	− 1.3	− 2.9	− 3.2	− 3.3	− 1.5
Oct	−6,800	75	− 5.8	− 6.4	− 6.7	M	− 8.3	− 9.1	−10.4	−13.3	−12.6
Nov	−3,500	84	− 9.1	− 9.3	− 9.2	− 9.3	− 9.3	− 9.3	− 9.4	− 9.4	−10.7
Dec	−5,500	65	−12.9	−13.3	−13.4	−13.6	−14.3	−14.9	−15.9	−16.9	−24.7
1966											
Jan	−8,300	32	−15.4	−15.8	−16.0	−16.1	−16.8	−17.2	−17.4	−17.8	−26.5
Feb	−6,100	40	−17.6	−18.1	−18.3	−18.5	−19.3	−19.6	−19.9	−20.2	−30.2
Mar	−7,400	45	−19.0	−19.4	−19.6	−19.7	−20.4	−20.6	−20.8	−21.2	−30.5
Apr	−5,200	54	−17.3	−17.4	−17.4	−17.7	−17.7	−17.8	−17.9	−18.0	−14.9
May	−1,000	80	−10.6	−10.4	−10.2	− 9.8	− 9.6	− 9.4	− 9.2	− 9.0	− 8.8
June	33,100	68	− 3.4	− 2.7	− 2.1	M	− 0.1	− 1.3	− 1.7	− 1.5	− 1.7
July	33,300	88	2.3	3.2	3.8	M	5.4	M	M	M	3.0
Aug	22,300	83	1.8	2.2	2.4	M	2.8	M	M	M	1.6
Sept	2,600	95	− 0.2	− 0.1	0.1	M	− 0.1	M	M	M	− 0.6

[1] joule cm^{-2} = 0.239 cal cm^{-2}.
[2] Centimeters below, at, or above the tundra surface.
M refers to missing data.

Highest average hourly temperatures were recorded at the tundra surface under conditions of low wind and low cloud cover. On two occasions surface temperatures exceeded 20°C for more than an hour (Kelley and Weaver 1969, and Weaver 1969, 1972).

Continuous measurements of incoming short-wave and total radiation were made in 1964 at North Meadow Lake (Lieske and Stroschein 1968). Incoming short-wave radiation reached a maximum in May, with a sum for the year of 343 kJ per cm^2. Monthly incoming long-wave radiation exceeded incoming short-wave radiation in every month except April and May, with the maximum occurring in August and with the sum for the year being 737 kJ per cm^2. Net total radiation reached a minimum of -7.7 kJ per cm^2 in March and a maximum of 43.2 kJ per cm^2 in June, with an annual balance of 63.8 kJ per cm^2. Measurements of the tundra surface albedo on various beach ridge locations at North Meadow Lake during the summer indicated values of 4 to 34 percent, showing the importance of measuring net total radiation over representative surfaces. There was a tendency for albedo values to increase from July to August, which likely relates to the seasonal drying of the tundra.

According to National Weather Service records, the average annual temperature for Barrow is -12.4°C. The year 1966 was of special interest because it could be considered climatologically normal based on temperature. During that year a complete series of radiation measurements were made over the tundra and North Meadow Lake (Weaver 1970). A summary of these results is given in Table 3.

Albedos for the winter months varied from 80 to 90 percent, depending on changes in snow surface conditions. After late May, daily averages gradually decreased to 70 percent. During a 4-day period in mid-June, the albedo dropped from 70 percent to 10 percent, which indicated a short thaw period. Summer albedos for the exposed tundra averaged 18 percent, with occasional higher values in September as a result of light snowfall. By mid-October, albedos returned to winter levels of 80 to 90 percent. A program is now under way at the University of Washington to develop an empirical method to compute the long-wave component of incoming radiation based on micrometeorological data obtained at Barrow from 1962 to 1966 (Church and Maykut 1972).

Specific microclimatic information plays a vital role in interpreting certain biological data. Because solar heat is distributed unevenly, the microclimatic conditions for plants and animals are likewise not uniform. The most favorable thermal regime occurs in the interface layer between the atmosphere and soil, where the basic biological processes are concentrated. In 1971 and 1972, the microclimate of the tundra was intensively investigated (Weller and Cubley 1972) under sponsorship of the tundra biome division of IBP. This project was located on flat tundra about 3 km inland from the coast, where soil and vegetative characteristics differed from the University of Washington site on the predominantly gravel beach ridge of North Meadow Lake.

At the tundra biome site, albedos ranged from 10 to 24 percent over a variety of natural conditions and manipulated situations, such as oil spills and vehicle tracks. The most dramatic changes in energy balance occurred during snowmelt in the spring. At this time, the albedo decreased and allowed more energy to be absorbed. Weller and Benson (1971) reported that during the spring thaw, 9 percent of the solar energy was required to heat the soil, 18 percent to heat the air, and 73 percent to evaporate water from the tundra. In midsummer, 2 percent of the solar energy was used to heat the soil, 32 percent to heat the air, and 66 percent to evaporate water from the tundra.

The amount and character of the snow cover on the Alaskan North Slope are important to most meteorological investigations. Aside from the perennial snow of the

Table 3. Monthly radiation totals over tundra and at North Meadow Lake for 1966 (joules/cm^2).[1]

Month	Global short-wave radiation	Reflected short-wave radiation		Net short-wave radiation		Net long-wave radiation		Net total radiation	
		Tundra	Lake	Tundra	Lake	Tundra	Lake	Tundra	Lake
Jan	241	205	(205)	36	(36)	−8,342	(−8,342)	−8,306	−8,306
Feb	3,779	3,210	(3,210)	529	(529)	−6,654	(−6,654)	−6,085	(−6,085)
Mar	20,757	17,512	(17,512)	3,245	(3,245)	−10,695	(−10,695)	−7,450	(−7,450)
Apr	47,645	39,350	(39,350)	8,295	(8,295)	−13,483	(−13,483)	−5,188	(−5,188)
May	68,672	58,854	(55,854)	9,818	(9,818)	−10,807	(−10,807)	−989	(−989)
June	74,062	31,646	29,338	42,416	44,724	−9,327	−8,516	33,089	36,208
July	51,049	9,224	4,187	41,825	46,862	−8,486	−8,880	33,339	37,982
Aug	38,553	7,681	3,297	30,872	35,256	−8,592	−9,320	22,280	25,936
Sept	14,722	3,634	1,838	11,085	12,884	−3,503	−3,748	7,582	9,136
Oct	4,427	3,143	3,079	1,284	1,348	−3,382	−3,610	−2,098	−2,262
Nov	478	420	(420)	58	(58)	−9,567	(−9,567)	−9,509	(−9,509)
Dec	0	0	0	0	0	−7,344	(−7,344)	−7,344	(−7,344)
Totals	324,385	174,879	158,290	149,463	163,055	−100,182	−100,966	49,321	62,129

[1] Weaver (1970).
( ) Estimated values.

mountainous areas, the snow cover remains longest on the North Slope, an area one-third the size of the state of Alaska. For 9 months of the year, the entire North Slope is covered with dry, wind-packed snow. Distinct features of the snow include a thin wind-swept sastrugi surface and large drifts along banks which may be several kilometers long, up to 20 m wide, and 6 to 8 m deep (Benson, Personal Communication).

The IGY program provided an opportunity to inventory carbon dioxide and to investigate its worldwide distribution for use as a baseline reference for future evaluation of changes that might result from fossil fuel consumption (Plass 1956, and Revelle and Suess 1957). If all the carbon dioxide produced by man were retained in the atmosphere, this gas could increase annually at a rate of 1.6 ppm. The question of an annual rise in carbon dioxide in the atmosphere and its implications of thermal atmospheric modification led to an investigation of its concentration and variation in the atmosphere and to a determination of its sources and its sinks. The investigation was conducted from July 1962 to September 1967 at a site provided by NARL (Kelley 1968). The air at the site was generally free of local sources of combustion products. The study required a precise measurement of carbon dioxide in the atmosphere and was carried out by the Department of Atmospheric Sciences of the University of Washington, in cooperation with the Scripps Institution of Oceanography of the University of California.

This study revealed a distinct cyclic variation of carbon dioxide in the near-surface atmosphere (Figure 3). The monthly average concentration was high in winter and low in summer. The low concentration in the summer (with minimum in August) reflected an uptake from the atmosphere by vegetation. The concentration rose rapidly in the fall, reaching a maximum in the spring. The record of these measurements at Barrow did disclose a long-term secular trend of 0.6 to 1.0 ppm per year, which corresponded closely to trends noted at Mauna Loa, Hawaii and Amundsen-Scott, Antarctica. The annual variation was much greater at Barrow than at these two stations, however.

Investigation of the sources and sinks for carbon dioxide in the near-surface environment still continues at NARL. An understanding of these sources and sinks is fundamental in determining carbon cycling in an arctic ecosystem. During each year of the study, large increases in CO_2 concentration over ambient air at the tundra surface have been observed a few days after the first snowfall. This steady increase continues into December, after which the concentration stabilizes at a level approaching that of ambient air. In the spring, subnivean CO_2 levels again increase until the snow cover disappears in June.

In 1966, an investigation was undertaken to explain the sources of subnivean carbon dioxide. At this time, a laboratory program was designed to elucidate the phenomenon of CO_2 outgassing during freezing of the tundra (Coyne and Kelley 1971b). Depending upon the type and texture of the tundra samples analyzed under the laboratory conditions, 500 to 90,000 liters of carbon dioxide per hectare were found, which suggested that the carbon dioxide released from solution escapes to the atmosphere at varying rates throughout the freezing period. The highest rates of escape were observed in autumn and spring.

During the summer, decomposition within the tundra results in a soil saturated with carbon dioxide that should evolve as the soil freezes. Unlike an ice cube, in which dissolved gas is trapped in the center of a volume of freezing water, a soil core contains plant roots, organic matter, and soil particles that provide escape routes for entrained gas.

The ice cube effect was apparently observed when autoclaved bentonite, saturated with CO_2-enriched water, was rolled into cores and subjected to the same freezing

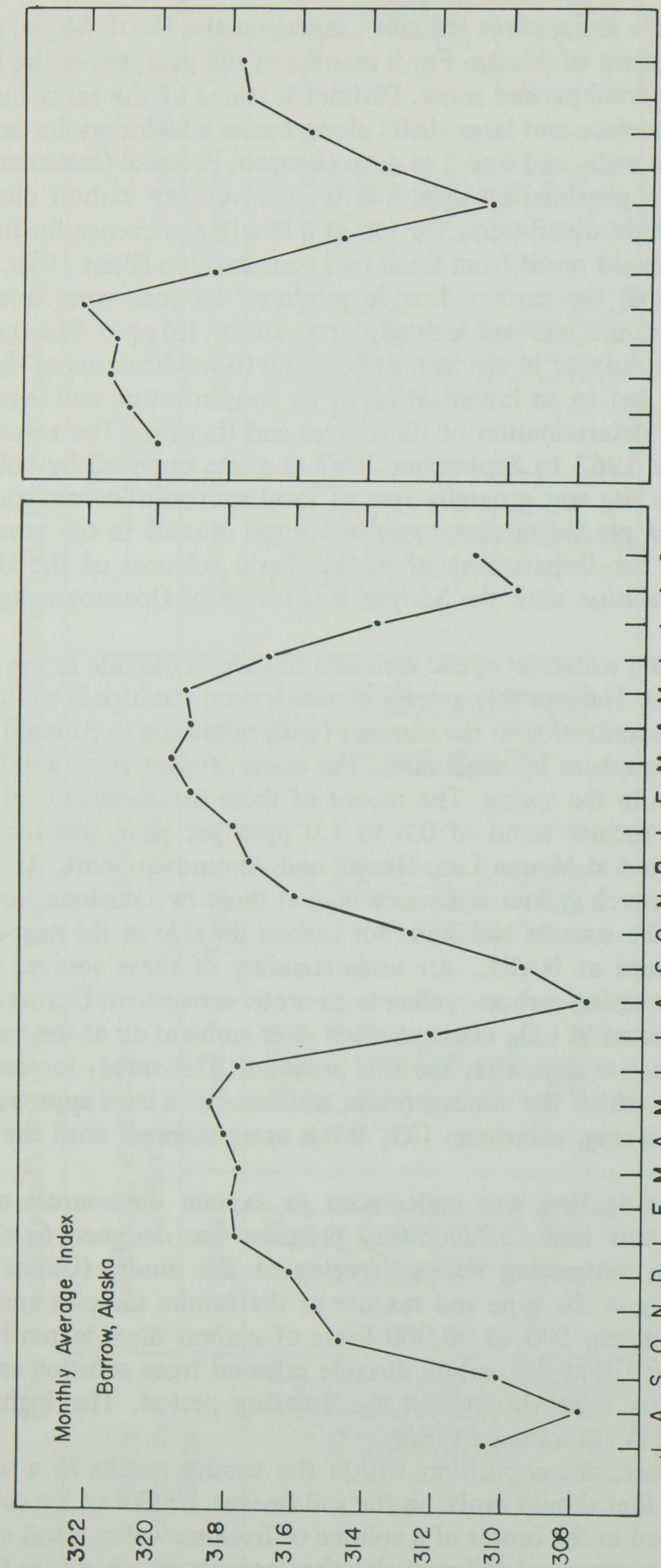


Figure 3. Average monthly concentration of carbon dioxide in atmosphere near Barrow for 1961-1963 and 1965.

treatment as the soil cores. No increase in evolution of carbon dioxide occurred upon freezing. The possibility that a high proportion of the carbon dioxide remained dissolved in unfrozen interstitial water in the clay core cannot be discounted, however.

Cores providing the highest evolution of carbon dioxide were characterized by coarse texture and high moisture content. Cores collected from a sandy bluff along Meade River 100 km south of Barrow were relatively dry and showed no increase in CO_2 evolution when frozen. On the other hand, cores from a beach ridge near Barrow, a site which contained gravel mixed with silt and clay-size particles and which was 5 to 15 percent higher in moisture content than the Meade River cores, had detectable CO_2 evolution.

During laboratory analysis of the cores, freezing was induced from the outside to the center. Tundra, however, is known to freeze bidirectionally, with subfreezing temperatures at the soil surface and at the upper surface of the permanently frozen ground inducing two freezing fronts. As these two fronts approach each other in autumn, some of the carbon dioxide may rise to the surface in proportion to texture, cracking, and other avenues of escape, producing a variable autumn rise in CO_2 concentration (Kelley *et al.* 1968). Some carbon dioxide may become trapped within the freezing soil layer and then slowly escape, causing a slightly higher CO_2 level in the subnivean air than in the ambient air during the winter months. In areas where the snow cover would offer high resistance to diffusion of carbon dioxide to the atmosphere, sufficiently high concentrations may build up near the surface to have an effect on subnivean animal populations. For example, observations made in areas of low relief near Moscow show that subnivean CO_2 concentrations near 4 percent may inhibit the movement of voles from their burrows and thus influence the placement of their nests (Bashenina 1956).

Associated with the increase in tundra temperatures in the spring is an increase in subnivean and ambient concentrations of carbon dioxide. Further release of trapped gas resulting from differential warming of the soil may be the source of the spring rise in the atmosphere (Kelley 1968), but amplification of the spring rise by biological systems cannot be ruled out once the minimal conditions for growth and assimilation have been met.

A micrometeorological method was used recently to assess primary productivity of a tundra plant community (Coyne and Kelley 1971a). The abiotic section of the tundra biome studies resulted in high-quality wind and temperature gradient measurements above the ground (Weller and Cubley 1972), which enabled the use of an aerodynamic method to assess CO_2 exchange over the tundra surface. In this method, micrometeorological parameters were utilized indirectly to quantify CO_2 exchange between the biosphere and the atmosphere. Other concurrent approaches included the direct measurement of net CO_2 uptake by plants enclosed in chambers and the employment of a harvest method.

The aerodynamic method integrates over larger areas than *in situ* chamber techniques that respond to photosynthesis at the community level, which includes both vascular and nonvascular flora as opposed to the individual vascular plant response of the chamber method. In contrast to harvest techniques, the aerodynamic method was sensitive to immediate environmental conditions and could be applied with minimal disturbance of the environment.

Parameters of wind, temperature, and CO_2 profiles above the vegetative canopy were measured, and fluxes were calculated from integrated values at half-hour intervals throughout the summer. The net flux represents the difference between total CO_2 production by respiration in the plant-soil system and photosynthetic fixation by

chlorophyllous tissue (Montieth 1962). The integrated seasonal flux (Coyne and Kelley 1972) was 140 g CO_2 per m^2 for a 60-day period in 1971 (June 27 to August 26). Adding an assumed constant daily input from soil and litter respiration of 8 g per m^2 yielded an estimated total seasonal flux of 620 g CO_2 per m^2.

Surface water masses are important to the tundra microclimate and ecological environment to the extent that small pools and lakes occupy 50 to 80 percent of the tundra surface. An exploratory investigation on a small tundra pond was carried out during the summer of 1971 by researchers from the University of Alaska and U.S. Army CRREL. The investigation sought to determine the equilibrium concentration of carbon dioxide and to ascertain whether these natural water bodies were sources or sinks for carbon dioxide in the atmosphere. Findings showed that the pond was always supersaturated with carbon dioxide with respect to the atmosphere, with equilibrium values varying from about 500 to 1,500 ppm by volume. These data reflected a strong interdependence of carbon dioxide with windspeed and water temperature.

Baseline measurements of atmospheric ozone were carried out near NARL from 1965 to 1967 by the Department of Atmospheric Sciences of the University of Washington, in conjunction with investigations of carbon dioxide, in order to observe the behavior of a trace gas of different origin in the atmosphere (Kelley 1970). Ozone, or net oxidant (as it was often referred to then because the analysis was not specific for ozone alone), is produced in the upper atmosphere by the action of solar radiation on oxygen. Ozone also exists in small amounts near the ground surface up to about 70 km, with a maximum concentration between 20 and 30 km (Paetzold and Regener 1957). When this investigation was planned, several major air pollution centers across the country included ozone as an indicator of air pollution associated with photochemical oxidation of hydrocarbons. The NARL facility offered an opportunity to measure a baseline value for this gas with little interference from man-made sources.

To accomplish this work, it was necessary first to adapt existing analytical equipment to arctic conditions and then to establish an accurate system of calibration for reliable measurements of small variations. Throughout the period of analysis, a systematic calibration program was established with the Washington State Public Health Service. A distinct seasonal variation in ozone was seen, with daily concentrations varying from 7 pphm to less than 1 pphm by volume (Figure 4).

Unlike carbon dioxide, neither strong nor consistent diurnal variation in ozone was observed. Highest concentrations occurred in the spring, and the sharpest increases lasted from several hours to a few days, correlating with storm front passages. The concentration in surface ozone from late spring through summer and fall showed less variation from day to day than in the spring, with the lowest ozone concentrations occurring from late May to early June.

From time to time other near-surface atmospheric chemical observations have been made at NARL. In 1967, under a contract with ONR, the Stanford Research Institute measured carbon monoxide, organic gases, methane, and condensation nuclei at North Meadow Lake (Cavanagh 1968). Carbon monoxide concentrations measured during mid-September were low, varying from 55 to 260 ppb, although fluctuating usually less than 20 ppb during any given day. In general, the CO concentrations at Barrow were consistently low and less varied than those measured previously in clean atmospheres. They were also lower than values recorded on the Greenland ice cap during the summer.

There is some evidence in biological literature that carbon monoxide may be liberated by growing plants (Wilks 1959). If this were a major source of carbon monoxide in arctic areas, however, seasonal patterns of higher concentrations should

be apparent in summer. Thus, CO levels may undergo seasonal variations as a function of both photosynthetic activity and contamination by man-made activities. In this regard, carbon monoxide would resemble carbon dioxide in its strong correspondence to both natural and man-made sources.

Most organic components of the arctic atmosphere were present in concentrations of 1 ppb or less. The most obvious anomaly in the organic gas measurements was the presence of n-butanol at 100 times the concentration of any other nonmethane organic compound. Its presence was considered unique, since there was no immediately identifiable source (Williams 1965). There was speculation that the presence of n-butanol might be due to fermentation of the tundra cover (Fieser and Fieser 1966). The mean methane concentration was 1.59 ppm, which compared with the estimated worldwide range of 1.2 to 1.5 ppm. Possibly, the presence of natural gas near Barrow could contribute methane through leaks and seepages. Condensation nuclei concentrations were extremely low and indicative of an atmosphere unpolluted by local combustion sources. A program supported by the Arctic Institute of North America (Went 1972) confirmed the low number of nuclei.

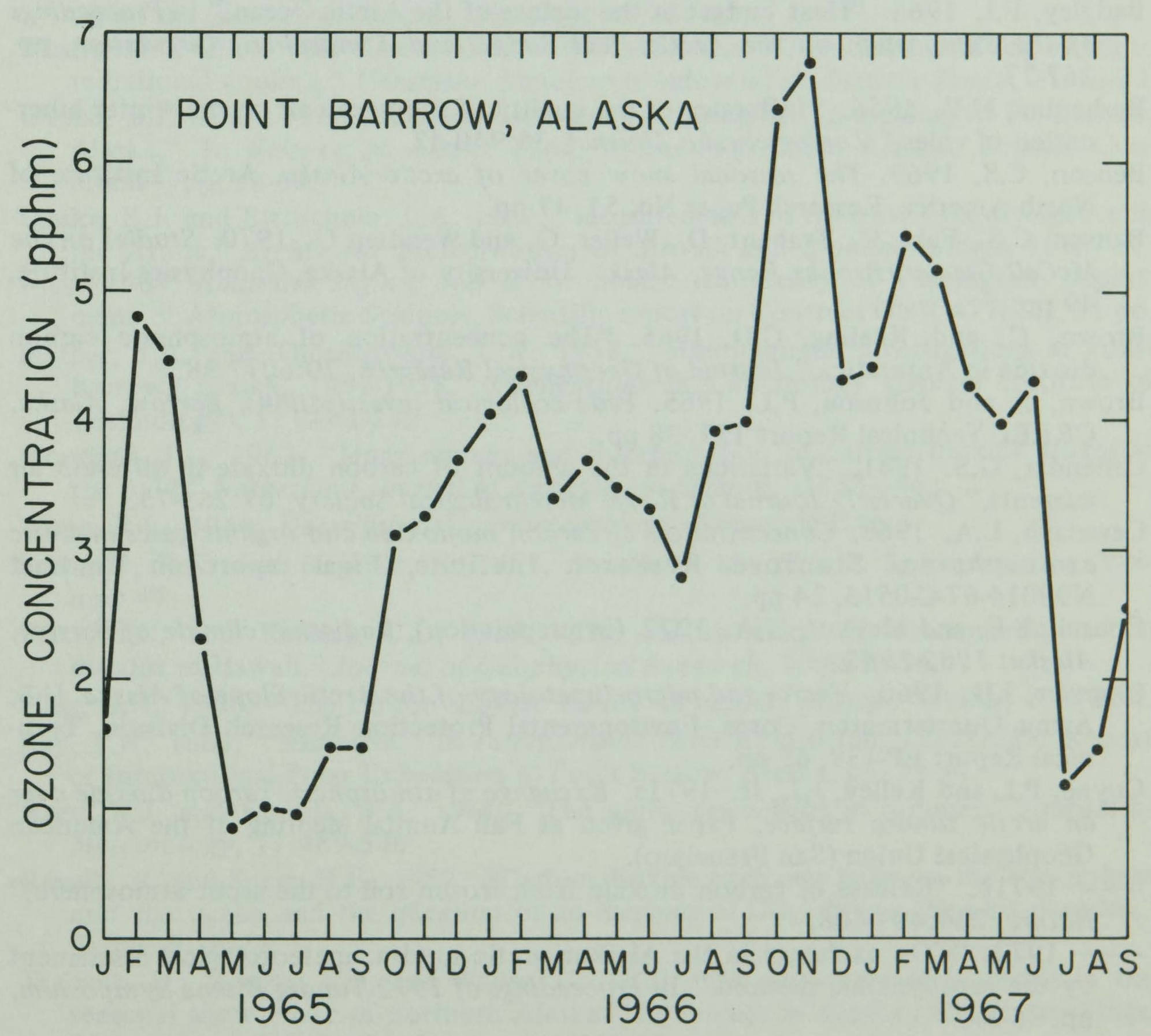


Figure 4. Average monthly concentration of ozone near Barrow for 1965-1967

The progress of research in arctic micrometeorology has been traced from the modest efforts of more than two decades ago to the integrated, interdisciplinary projects of recent years. Much of the research of past years in arctic regions, as elsewhere, has been exploratory, which contrasts with the process-scope investigations now being applied to national and regional needs. The Naval Arctic Research Laboratory, through its logistic support of a continuing program, has made possible a unique advancement of arctic micrometeorology.

Acknowledgments

Appreciation is expressed to the many investigators who generously made their time available for consultation on this paper, to Eleanor Kelley for editorial assistance, and to the Institute of Marine Science of the University of Alaska for graphic and secretarial support.

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ARCTIC LIMNOLOGY: A REVIEW

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Except for some lakes that have a permanent ice cover, arctic freshwaters do not differ appreciably from subarctic or alpine aquatic systems. No convenient grouping or classification allows us to delimit arctic water bodies on the basis of biology, chemistry, or physics, so we must rely on a geographical definition as follows: Arctic limnology is the study of freshwaters of northern tundra regions. More particularly, tundra regions include areas where the mean air temperature of the warmest month lies between 0° and 10°C and where the average temperature lies below −3°C for the coldest month (Sater 1969). This definition includes most of the treeless tundra but excludes tundras where the climate is maritime, such as the Aleutian Islands and parts of Iceland, Scotland, and Scandinavia. It also excludes mountainous areas of northern Scandinavia because the tundra there results from increased altitude and is surrounded by wooded valleys. Thus, lakes near Abisko in northern Sweden (68°N) are properly subarctic-alpine rather than arctic (Thomasson (1956) also classed these lakes as subarctic).

There are seven types of arctic freshwater environments: deep lakes, shallow lakes, ponds, large rivers, small rivers, streams, and springs. The physical and geological processes that created freshwater lakes provide useful parameters for separating them into types. Thus, most shallow lakes were formed by the melting of permafrost (thermokarst processes) and are seldom greater than 5 m deep. This depth, then, may be taken as the upper limit of shallow lakes. An ice cover of up to 2 m, which forms during the winter, prevents fish from permanently living in shallow waters less than this depth. Ponds are therefore defined as bodies of standing water, less than 2 m deep, which freeze solid every winter. Large rivers contain water throughout the year and have unfrozen holes where fish can overwinter. Small rivers flow all summer, while streams are intermittent and contain water only during snowmelt or after an especially big rain.

This review will not treat the limnology of each of the seven types of water but will instead concentrate on the processes that go on in all arctic freshwaters. In part, this is a necessary approach because there is almost nothing known about the limnology of flowing water in the Arctic. This approach also omits taxonomic or distributional studies, as we do not yet know enough about the detailed biology of specific

species to gain meaningful limnological information in this way. This review concentrates on the North American Arctic, Greenland, and Spitsbergen. (See Figure 1 for locations of many lakes mentioned in the text.) As noted, the well-studied lakes of northern Scandinavia lie outside the true Arctic. Northern reaches of the USSR do lie within the arctic zone, but most of the limnological work there has been reconnaissance and does not offer insights into the processes affecting the waters and their biota. Other evidence that little is known about the limnology of this region is that the tundra section of the International Biological Program (IBP) in the USSR is strictly terrestrial and that no Russian papers were given on arctic limnology at the 1971 Congress of Limnology at Leningrad.

Historical Overview

Arctic limnology has passed through three phases. The first limnological data were gathered incidentally during expeditions devoted to exploration or natural history collections. In the second phase, that of descriptive limnology, investigators measured changes from lake to lake or throughout an annual cycle. The final phase involves intensive studies of the factors affecting and controlling various limnological processes.

Many arctic expeditions collected plant or animal specimens from lakes and ponds or published observations on freezing or thawing dates of rivers and lakes. For example, many of the volumes of *Reports of the Canadian Arctic Expedition* contain brief limnological data (Johansen 1922), and the ice cover of Lake Hazen (Ellesmere Island) was mentioned several times by members of Greeley's expedition (Greeley 1886). One of the most comprehensive detailers of limnological phenomena was Leffingwell (1919) who conducted a geological and geographical reconnaissance of northeastern Alaska. Not only did he describe rivers and lakes, but also he speculated about lake origins and described several springs.

Studies of arctic freshwaters that took place before World War II were severely limited by transportation problems and by a lack of field laboratories. Accordingly,

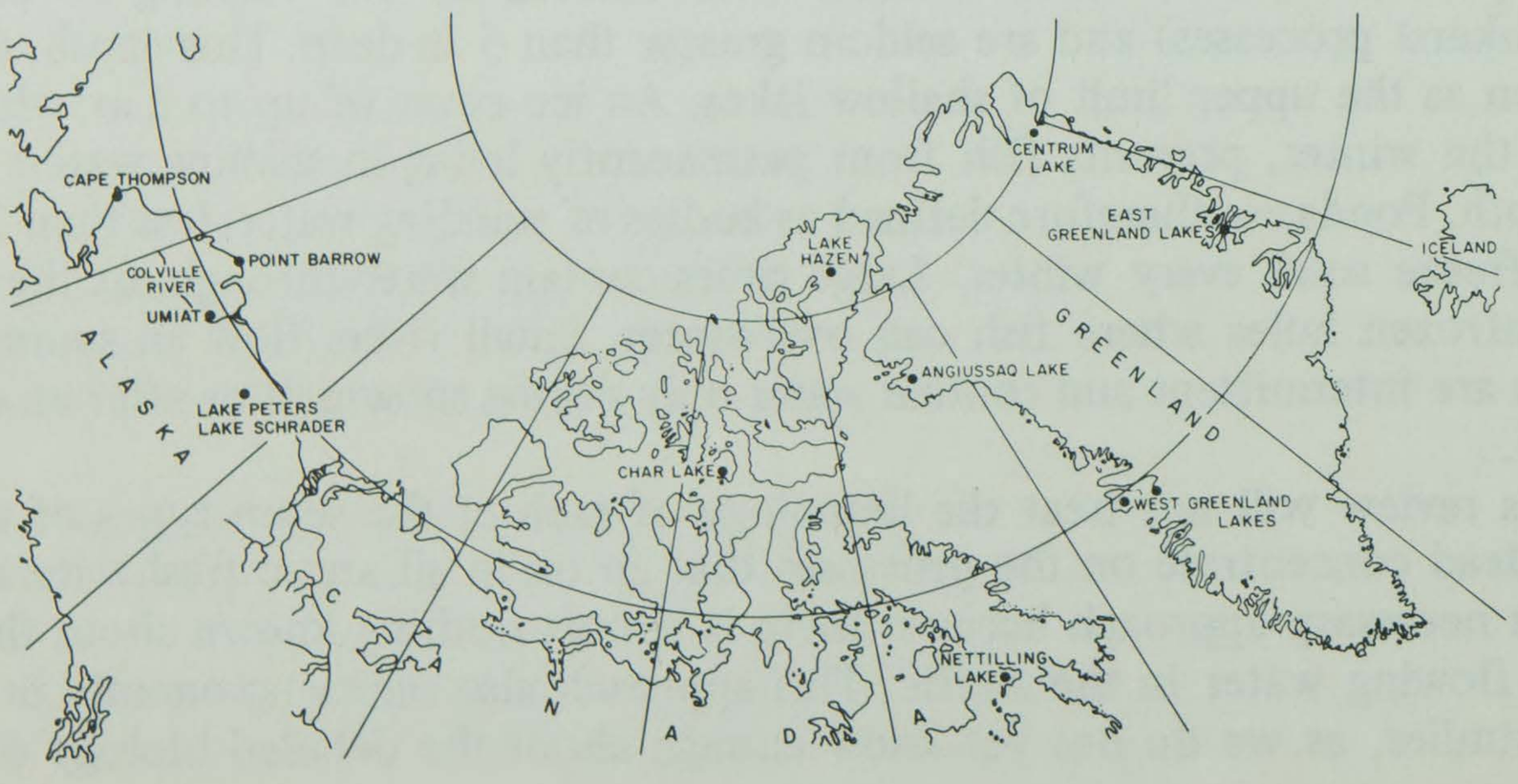


Figure 1. Map of North American Arctic and Greenland with location of principal lakes and study regions.

the only prewar work was collecting, and the only locations visited were those accessible by ship, such as Spitsbergen, Baffin Island, and Greenland. No professional limnologist visited the Arctic, but a few descriptions of aquatic habitats by ecologists did appear (Summerhayes and Elton 1923, 1928).

After World War II, the pace of limnological research increased rapidly. Lakes were investigated in east Greenland (Andersen 1946) near the Danish Expedition base camp at 73°N and in west Greenland (Hansen 1967) near the Arctic Station of the University of Copenhagen at Godhavn (69°N). Another center of research was northern Alaska where first the oil exploration camps and then the Naval Arctic Research Laboratory at Barrow provided support. Over 30 papers have now been published on various aspects of limnology in northern Alaska. Less intensive studies have also been carried out on lakes in northwest Greenland (Barnes 1960), northeast Greenland (Krinsley 1960), Baffin Island (McLaren 1967, and Oliver 1964), Spitsbergen (Amren 1964a,b), and Lake Hazen on Ellesmere Island (McLaren 1964).

These studies as well as many others are part of a progression running from the incidental observations of explorers, to collections of aquatic organisms, to ecological observations of lakes, to limnological studies during the summer months, to year-round limnological studies. The most detailed studies yet undertaken are IBP investigations of a high arctic lake (Char Lake at Resolute Bay), and of a pond and a lake at Barrow. Not only have these studies described the physical, chemical, and biological events in these aquatic systems, but also they have carried out experiments to discover the control mechanisms that are operating. The material from these two projects is largely unpublished at this time.

There have been five reviews of arctic limnology in the past 20 years. The first (Rawson 1953) mentioned only seven papers that dealt directly with arctic lakes. Of necessity, this review as well as that of Thomasson (1956) was rather general. The next to appear (Livingstone 1963) was the first where enough data were available for a proper limnological discussion. Recently, a review by Kalff (1970) summarized much recent biological information. There is also a chapter on limnology in an Arctic Institute of North America publication *The Arctic Basin* (Sater 1969).

Lake Origins

Most arctic lake basins result from glacial activity or from the effect of permafrost. The terminology follows Hutchinson (1957). Perhaps the most abundant type of water body in the Arctic is the shallow pond formed inside an ice-wedge polygon. Ice wedges grow in the permafrost from water seepage through cracks in the surface of the ground. Eventually polygonal networks of ridges are formed that often contain ponds from 10 to 50 m in diameter. There are millions of these ponds on the Arctic Coastal Plain of Alaska (Britton 1957) and in similar flat regions in Siberia.

The shallow ponds may coalesce into large ponds, or large amounts of ice deeper in the permafrost may melt and form a shallow thermokarst lake (Rex 1961). These larger oriented lakes are abundant in northern Alaska (Black and Barksdale (1949) estimated tens of thousands), where the entire coastal plain is either lake, pond, or old lake bed (Figure 2). Mackay (1956) discussed the same type of lake found at Liverpool Bay, Canada. Their orientation results from wind-generated currents (Livingstone 1963, and Carson and Hussey 1960).

Another abundant lake type is scoured out by glaciers. These irregularly shaped lakes are abundant in northern Canada where glaciers did not redeposit much material.



Figure 2. Lakes on Arctic Coastal Plain near Barrow. (Photograph by J. Brown)

In areas where extensive end and ground moraines were laid down by glaciers, kettle lakes are found. These lakes, formed when large pieces of buried glacial ice finally melt, are rare in the Arctic but have been noted in the foothills of the Brooks Range (Livingstone *et al.* 1958).

Glaciers also deepen valleys and, if a resistant sill is left, a fiord lake may form. These lakes, usually occurring in areas rebounding from glaciation, form a progression from fiords, to lakes slightly above sea level containing salt water in their depths, to completely freshwater lakes some distance above sea level. Ogac Lake on Baffin Island receives influxes of sea water approximately every fifth day (McLaren 1967) while Lake Taserssuaq near Atâ, west Greenland has no salt water at all (Hansen 1967).

Moraines left by glaciers may block narrow valleys, creating a moraine lake. These lakes are relatively numerous in northern Canada and in the Brooks Range; for example, Lake Peters and Lake Schrader, Alaska (Holmes and Lewis 1965).

Glaciers may also form dams and create ice-dammed lakes. These are rare and are located mostly along the Greenland ice cap. An example is Angiussaq Lake at 77°N in northwest Greenland (Barnes 1960).

The last type is oxbow lakes. These lakes are formed by the movement of channels of rivers and are common along many major arctic rivers.

Physical Limnology

Ice. Ice begins to form on arctic rivers and ponds by mid-September and in lakes by early October. A map by Hastings (1961) gives probable dates of river freezeup

throughout the Arctic. By early September there is no surface flow in streams in the Arctic (there is subsurface flow for another month), and, unless there are headwater lakes, the smaller rivers have virtually stopped flowing also. Lakes will take a variable length of time to cool, depending on summer heat income, depth, and cloud cover. At Barrow, Brewer (1958) observed that 2.5- to 3.0-m-deep lakes may freeze over any time after September 1. The average freeze date is September 15-20, but open water may extend until September 30. Lake Peters and Lake Schrader, two deep lakes (50 to 60 m) in the Brooks Range, did not freeze until October 7 (Hobbie 1962). While the Barrow lake reached 0.2°C before freezing, the deep lakes were at 2.0°C. As in temperate lakes, the exact date of freezing depends mostly upon wind and cloud cover.

The rate of freezing as well as the maximum thickness of the ice sheet depends on air temperature and snow cover. Most differences in thickness from year to year depend upon the amount of snow on the ice, but the maximum thickness is about 2 m. For example, at Lake Peters in 1959 (Figure 3) the ice was almost completely blown clear of snow when first seen at the end of April. In contrast, there was a 25-cm snow cover in early May 1961 and 60 cm less ice than in 1959. The ice on arctic lakes reaches a maximum thickness in late April or early May, but the start of actual melt depends on the snow cover.

Ice on deep arctic lakes is usually extremely clear, with no bubbles. This ice has a transmissivity for light similar to that of distilled water (Lyons and Stoiber 1959). The slightly less than 20 cm of bubbly ice found on most temperate, subarctic, and shallow arctic lakes will reduce incident light by 50 percent, while the same 50-percent reduction takes 347 cm of clear ice. In the Subarctic, lake ice is often pushed below the water surface by the weight of the snow. Water seeps through cracks in the ice and "snow ice" is formed, often in many layers alternating with unfrozen water and snow. (See Shaw (1965) for a description of snow ice in the Subarctic.) Because of the low precipitation, this phenomenon does not occur in the Arctic.

The ice begins to melt only when the air temperature approaches freezing and the sunlight can reach the ice surface. The usual chain of events is: (1) the last of the snow melts, leaving water or slush on top of the ice; (2) solar radiation and above-freezing temperatures cause melting to occur along the crystal boundaries; (3) the ice becomes porous and water drains off; (4) the surface ice becomes candled to a depth of 20 or 30 cm; (5) wind, warm air, and sunlight cause melting at the surface (Barnes

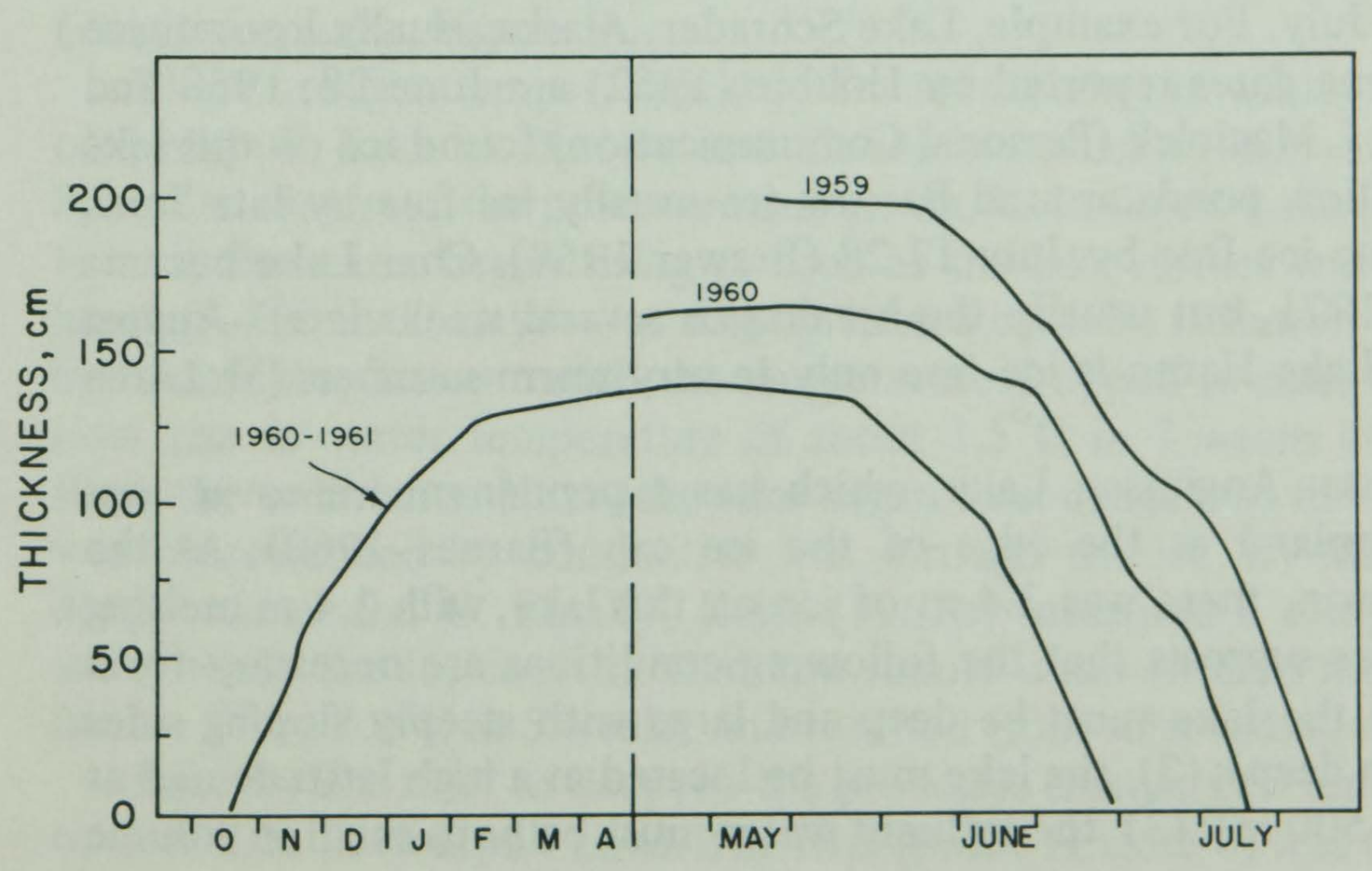


Figure 3. Freezing and thawing of ice in Lake Peters. (Hobbie 1962)

and Hobbie (1960) calculated that less than 5 cm of melting occurred at the bottom of the ice sheet); (6) when the ice sheet is reduced to 1 m in thickness, the entire sheet may be candled and the ice becomes unsafe for vehicles; (7) surface ablation continues but the ice floats free of the shore and portions may crack and be moved about by the wind; and (8) the final breakup may occur any time after the ice becomes less than 0.5 m thick. By this time the candles are floating free of each other, and a wind will cause them to tip onto their sides and quickly melt. In this way, a lake 80 percent covered with ice can become ice free in 24 hours.

The crystallography of arctic lake ice has been well studied and has several interesting limnological implications. For unknown reasons, ice crystals in different parts of a lake may have different orientations at the time of freezeup (Knight 1962). This initial orientation almost always controls the orientation of the crystals throughout the entire ice sheet. Usually the *c* axis is horizontal, and the crystal boundaries allow air and vapor bubbles to migrate vertically when the ice is altered by solar radiation in the spring. In contrast, when the *c* axis is vertical, the bubbles are trapped and give the ice a much higher albedo (35 percent versus 20 percent). This white ice is much stronger than the gray ice with the horizontal *c* axis and also takes longer to melt. In addition, less solar radiation passes through the white ice, and less energy is, therefore, available for algae beneath the ice. This distribution between the two crystal orientations becomes apparent to the eye only after melting starts. Otherwise, both types appear the same.

Ice also affects the shores of lakes by removing vegetation and by creating ice-push ridges. These ridges, which may be 4 to 5 m high (Livingstone *et al.* 1958), are formed along the shores of lakes by the movement of ice. Littoral vegetation is completely destroyed by this ice push, but the ice also affects the littoral zone in sheltered bays, so another process is also at work. This may be the disruption that occurs when the ice freezes to the sediment and then is lifted up in the spring when the water level rises rapidly. Whatever the cause, the deeper lakes usually have no submerged or emergent vegetation from the 0- to 2-m depth. In Lake Peters, for example, the only aquatic vegetation occurs in shallow bays that become completely dry when the water level falls in September. In Char Lake, the zone of submerged mosses begins at the 3- to 4-m depth (Kalff and Wetzel 1971).

Only a few arctic lakes retain a permanent ice cover; a few in the High Arctic are open most years, but the majority are completely open every year. A deep lake, however, can retain its ice cover into August as a result of a thick ice cover and bad weather during June and July. For example, Lake Schrader, Alaska usually loses its ice cover by July 15. Extreme dates reported by Hobbie (1962) are June 28, 1958 and July 26, 1959. However, J. Maciolek (Personal Communication) found ice on this lake during August 1964. Shallow ponds around Barrow are usually ice free by late June, while deeper lakes become ice free by July 17-28 (Brewer 1958). Char Lake became ice free about July 29, 1971, but usually the breakup is several weeks later—August 12, 1969 (Rigler 1972). Lake Hazen is ice free only in very warm summers (McLaren 1964).

The most extreme case—Angiussaq Lake, which has a permanent ice cover—was found in northwest Greenland at the edge of the ice cap (Barnes 1960). At the beginning of the melt season, there was 3.4 m of ice on this lake, with 1.4 m melting during the summer. Barnes suggests that the following conditions are necessary for a permanent ice cover: (1) the lake must be deep and large with steeply sloping sides (Angiussaq Lake is 187 m deep); (2) the lake must be located at a high latitude and at a high elevation (at least 500 m); (3) the influent water must be both small in volume

and cold; and (4) the lake must be in contact with glacial ice so that heat is lost from the deep water. Using these criteria, there are probably no more than six lakes with a permanent ice cover in arctic regions.

Water temperatures. The extended duration of the ice cover in the Arctic means that ponds and lakes become ice free after the insolation peak. This, combined with the generally cloudy weather of July and August, keeps available insolation low in the summers and ensures that water temperatures of lakes never exceed 15°C. Indeed, temperatures this high are found only in shallow lakes such as Imikpuk Lake (3 m deep) near Barrow, where Brewer (1958) noted a summer maximum of 12°C, or Thygesens Sø in west Greenland (Hansen 1967), where a maximum of 15.4°C was reached. Ponds may become slightly warmer but never warmer than 18°C due to the low sun angle and cool air. Ponds have diurnal temperature cycles, however, and one at 75°N on Bathurst Island ranged from 4° to 8°C with the maximum in midafternoon (Danks 1971). Flooded shallows behind the beach berm at Ikroavik Lake, near Barrow, reached 18°C on June 20, 1971, while the nearby lake was still frozen. On July 27, 1972, these flooded shallows had a diurnal variation of 14°C (3° to 17°C) (Cameron *et al.* in press).

The thermal cycle of deep lakes in the Arctic exhibits tremendous variation, depending upon location and summer climate. In a warm and calm summer, lakes in relatively sheltered locations near the southern limit of tundra may even stratify, although this is a rare event. The determining factor for stratification is likely the occurrence of warm and calm weather immediately after lake waters rise above 4°C. Hobbie (1961) reported that Lake Schrader in the Brooks Range (maximum depth is 57 m) stratified during 1958 (Figure 4) when the epilimnion was at 10°C and the hypolimnion at 4°C. In contrast, during the next summer the lake did not warm past 4°C, since the breakup did not occur until July 26, one month later than in 1958. The summer of 1961 resembled 1958, but no stable stratification occurred. Air temperature degree days—daily average (°C) summed for 2 months—were 650 and 450 for July and August 1958 and 1961, respectively, while the warming of the lake above 4°C was 9,050 and 8,900 cal per cm^2 for the same years. Thus, the total heat taken up by the lake was almost the same in 1958 and 1961, but the resulting thermal structure was different. In an average summer, most deep lakes will warm to 6° to 8°C.

Deep lakes that become ice free may never reach 4°C or will warm only a little. Even lakes beneath a permanent ice cover, however, do show summer warming (Angiussaq Lake, Figure 5).

There are few temperature data for arctic lakes in winter. Brewer's studies (1958) of Imikpuk Lake at Barrow and Hobbie's studies (1962) of Lake Peters and Lake Schrader illustrate the processes that go on. In Imikpuk Lake (3 m deep), the temperature of the water began rising as soon as the lake surface was completely frozen. This heating—2°C in 11 days—was mostly caused by solar radiation passing through the thin ice. After the first snowfall the temperature dropped to close to 0°C. Then followed a slow rise in water temperature of about 1.5°C in 7 weeks as a result of heat gained from the sediments. Next, the lake began to cool again as the heat from the sediments was overbalanced by conductive loss through the ice. By May, the water (only 1 m deep) was at 0.6°C. Finally, Kalff (1967b) measured a temperature increase in the water while the ice sheet melted and runoff water entered the lakes. The increase was from 1.5° to 2.0°C in 5 weeks, and resulted from solar radiation and runoff.

Lake Peters is 47 m deep, so the processes changing its temperature are not as easy to detect as in Imikpuk Lake. The first profile (Figure 6) was taken the day before the

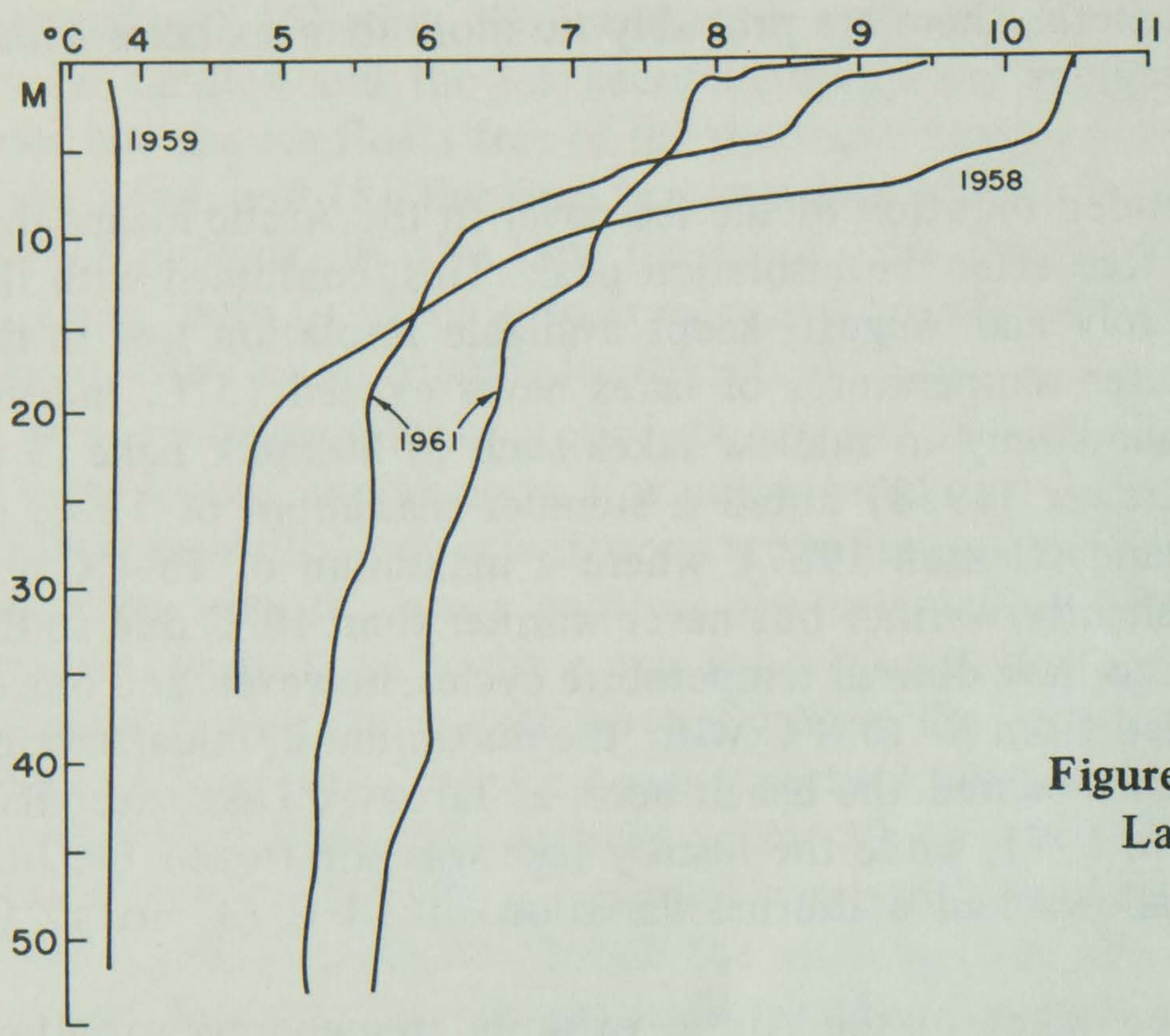


Figure 4. Summer temperatures in Lake Schrader. (Hobbie 1962)

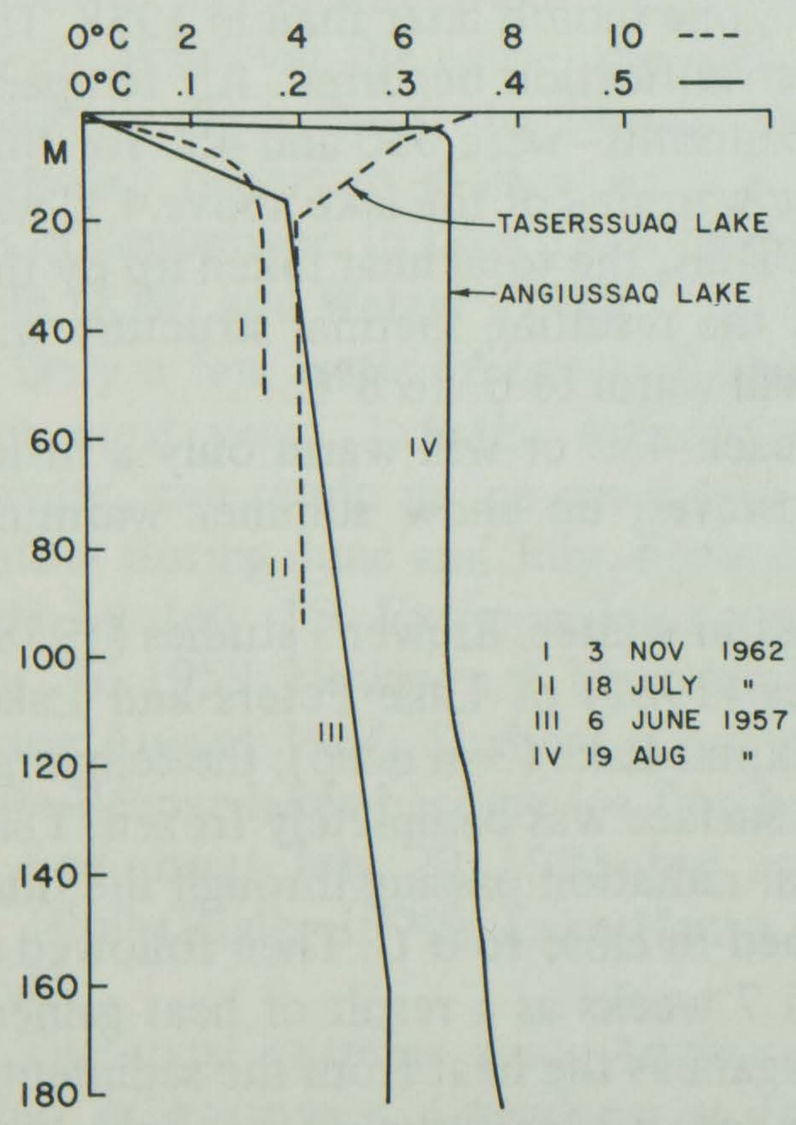


Figure 5. Temperatures in Angiussaq Lake in northwest Greenland. (Barnes 1960) and in Taserssuaq Lake in west Greenland (Hansen 1967)

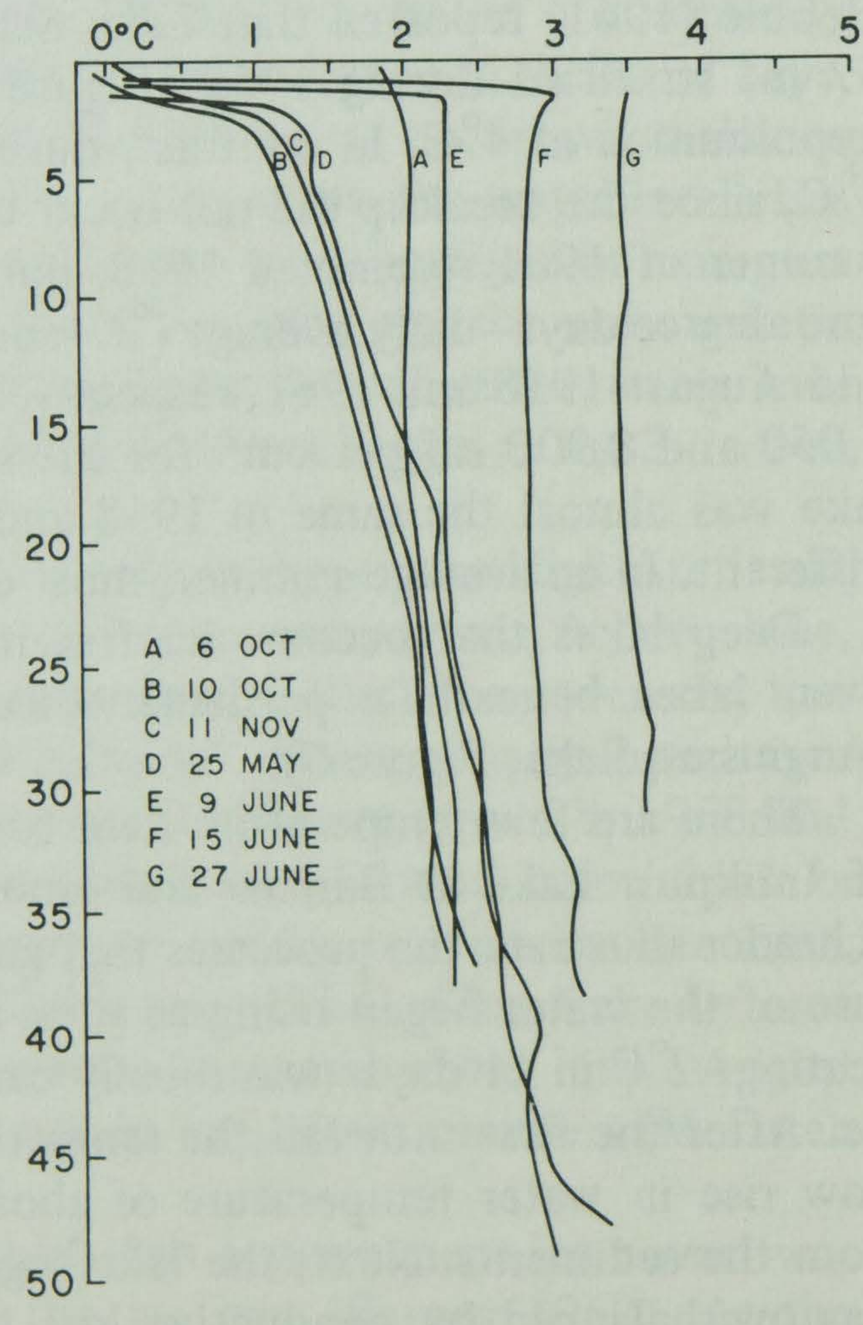


Figure 6. Temperatures in Lake Peters during freeze-thaw cycle of 1960-1961. (Hobbie 1962)

lake froze. Four days later the upper 20 m had cooled by 0.5°C or so and the bottom waters by several tenths. This overall cooling continued until mid-November, when a slight warming began at all depths (that continued until June), presumably from sediment-stored heat. (See May 25 profile, Figure 6.) By May 25 a slight solar heating had taken place in the upper 5 m, and by June 9 the top 18 m was warmed to 2.3°C. Shortly after June 9, great quantities of runoff water began entering the lake and the water temperature rapidly increased (1°C in 2 weeks).

All arctic lakes lie in the permafrost zone, but lakes and rivers cause large amounts of heat to be transferred downward and are, therefore, underlain by a zone of unfrozen ground. The thickness of this zone, called a "talik" in Russian (Grigorĕv 1959, in Legget *et al.* 1961), varies with the area and depth of the water body, and with the composition of the sediments and underlying formations. Beneath Imikpuk Lake, for example, Brewer (1958) measured a talik that was 60 m thick. Thus, except in those rare cases where the talik exceeds the permafrost depth, there will be heat loss from the bottom of every lake. Usually, a lake that circulates picks up enough heat in its sediments so that the heat loss cannot be noticed. Char Lake, however, which never warms above 4° to 5°C, does lose heat from the water during winter (Roff and Carter 1972), so evidently in this case the heat stored in the sediments is not enough to balance the heat loss to the underlying ground. Earlier permafrost studies at Resolute Bay did not take into account the effect of heat transfer from a lake (Char Lake or Resolute Lake) and from the ocean (Lachenbruch and Marshall 1969). Accordingly, it was believed that there was an exceptionally high rate of heat flow from the earth at this station.

Light. Data on summer light conditions in arctic lakes are sparse and consist mainly of Secchi Disc readings (approximates the depth of penetration of 5 percent of the surface light). In all ponds and most shallow lakes, the Secchi Disc is visible on the bottom of the lake. In lakes deeper than 2 m there may be a tremendous variability (Table 1). Winds keep the shallow lakes circulating so that fine inorganic particles remain in circulation and reduce the Secchi depth to 2 to 4 m. Deeper lakes are all relatively turbid as a result of the extremely fine glacial "rock flour" brought in either by glacial streams draining active glaciers or by streams flowing through morainic material. Large lakes that receive runoff for only 2 months, such as Nettilling Lake and Lake Hazen, are not half as clear as the clearest lakes in the world (Secchi depth of 40 m). Evidently this fine "rock flour" takes years to settle out. Naturally, within a single large lake there will be variability as well. For example, a river that originates in the Penny ice cap enters the northeastern corner of Nettilling Lake (Oliver 1964). About 5 km from the river mouth the Secchi reading in the lake was 1.1 m; 16 km from the mouth it was 5 m. The rest of the lake had 13- to 20-m Secchi depths.

The light conditions can be more accurately expressed as an extinction coefficient, n. The light at depth z equals the light at the surface times the quantity (e^{-nz}). As seen in Table 1, the larger the n the smaller the amount of light that penetrates into the lake and the smaller the Secchi depth. The information in Table 1 is for the penetration of white or visible light. Even more information is gained if colored filters are used and extinction coefficients calculated for the different wavelengths of light. Thus, in Lake Schrader on May 22, 1968, the unfiltered (white) light had a coefficient of 0.23; blue, 0.274; red, 0.442; and green, 0.171. The green light penetrates the deepest; red, the least.

The effect of glacial "rock flour" on the lakes may be illustrated by data from Lake Peters and Lake Schrader (Hobbie 1962, and unpublished data). These lakes

Table 1. Light penetration and extinction coefficients in arctic lakes.

Lake	Latitude (°N)	Location	Secchi or 5% light level (m)	Extinction coefficient (white light)	Reference
Taserssuaq	70	West Greenland	21-33	0.154	Holmquist (1959)
Nettilling	66	Baffin Island	1.2-21.3	....	Oliver (1964)
Angiussaq	77	Northwest Greenland	10	....	Barnes (1960)
Unnamed	69	East Greenland	9.5	0.20	Holmquist (1959)
Hazen	82	Ellesmere Island	8.3	....	McLaren (1964)
Schrader	69	Alaska	2.2-13	0.23-0.54	Hobbie (1962)
Chandler	68	Alaska	5	....	Livingstone *et al.* (1958)
Imikpuk	71	Alaska	2	....	Livingstone *et al.* (1958)
Peters	69	Alaska	0.3-9	0.32-2.5	Hobbie (1962)

occupy a single deep valley at the northern edge of the Brooks Range. Lake Peters lies at the southern end of the valley and is fed by melt water from several glaciers. It is connected to Lake Schrader by a 1-km-long channel that is only 1.5 m deep. The flow is from Lake Peters into Lake Schrader so that Lake Peters acts as a settling basin for the glacial material and is more turbid than Lake Schrader (Table 1). In September 1960, the inflow of material into Lake Peters ceased, and the water began to clear slowly as the particles settled to the bottom (Figure 7). In early June 1961, the water was at its maximum clarity but then became rapidly turbid as the glacial melt water entered the lake (ice did not leave until the end of June). It is interesting, but unexplainable, that the 1958 summer had the highest n values, which was followed by the 1959 spring with the clearest water. Perhaps some coagulation phenomenon is involved. As expected, Lake Schrader does not show the same strong changes and is much clearer at all times.

When the glacial melt water begins to enter Lake Peters in June, it is denser than the lake water and sinks to the bottom (turbidity current). As a result, the lake fills upward from the bottom with turbid water. This was measured (Figure 8) with an instrument having a light source and a photocell 0.5 m apart. Transmission was 70 to 80 percent on June 3, 1961, but was reduced to 20 to 30 percent by June 12. Eventually, the transmission may become as low as 2 percent throughout the water column.

A more meaningful measure is for solar energy entering and being absorbed within the lake. Since ultraviolet and infrared are absorbed within the first 0.5 m of water, it is not surprising that the n for solar energy followed closely that for blue and green light. For example, on July 22, 1961, the extinction coefficients in Lake Schrader (no ice cover) were 0.374 for green; 0.426 for white; 0.511 for blue; 0.547 for red; and 0.404 for energy. Ninety-nine percent of the energy had been absorbed in the top 7.8 m.

Because snow effectively reduces light penetration, the light climate beneath the ice and thin snow cover of arctic lakes is more favorable for algal photosynthesis than

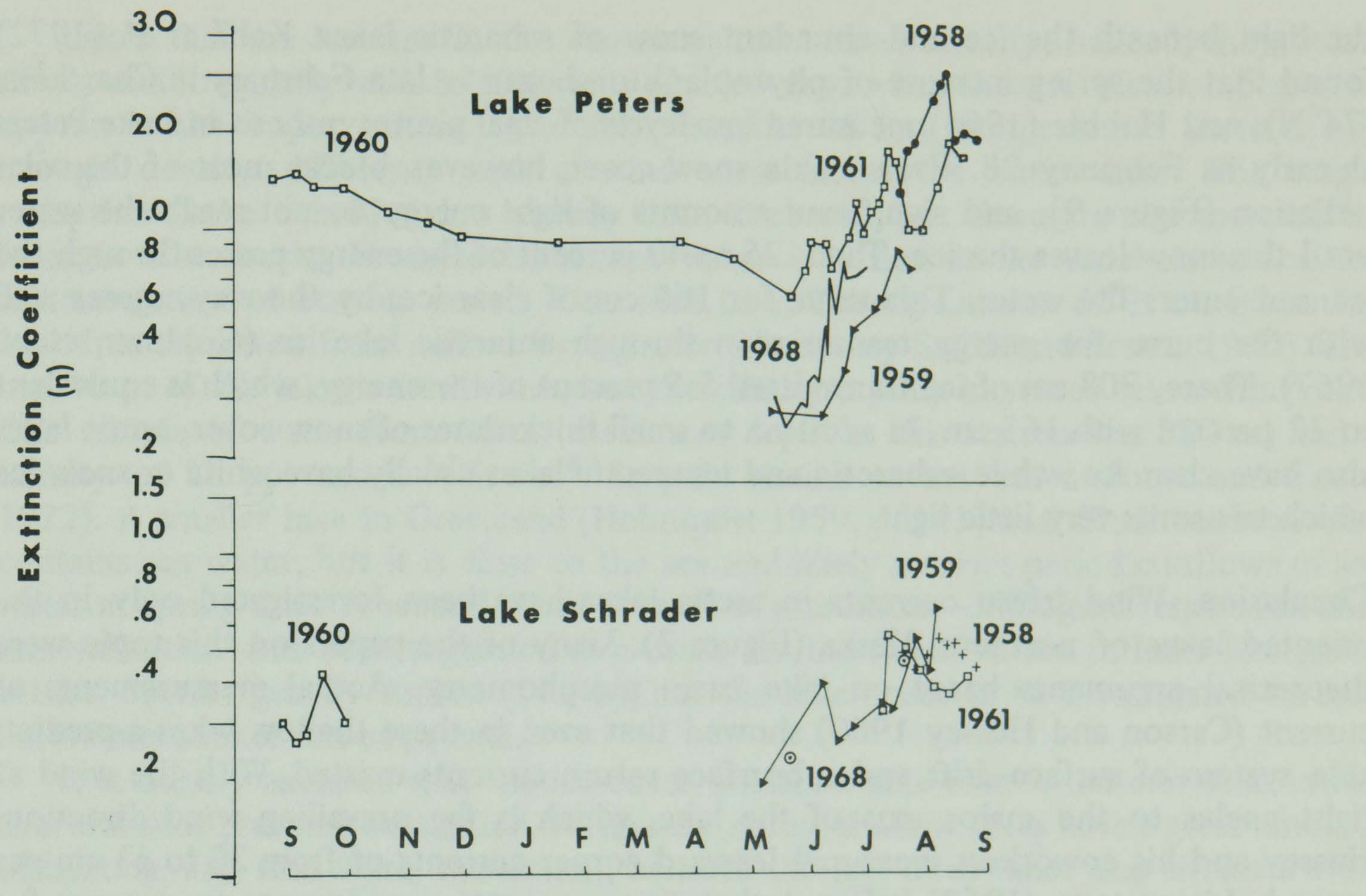


Figure 7. Extinction coefficient per meter in Lake Peters and Lake Schrader. (Hobbie, Holmgren, and Kalff, unpublished)

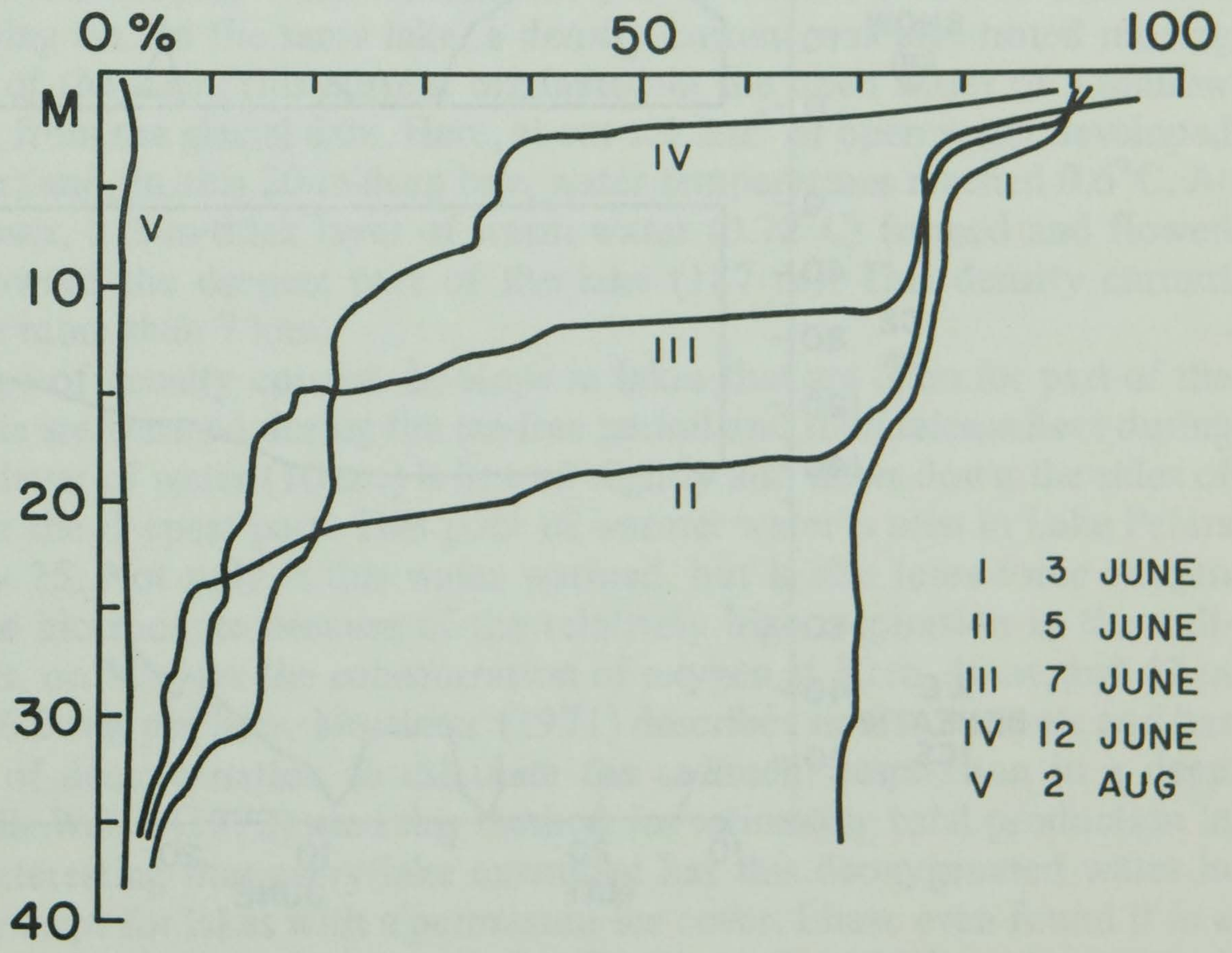


Figure 8. Transmission rate of 0.5 m of water at various depths in Lake Peters. (Hobbie, Holmgren, and Kalff, unpublished)

the light beneath the ice and abundant snow of subarctic lakes. Kalff *et al.* (1972) found that the spring increase of phytoplankton began in late February in Char Lake (74°N), and Hobbie (1964) measured low levels of algal photosynthesis in Lake Peters as early as February 28. Even a thin snow cover, however, blocks most of the solar radiation (Figure 9), and significant amounts of light energy do not reach the water until the snow leaves the ice. Then, 25 to 40 percent of the energy passes through the ice and enters the water. This value for 165 cm of clear ice, by the way, agrees well with the curve for energy transmission through antarctic lake ice (Goldman *et al.* 1967). There, 308 cm of ice transmitted 5.5 percent of the energy, which is equivalent to 22 percent with 165 cm. In addition to small thicknesses of snow cover, arctic lakes also have clear ice, while subarctic and temperate lakes usually have white or snow ice which transmits very little light.

Circulation. Wind-driven currents in arctic lakes have been investigated only in the oriented lakes of northern Alaska (Figure 2). Many of the papers on this topic were theoretical arguments based on lake basin morphometry. Actual measurements of current (Carson and Hussey 1960) showed that even in these shallow lakes a predictable system of surface drift and subsurface return currents existed. With the wind at right angles to the major axis of the lake, which is the prevailing wind direction, Hussey and his coworkers measured leeward corner currents of from 30 to 61 cm per second. Livingstone (1963) believed that these currents are adequate to account for the erosion of the lake shore and the elongated shape.

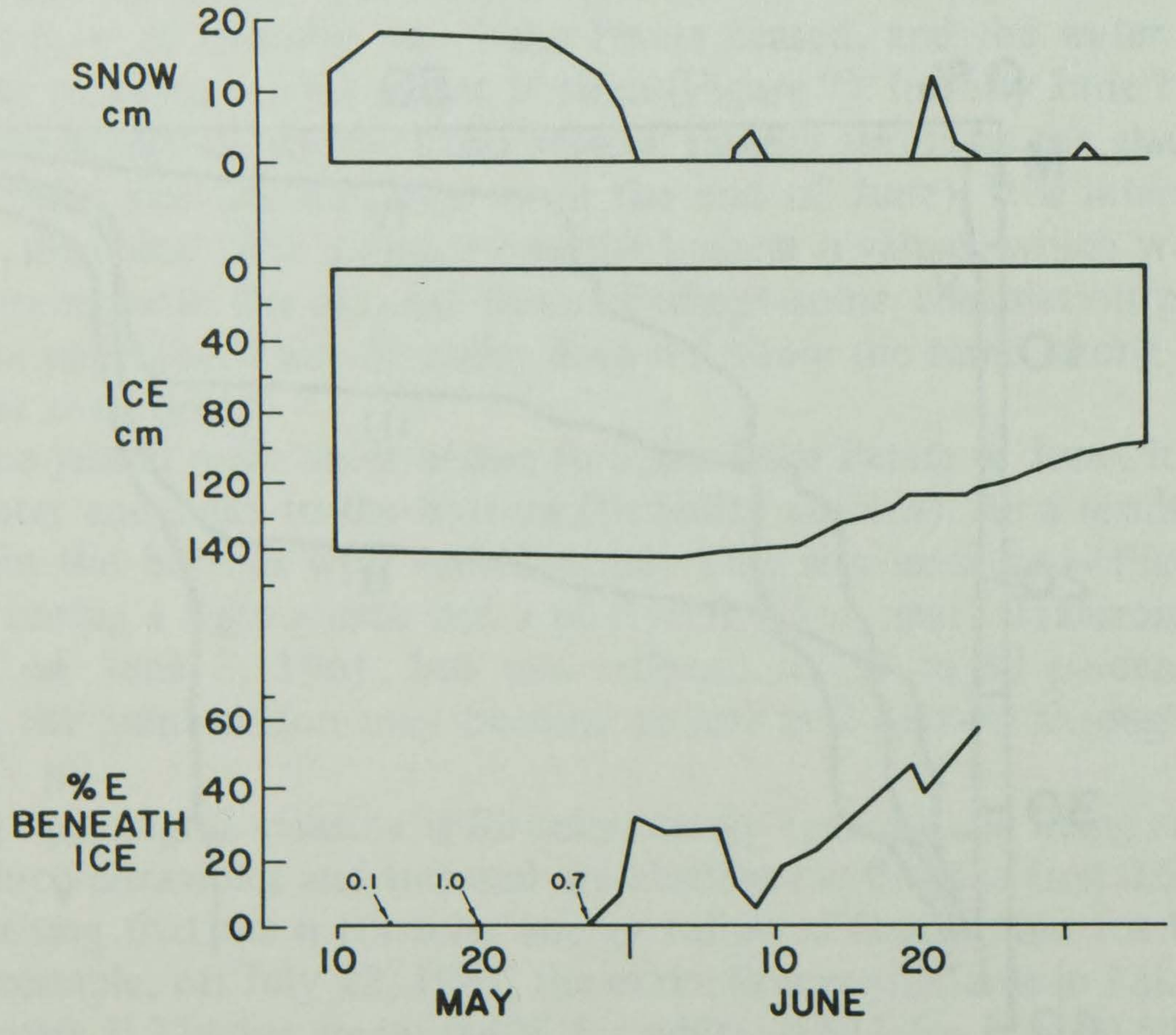


Figure 9. Solar energy (percentage of surface energy) penetrating ice and snow at Lake Peters. (Hobbie, Holmgren, and Kalff, unpublished)

Lakes that are ice free in the summer almost never stratify. Instead, they warm slowly and irregularly with brief periods of a few days when the stratification begins to appear in the upper waters. Invariably, because of low temperatures there is not enough density difference and a wind soon mixes the entire lake. The single exception—Lake Schrader—has already been discussed, but there are also meromictic lakes in the Arctic. In these lakes, sea water intrusion is the usual cause for the noncirculation of bottom waters. One such lake, Tuborg Lake at 82°N on Ellesmere Island, is separated from a fiord by a glacier (Hattersley-Smith and Serson 1964). The top 46 m of the lake is freshwater, but the salinity rapidly increases below this point. One sample of water from 90 m (maximum depth at this station was 130 m) had a salinity of 26 ppt and a ^{87}Sr to ^{80}Sr ratio similar to sea water (Jones and Faure 1972). A smaller lake in Greenland (Holmquist 1959, p. 143) near Christianshaab also contains sea water, but it is close to the sea and likely receives periodic inflows of sea water at spring tides. A second possible cause of meromixes—biological respiration and mineralization—has been suggested as a cause for the stratification in Lake Kongressvatnet, Spitsbergen by Amren (1964b), but the lake needs to be investigated further before meromixes can be proved.

It is usually assumed that the ice cover isolates a lake from wind and solar radiation and thus prevents circulation. As already noted, shallow lakes have a great amount of heating, and thus water movement, beneath the ice. Deep lakes also circulate even when ice covered, albeit at slower rates than when open. One mechanism for circulation is the solar heating of the water close to the ice sheet and the subsequent sinking of that water (Figure 6). This is even noted in permanently frozen Angiussaq Lake (Figure 5). Since this lake is in contact with a glacier, however, Barnes (1960) suggests that deep-water cooling is also at work (at temperatures below 4°C, the cooled water would rise toward the surface). That oxygen was also constant at 95 percent of saturation, even in the deepest water of this lake, is additional evidence that some circulation was going on. In the same lake, a density current was also noted moving down the bottom of the lake. This current originated in the open water of a shallow arm, about 10 km from the glacial dam. Here, about a 1 km^2 of open water developed during the summer; and, in this 20-m-deep bay, water temperatures reached 0.6°C. At the bottom, however, a 3-m-thick layer of warm water (0.72°C) formed and flowed beneath the ice toward the deepest part of the lake (187 m). This density current could be traced for more than 7 km.

A different type of density current develops in lakes that are open for part of the year. The sediments are warmed during the ice-free period and then release heat during the winter. A thin layer of water (10 cm) is heated slightly and flows down the sides of the lake to pool in the deepest part. This pool of warmer water is seen in Lake Peters (Figure 6) for May 25. Not only is this water warmed, but it also loses some oxygen and picks up some bicarbonate because of the relatively high respiration in the sediment surface. Thus, on May 24 the concentration of oxygen at 30 m, 40 m, and 47 m was 7.9, 7.8, and 6.0 mg per liter. Mortimer (1971) describes similar currents and has used the amount of deoxygenation to calculate the sediment respiration in a deep subarctic lake, while Welch (1972) used this method for estimating total production in Char Lake. It is interesting that every lake examined has this deoxygenated water in the deepest part, except for lakes with a permanent ice cover. I have even found it in a 56-m-deep subarctic lake (Kuoblatjakkojaure) (see Rodhe *et al.* 1966 for a description) that circulated briefly at 2.8°C (maximum) during the summer, so possibly the added ions alone are enough to cause a density change.

Hydrology. The hydrology of arctic regions has been little studied, but it is strongly affected by low precipitation and permafrost. The entire arctic region receives annually less than 40 cm of precipitation, and much of it receives less than 25 cm. The coastal regions of southern Greenland may receive more than 50 cm, but the interior of Greenland gets less than 12 cm as does most of the Canadian archipelago (Hastings 1961). Much of the precipitation accumulates during the winter as snow which melts and runs off rapidly in early June. The active layer is completely frozen at the beginning of the melt, so the water cannot sink into the soil. After several weeks, the active layer has thawed, evapotranspiration of plants has increased, and the streams virtually dry up. Any brief rainfall will quickly fill the streams again as the permafrost keeps water from penetrating into the soil more than 1 m or so.

In an extreme example, Brown *et al.* (1968) found that evapotranspiration almost exactly matched summer precipitation on a drained lake bed near Barrow. Thus, although 50 percent of the annual precipitation of 12 cm ran off in stream flow, this was mostly snowmelt, and only 5 percent of the summer rainfall entered the streams. While an annual budget was not calculated, Likes (1966) found that from 40 to 100 percent of summer storm precipitation appeared in Ogotoruk Creek, Cape Thompson, where the drainage was much better developed than at the Barrow site.

An estimate of the water balance of Novaya Zemlya (Kuziu 1960, quoted in Sater 1969) is that only 15 percent of the 35 cm of precipitation is evaporated. This is exactly the same value calculated for the Peters-Schrader drainage basin in Alaska (Hobbie 1961), where 15 percent of the annual 30.5 cm of precipitation was lost by evaporation (Table 2). Angiussaq Lake (Table 2) is at the edge of the Greenland ice cap from which it receives 80 percent of its flow. At this location, near Thule, the ablation zone extends up to 800 m in altitude and up to 1 m of ice is melted each summer. Because of the stored water, the lake receives five times more water than it should for the size of its drainage basin. Livingstone (1963) pointed out that Greenland lakes can lose more water by evaporation than they gain by inflow, thereby concentrating the salts. From the Angiussaq Lake data, this would occur only where the lake was not draining a part of the ice cap.

Another feature of arctic hydrology is the continued loss of water from large lakes during the winter. All inflow into arctic lakes ends during September, except for some subsurface flow, yet the rivers draining those lakes continue to flow and the lake level falls. Greely (1886) noted that over a winter the water level of Lake Hazen fell 3 to 4 m so that in the spring the ice close to shore was higher than that farther out in the lake. Nettilling Lake drops about 1 m during the winter (Oliver 1964) as do Lake

Table 2. Hydrology of two lake systems.*

Measurements	Peters (1959)	Schrader (1961)	Angiussaq (1957)
Flow through lakes ($10^6 m^3$)	76.0	84.0	100
Replenishment time (year):			
Peters	2.5	2.2	20
Schrader	5.2	4.7	
Total runoff (cm)	23.0	26.0	50 (est.)
Total precipitation (cm)	....	30.5	10 (est.)

*Data are from Barnes (1960) and Hobbie (1962).

Peters and Lake Schrader (Hobbie 1962). In these latter lakes, the water level fell from 125 cm to 34 cm in August and September. This 34-cm level was the elevation of the bottom of the outlet stream. After October 1, the lake continued to drain but underground through the end-moraine that dams the lakes. By June of the following year, 34 cm of water had drained from the lakes and the ice was raised by this amount close to shore. This overwinter loss was equivalent to 6 percent of the total runoff in the drainage basin. The implications for limnology of this water loss is that the ice affects the upper 3 m of the littoral zone and will keep all vegetation out of this zone.

Chemical Limnology

Inorganic ions (except nutrients). It is remarkable that the concentration of ions in arctic freshwaters is similar to the concentration in temperate waters. In both environments, ionic concentrations in streams and lakes depend upon the soil characteristics and, ultimately, upon the parent bedrock of the drainage basin. One important variable in arctic soils is the depth of the active layer. During snowmelt, the chemical composition of the water resembles that of the precipitation, which is extremely dilute in the Arctic (Table 3). After snowmelt, the active layer begins to thaw and the concentration of ions in the stream water increases. For example, at Prudhoe Bay, Bilgin and Douglas (1972) found that the stream water concentration of potassium, calcium, and magnesium increased 80 to 130 percent over the summer, while ions increased 470 percent as a result of leaching through a deeper active layer. Although all the soils in this region arose from the same parent material, the chemical characteristics of the runoff water still varied according to the degree of drainage, amount of sand or organic matter, and degree of wetness.

Not only will the ionic concentration vary with the soil type, but also there are tremendous differences between waters on different types of bedrock. For example, the stream entering Lake Peters (Table 3) flows over the Neruokpuk formation of acidic quartzites and schists (Brown *et al.* 1962). In contrast, the stream entering Char Lake passes over the Read Bay formation of limestones, shales, sandstones, and silts (Roff and Carter 1972). Ions in arctic streams do vary with the flow rate, however, especially when some of the water is coming from snow or ice melt. For example, one stream entering Lake Peters drains a glacier (Table 3). Between July 7-14, the stream was composed of nine parts glacial melt water to one part ground water and had a hardness of 4 ppm $CaCO_3$. Between August 17-31, the flow had decreased so that there were only 1.5 parts glacial melt water to 1 part ground water. The hardness had increased to 20 ppm $CaCO_3$ (Rainwater and Guy 1961).

Small tundra ponds may become quite concentrated as a result of evaporation over the summer. Kalff (1965) measured a conductivity of 90 in early June and of 190 in mid-August in a shallow pond near Barrow. This pond became very concentrated as the ice thickened during September and excluded salts. This concentration by freezing also occurs in shallow lakes where all the salts become concentrated into the bottom 1 to 1.5 m. Thus, Imikpuk Lake at Barrow (maximum depth is 3 m) had a total alkalinity (as $CaCO_3$) of 190 ppm at 2.5 m at the beginning of the melt period. During the summer, the normal alkalinity is 40 (Kalff 1967b).

In general, Kalff (1968) concluded that the 58 rivers and lakes he examined in northern Alaska and northwestern Canada were dilute bicarbonate waters with levels of major electrolytes similar to those in low electrolytic temperate waters. The Alaskan waters resembled waters of standard composition, determined by Rodhe

Table 3. Concentration (ppm) of inorganic ions, conductivity, and pH in arctic waters.

Location and reference	Conductivity (25°)	pH	HOC_3^-	$SO_4=$	CT^-	Ca^{++}	Mg^{++}	Na^+	K^+	Si^{4+}
Precipitation at Char Lake, June-August (Schindler and Kritsch 1972) mean:										
Rain	–	7.8	18.5	1.2	2.7	5.6	0.7	0.7	0.2	0.04
Snow	–	6.5	6.4	2.0	7.0	2.0	0.6	1.1	0.2	0.01
Streams entering Char Lake (Schindler and Kritsch 1972) mean . .	–	8.0	10.3	7.7	4.5	21.8	3.6	2.7	0.0	0.33
Char Lake (Schindler and Kritsch 1972 and unpublished)	215 to 252	7.8 to 8.2	90 to 153	5.4 to 14.0	3.9 to 14.9	34 to 37	6-7	4-7	0.6 to 1.1	0.2 to 0.3
Precipitation at Lake Peters (Rainwater and Guy 1961)	8.1	5.7	5.4	0.4	0.0	0.7	0.1	0.3	0.1	0.0
Glacial stream entering Peters (Rainwater and Guy 1961), July 7-14	11	6.5	9.0	1.4	0.2	1.5	0.1	0.1	0.0	0.06
Stream entering Peters at Camp (Rainwater and Guy 1961)	97	7.0	35.0	19.0	0.2	12	3.3	0.2	0.1	0.28
Lake Peters (Rainwater and Guy 1961)	60	7.0	25.0	9.4	0.3	8.2	1.9	0.2	0.3	0.17
Pond 2 at Barrow (Kalff 1968) mean . . .	197	6.9	–	–	45.0	7.9	5.1	–	–	–
Colville River, Aug. (Kalff 1968)	105	7.2	–	–	1.0	14.7	3.2	–	–	–

(1949) for Scandinavian lakes, except for lakes lying within 25 to 50 km of the Arctic Ocean where the chloride content was appreciably increased.

Nutrients and trace metals. In Alaska, trace metals have been analyzed by Kalff (1968) for a Barrow pond; by Barsdate (Personal Communication) for a large series of lakes in the coastal plain, foothills, and mountains; and by Brown *et al.* (1962) for a large number of streams and lakes throughout northern Alaska. The method of concentration used by the authors of the latter paper allow comparisons to be made only within their data. Kalff gives the most extensive analyses (18 elements) and found that iron was higher than expected, probably because of the high amounts of dissolved organic compounds. Both Barsdate and Kalff found total iron as high as 1.5 to 2.5 mg per liter in shallow ponds and in a creek near Barrow. Bilgin and Douglas (1972) found that the total iron was high in streams draining organic and Bog soils at Prudhoe Bay. Data reported in Table 4 for the coastal plain do not include shallow ponds, so these high values do not appear. The high values for Brooks Range lakes in this table come from Lake Peters, where the particulate material from glacier runoff reached 806 μg per liter. Although all the other metals are present at extremely low concentrations, these elements can play important roles in limiting algal photosynthesis. For example,

Barsdate (Personal Communication) reduced photosynthesis by 40 to 70 percent over controls by adding just 3 μg per liter of cobalt, copper, lead, and zinc to tundra pond samples. Another series of experiments using a trace metal mixture showed that low levels of addition sometimes enhanced photosynthesis while higher levels usually depressed the process (Kalff 1965).

Nutrients are always low in arctic waters undisturbed by man. In fact, they are so low that special methods must be used in analysis. For this reason, all of the analyses carried out before the mid-1960's are suspect. One reason for the extreme values is the low nutrient content of the precipitation. For example, Kalff (1968) measured 3 μg of reactive phosphorus per liter and 9 μg of NO_3-N per liter at Barrow, while Schindler and Kritsch (1972) found only 8 μg of total phosphorus per liter at Char Lake. While temperate zone precipitation is not too different in the amount of phosphorus, it contains much more nitrogen.

Phosphorous concentrations are always low in arctic waters, while the nitrate is low in lakes and high in ponds and rivers (Table 5). Most of the phosphorus is present as dissolved organic forms while the biologically active, dissolved reactive phosphorus is usually less than 5 μg per liter. Dissolved organic nitrogen (DON) is the most abundant form of that element, but this also is relatively inert. Even in the dilute waters of Char Lake, there are likely 300 μg of DON per liter (dissolved organic carbon (DOC) of 3 mg, C:N = 10:1). Aside from DON, nitrate and then ammonia are the most important. Silica is present in low concentrations in ponds, moderate amounts in lakes, and relatively high amounts in rivers (Table 5). Fertilization experiments by Bilgin and Douglas (1972) revealed that Tundra soils reacted similarly to other soils, and immobilized phosphorus and NH_4. Nitrate was rapidly converted to ammonia and did not appear in the drainage stream.

Because of the low levels of nutrients, annual cycles are difficult to detect. They could not be measured in Lake Peters (Hobbie 1962) for phosphorus, or in Char Lake for phosphorus or nitrogen except for changes due to the inflow of dilute melt water. However, a lake close to Char–Meretta Lake–receives sewage from the Resolute Bay camp during the spring runoff. Schindler and Kritsch (1972) found that phosphorus was undetectable in this lake before the spring runoff, attained 194 μg per liter shortly after runoff began, and then was back to undetectable levels one month later. Ammonia followed a similar pattern, although there was a small amount present before runoff began. In the case of nitrate, however, a large amount had accumulated

Table 4. Trace metals (μg per liter) in lakes of northern Alaska.*

Area	Composition	Co	Cu	Fe	Mn	Pb	Zn
Coastal plain (3-8 samples)	Dissolved	3.7	1.7	138	1.7	0.6	2.0
	Total	5.4	3.3	224	91.0	–	5.1
Foothills (1-3 samples)	Dissolved	3.3	2.1	15	1.0	1.0	3.2
	Total	5.1	2.7	64	7.0	–	–
Brooks Range (7 samples)	Dissolved	1.2	0.4	24	1.0	–	–
	Total	1.8	0.6	315	7.5	–	2.0

*Barsdate (Personal Communication).

Table 5. Phosphorus, nitrogen, and silica (μg per liter) in arctic waters.

Nutrient	Barrow ponds[1]			Colville River[2]		Ikroavik Lake[3]	Char Lake[4]
	June	July	August	Umiat	Delta		
Dissolved reactive (P) . . .	1.4	1.6	1.6	3.7	1.9	5.9	0.6-1.0
Dissolved unreactive (P) .	14.0	11.9	11.2	–	–	–	0.4-5.0
Partial (P)	9.4	7.4	5.9	–	–	–	1.0-5.0
Nitrate (N)	32.7	50.3	9.7	41.0	61.0	4.4	[5]1-30
Nitrite (N)	0.3	0.3	0.2	1.2	2.5	–	[6]
Ammonia (N)	23.7	30.7	43.3	–	–	–	1-11
Dissolved organic (N) . . .	920.0	907.0	170.0	–	–	–	[7]64-100
Partial (N)	74.0	52.3	54.0	–	–	–	11-99
Silica (Si)	65.0	91.0	52.0	868.0	599.0	419.0	230-330

[1] Barsdate and Prentki (1972).
[2] Kinney *et al.* (1972).
[3] Kalff (1968).
[4] Schindler and Kritsch (1972).
[5] Includes nitrate (N).
[6] Undetectable.
[7] Total dissolved N minus ($NO_3 + NO_2 + NH_3 - N$).

in the lake before runoff started, presumably from decomposition. After the spring, the pattern for nitrate was similar to that for phosphorus and ammonia. In spite of intensive efforts, no pattern has emerged from nutrient measurements in the Barrow IBP ponds (summarized in Table 5).

In shallow ponds, the sediments dominate the nutrient cycling. One bit of evidence for this is the rapid loss of added phosphorus from the water of ponds (Barsdate and Prentki 1972). With added phosphorus of from 21 to 778 μg per liter, the ponds returned to a concentration within 2 percent of the original level within 6 days. Not only did the sediments remove phosphorus, but also they acted to buffer the concentration in the water and hold it relatively constant. One way these equilibria act is through exchange with surficial and wind-suspended particulate matter. Another mode of action is by exchange with interstitial water which contains 1.5 to 7.1 μg of reactive phosphorus per liter (about 600 times that amount exists in particulate forms readily exchangeable with the interstitial phosphorus). Additional phosphorus is released through leaching of litter and by live plant excretion into the water column. Barsdate (Personal Communication) has estimated that *Carex aquatilis* in one pond excretes enough phosphorus to account for all phytoplankton growth. The sediments are also active in nitrogen cycling. Evidence for this is that artificial ponds without sediments rapidly became nitrogen limited for photosynthesis. This limitation never occurs in natural ponds fertilized with phosphorus even though ammonia and nitrate levels are never high.

Dissolved organic matter. The measurement of dissolved organic matter (DOM) or carbon (DOC) is not a part of usual water analyses. As a result we have only a few values. The general picture for large lakes is the same as that for oligotrophic temperate lakes; that is, 3 to 4 mg of carbon per liter–Char Lake has 3.1 (Schindler and Kritsch 1972). No data exist for rivers, but small tundra ponds have been studied in detail by Miller (1972a) at the IBP site near Barrow. In 1971, the melt water from the snow contained 0.4 to 3.3 mg of carbon per liter (mid-June). After thaw, the ponds

reached a maximum (13 to 20 mg of carbon) in early July. After this time, concentrations of DOC were relatively stable (although rainfall diluted the DOC in ponds with small drainage basins, or increased the concentration slightly in ponds with large watersheds). Humic materials, estimated by Miller to be at about 0.5 mg of carbon per liter, colored the water slightly. It is likely that the DOC comes from the decomposition of aquatic sedges and grasses, from soil processes in the drainage basin, from sediments, from excretion by aquatic plants and animals, and from snowmelt.

The DOC is composed of many compounds, most of them resistant to bacterial or physical decomposition. Miller (1972a) measured a photodecomposition of 0.43 mg of carbon per liter per day, but the bacteria take up small molecular weight compounds much faster than this. For example, in the Barrow ponds Hobbie (unpublished) measured turnover times for removing completely all of the compounds from the water of from 11 to 120 hours for glucose, proline, and aspartic acid. In Char Lake, Morgan and Kalff (1972) measured a turnover time of 40 to 1,300 hours for glucose. These rapidly cycling compounds come from decomposition as well as from excretion during photosynthesis and make up only a small fraction of the DOC at any one time.

Dissolved gases. When arctic lakes are ice free, they are almost always close to complete saturation of oxygen. Lake Peters, for example, was between 95 and 100 percent saturated during the summer, but then the saturation level fell to 88 percent on September 5 as the lake cooled faster than the water could take up oxygen from the air (Hobbie 1962). In February, under the ice, the top of the water column was at 100-percent saturation, probably due to exclusion of the gases during freezing, and the rest of the water down to 35 m was above 90-percent saturation. Below this depth, in both Lake Peters and Lake Schrader (Figure 10), was a pool of deoxygenated water

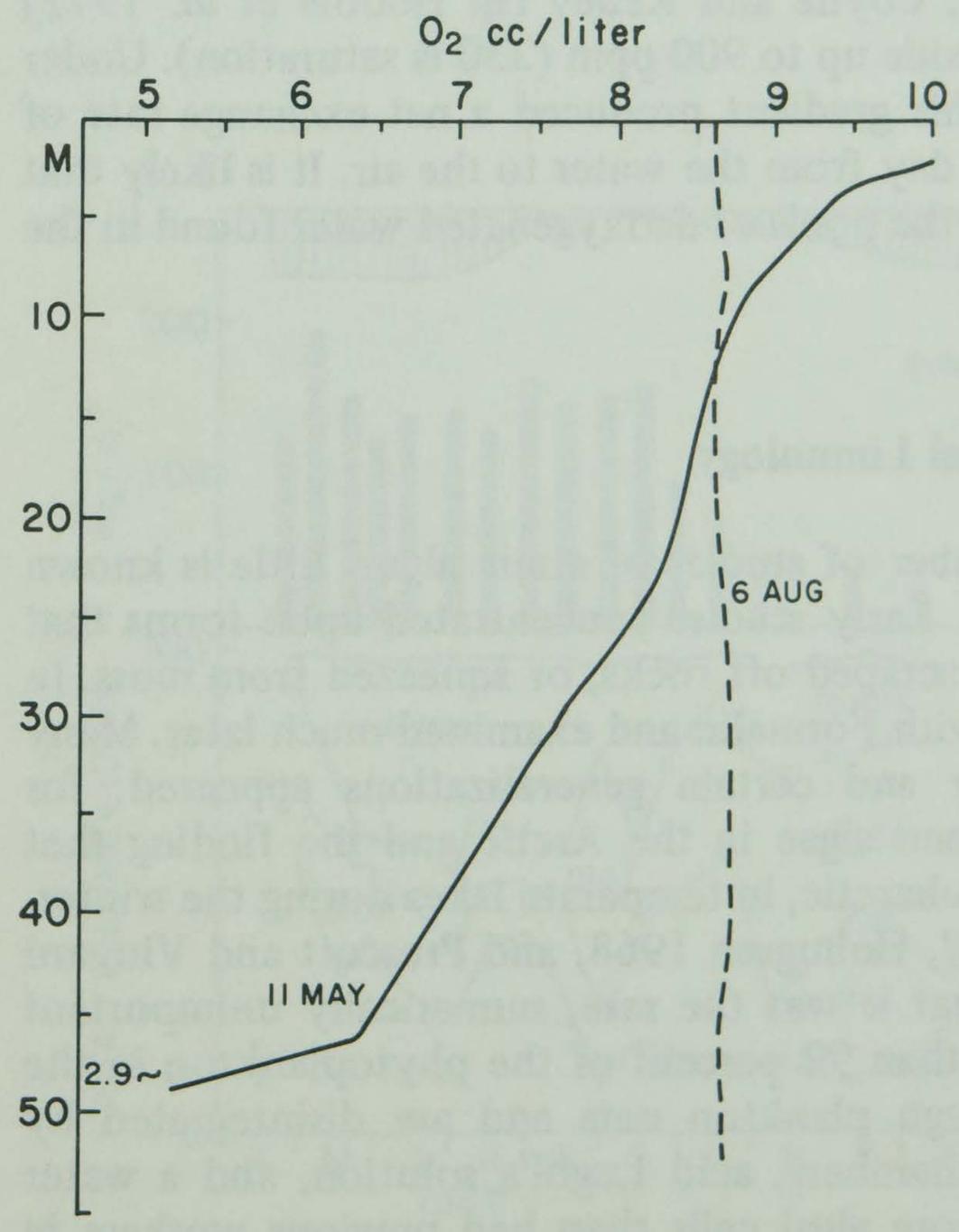


Figure 10. Oxygen concentration in Lake Schrader. (Hobbie 1962)

formed by density currents flowing down the sides of the lake. Slight supersaturation (120 percent) was found during May when there was high photosynthesis immediately beneath the ice. This supersaturation under ice has also been found in Ikroavik Lake, near Barrow, where the oxygen reached 174 percent in early June and 120 to 140 percent in early December (Barsdate, Trible, and Prentki, Personal Communication). Probably both exclusion and photosynthesis are at work here; but, since there was 1.6 m of ice and only 0.8 m of water in June, exclusion is the more important process.

Even in the Arctic, however, there may be severe deoxygenation in the water of shallow lakes beneath the ice. For example, Lake 5 (3 m deep) at Cape Thompson (Tash and Armitage 1967) had 5 ppm of oxygen at the end of January 1961, and 0 ppm on April 10. Although not discussed by these authors, there is a possibility that deep snow covered the ice and prevented the spring algal bloom, because the water was anaerobic until the ice left the lake.

Arctic lakes under ice and snow covers are sealed from oxygen exchange with the air. For 6 to 7 months, then, they act as sealed respirometers, and the rate of loss of oxygen from the water and sediment can be calculated. In Char Lake, Welch (1972) found that the rate of loss was constant from late September until the end of February while in the nearby sewage-affected lake (Meretta) the loss was linear until the end of December only. He suggested that the higher loss rates in the fertilized Meretta Lake resulted in severe oxygen depletion and eventual reduction of metabolism by the organisms.

Dissolved carbon dioxide, like oxygen, is changed mainly by biological processes in arctic lakes. Usually the change is slight and concentrations remain close to saturation. One case of a change caused by photosynthesis was indicated by the increase in pH from 7.2 to 9.4 in Meretta Lake under the ice (Schindler and Kritsch 1972). In shallow tundra ponds the respiration is so great in the bottom sediments that the water above becomes supersaturated with carbon dioxide and actually gives off large amounts to the air. Thus, in a pond near Barrow, Coyne and Kelley (in Hobbie *et al.* 1972) measured partial pressures of carbon dioxide up to 900 ppm (330 is saturation). Under the prevailing wind and temperature, this gradient produced a net exchange rate of 250 to 1,300 mg of carbon per m^2 per day from the water to the air. It is likely that carbon dioxide is also supersaturated in the pools of deoxygenated water found in the bottom of deep lakes.

Biological Limnology

Phytoplankton. In spite of a large number of studies of arctic algae, little is known about their taxonomy and distribution. Early studies concentrated upon forms that could be captured with a plankton net, scraped off rocks, or squeezed from moss. In addition, most samples were preserved with Formalin and examined much later. Many species were described in this manner and certain generalizations appeared; for example, the virtual absence of blue-green algae in the Arctic and the finding that almost all arctic forms also exist in the Subarctic, in temperate lakes during the winter, and even in the Antarctic (Hansen 1967, Holmgren 1968, and Prescott and Vinyard 1965). It is now obvious, however, that it was the rare, numerically unimportant species that were described, since more than 99 percent of the phytoplankton in the Arctic are small forms that pass through plankton nets and are disintegrated by Formalin. Kalff (1967a) used settling chambers, acid Lugol's solution, and a water immersion lens to identify 10 times more algal cells than had previous workers in

Imikpuk Lake. It is still easier to use the same chambers and preservative but to count with an inverted plankton microscope.

The annual cycle of phytoplankton succession and biomass is illustrated in Figure 11 for Char Lake. Biomass is given as wet weight determined from the number of organisms, the volume of each species, and the specific gravity of algae (assumed to be unity). In February, the populations began to increase and reached a level in early May which they held until early September. Beneath the ice in the spring the dominant forms were *Gymnodinium helveticum* (a dinoflagellate) and then *Chrysococcus, Chromulina,* and other Chrysophytes. Two species of *Cyclotella* were present most of the year. Data are also available for other arctic waters (Table 6), all of which have a biomass less than 400 mg per m^3. The subarctic lake, Nedre Laksjön, had slightly higher biomass but did not compare with the eutrophic Lake Esrom and Lake Erken (Jonasson 1972, and Nauwerck 1963) which had annual ranges of 400 to 3,000 and 300 to 6,000, respectively.

Surprisingly, arctic lakes have greater quantities of algae than do alpine or subarctic lakes; for example, the mountain lakes of northern Sweden which always have less than 50 mg per m^3 (Nauwerck 1968, and Rodhe *et al.* 1966). Holmgren (Personal Communication) suggests that both arctic and alpine lakes are relatively poor habitats for algae in the summer when the water is circulating. However, sizable populations of algae can build up under the ice of arctic lakes where spring conditions are stable. Because no light penetrates the ice of subarctic lakes until just before the ice leaves the lakes, the algae never have good growth conditions.

Most of the algae of arctic lakes are small flagellates whose numbers may exceed 10^7 per liter (Kalff 1967a). Small size and motility allow the organisms to choose the most favorable light level under the ice cover, but these may also play a role in nutrient uptake. Perhaps the high surface-to-volume ratio may be advantageous in these nutrient-poor waters (Kalff 1970).

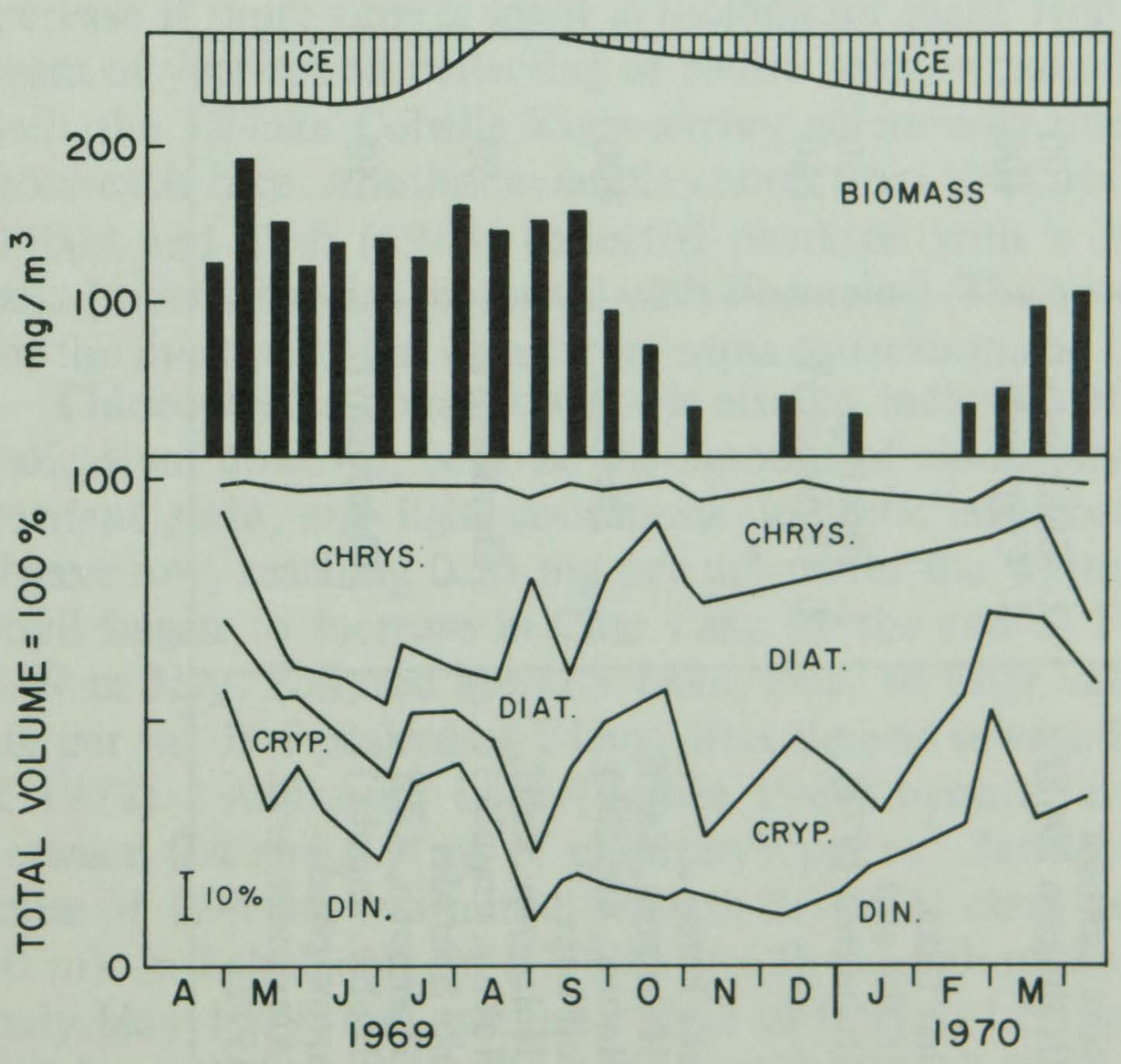


Figure 11. Average phytoplankton and its composition in Char Lake. (Kalff and Holmgren 1971)

Table 6. Phytoplankton biomass (mg wet weight per m^3) and dominant groups in arctic lakes and ponds (groups are listed in chronological order of dominance).

Lake and reference	Spring (under ice)		Early summer		Late summer		Late fall and winter (under ice)	
	Group	Biomass	Group	Biomass	Group	Biomass	Group	Biomass
Nedre Laksjön (Holmgren 1968) ..	1. Chlorophyt. 2. Cryptophyt.	100 400	1. Chrysophyt. 2. Cryptophyt.	550 550	Diatoms ...	400 –	Diatoms ...	124 –
Char Lake (Kalff and Holmgren 1971) ...	1. Dinoflag. 2. Chrysophyt.	150 150	Diatoms ...	150 –	... ...	– –	Diatoms Dinoflag.	50 100
Lake Peters (Holmgren, Kalff, Hobbie, unpubl.) ...	Diatoms	400	Diatoms	250	...	–	...	–
Wolf Lake (Holmgren, Kalff, Hobbie, unpubl.) ...	Chrysophyt.	50	Chrysophyt.	150	Cryptophyt.	150	...	–
Lake Schrader (Holmgren, Kalff, Hobbie, unpubl.) ...	Chlorophyt.	50	Chrysophyt.	200	Chrysophyt.	150	...	–
Barrow ponds (Alexander *et al.* 1972)	...	–	Chrysophyt.	100	Cryptophyt.	200	...	–

The dominant group of algae is usually the Chrysophyceae, although the Cryptophyceae, especially *Cryptomonas* and *Rhodomonas minuta,* are always present and may be dominant at certain times of the year. Diatoms may be important in deeper lakes (Table 6) but are rare in tundra ponds and shallow lakes. Dinoflagellates reached sizable populations only in the deeper water beneath an ice cover (for example, Char Lake). Some of these forms may well be phagotrophic at this time. All of the lakes studied in detail have so far had different algal succession patterns.

While similarities will emerge as the data base grows, the tremendous variability exhibited in 10 lakes of the Colville River drainage illustrates the difficulties. These lakes were sampled on a single day using a float-equipped plane (Figure 12), with zooplankton and chemistry also being measured. Biomass varied from 1 to 370 mg per m^3, and the dominant groups were Chrysophyceae, diatoms, and Cryptophyceae. Many of the diatoms were benthic or littoral forms, however, that were perhaps suspended by turbulence following high winds shortly before the sampling date. White Lake was extremely turbid and had a correspondingly low biomass, but the other variations are difficult to explain. A correlation analysis between the biomass of the various groups and the temperature or nutrients (silicon, phosphorus, nitrogen) indicated that the only good correlation (greater than 0.80) was phytoplankton biomass with silicon. In another example (Table 6), Lake Peters had an underice bloom of the diatom *Synedra* in 1968 while nearby Lake Schrader had a bloom of Chlorophyta (*Chlamydomonas, Pyramidomonas,* and *Ankistrodesmus*). Water chemistry and transparency were the same in both lakes, except that Lake Schrader had 40 cm of snow on top of the ice in early May while Lake Peters was clear of snow.

The number of species is lower in arctic lakes than in the temperate regions, yet the numbers are still large. For example, Willén (unpublished data) recorded 150 forms from the area around Linnevatnet, Spitsbergen; Holmgren (1968) found 465 species in Nedre Laksjön in the Subarctic; but Kinney *et al.* (1972) found only 221 in the Lake Peters area (unpublished) and 172 in the 10-lake survey of the Colville River drainage. All Char Lake species have also been found in southern Canada (Kling 1972). Yet, comparing numbers of species can be an unrealistic game because the numbers found increase if more time is spent in looking for them. Holmgren's high values from several years of year-round collecting in Nedre Laksjön cannot, therefore, be really compared with the 10-lake Colville River survey where only one plankton sample was counted from each lake. Another example comes from the Cape Thompson area, Alaska, where Hillard and Tash (1966) collected plankton with a 20-mesh net and identified 708 taxa (mostly species preserved with Formalin). The species found were not planktonic, for the most part, but came from moss squeezings and benthic debris.

Chlorophyll *a* concentration is also an indicator of algal populations. It is only an indication, however, because the amount of chlorophyll per cell will change with age, nutrient state, and light conditions. In arctic lakes concentrations of chlorophyll are always low, reaching 0.13 mg per m^3 under the winter ice of Char Lake. The chlorophyll began to increase in Char Lake by the end of February and reached a peak of 0.69 in May. Polluted Meretta Lake, close to Char Lake, usually had between 3 and 5 mg per m^3 but peaked at 24 mg after thawed sewage began to enter the lake (Kalff *et al.* 1972). Angiussaq Lake (Barnes 1960) beneath a permanent ice cover contained between 0.4 and 0.9 mg of chlorphyll per m^3 during the summer, but one early June value of 1.94 mg was noted beneath 2.7 m of clear ice (values decreased to 0.5 mg at 50 m). In Lake Schrader (Hobbie 1962), the chlorophyll was 0.32 to 0.6 mg per m^3 in early May 1959, but reached a peak of 0.53 to 1.60 just before the ice left the lake in mid-July. Open water values averaged 0.70 to 0.98 in 1958 and 1959. Barrow tundra

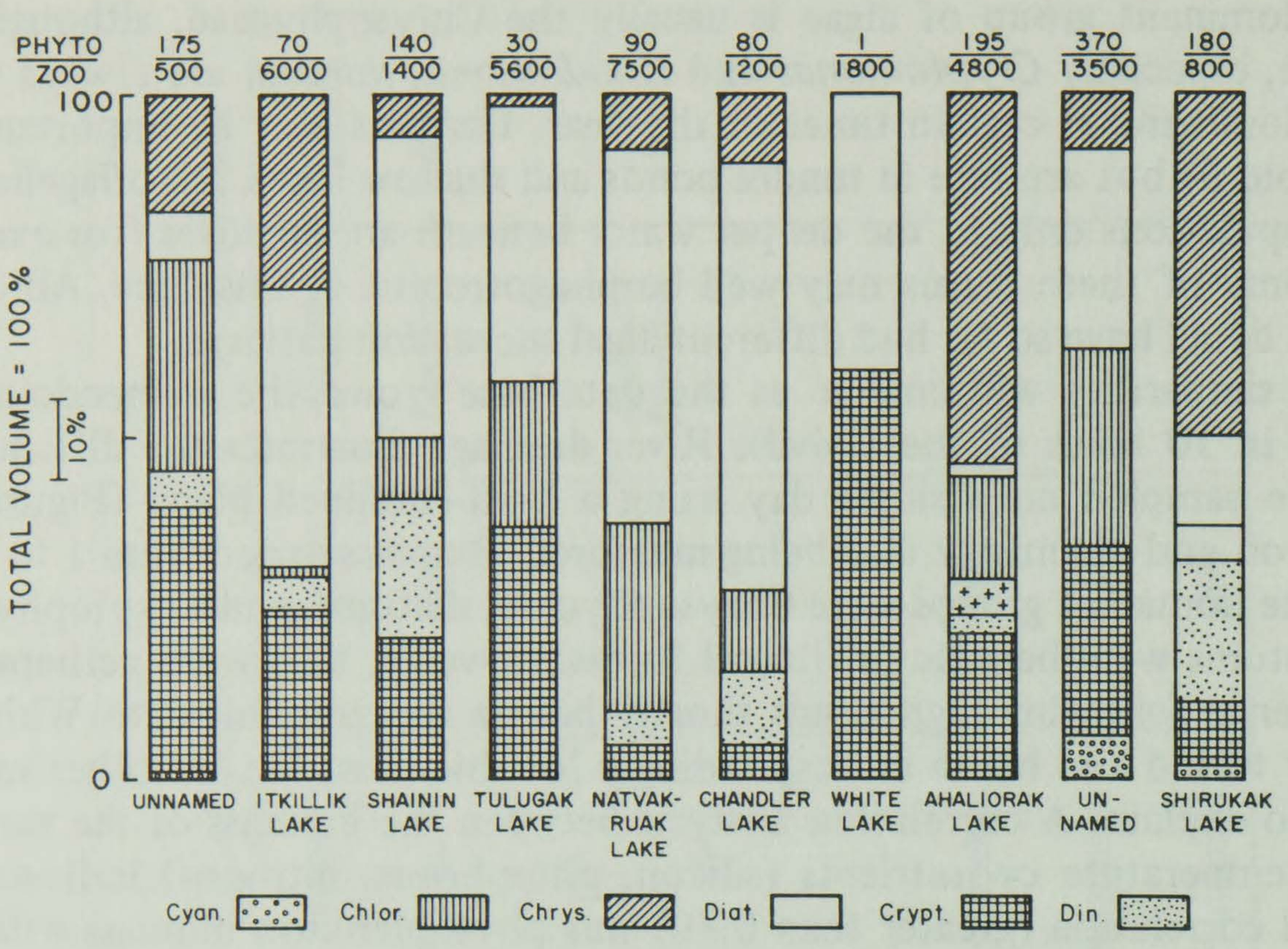


Figure 12. Phytoplankton and zooplankton quantities (mg wet weight per m^3) and percentage composition in 10 lakes in Colville River drainage basin. (Coulon, Holmgren, and Alexander in Kinney *et al.* 1972)

ponds peaked at 1.3 mg of chlorophyll *a* per m^3 only 11 days after the ice left the ponds but later fluctuated between 0.4 and 0.8 (Hobbie *et al.* 1972).

Phytoplankton production is so low in arctic ponds and lakes that only radioisotopic techniques have the needed sensitivity for making measurements. The productivity of Char Lake began in February (Figure 13) and increased to a peak in July and August of 70 mg of carbon per m^2 per day. Most of the values lay between 15 and 40 mg. Lake Schrader had high photosynthesis during the spring beneath the ice cover and reached peak rates of 167 mg of carbon per m^2 per day. Productivity during the open water periods lay between 30 and 60 mg. As a result, Hobbie (1964) found that 50 to 85 percent of the annual production occurred beneath the ice cover. In contrast, the turbid water of Lake Peters severely limited productivity, and between 0.6 and 14.0 mg of carbon per m^2 were produced per day. Both Char Lake and Lake Peters began to have positive photosynthesis in late February when only a fraction of a calorie of insolation penetrated the snow and ice cover.

With no nutrient input and clear water, the annual production was 6 to 8 gm of carbon per m^2 in arctic lakes (Table 7). Glacial melt water curtailed production drastically (Lake Peters), and sewage input during the summer raised production to the 15- to 30-gm-carbon range (Meretta Lake). Tundra ponds produce between 0.3 and 0.8 gm, but only because they are so shallow. Expressed on a cubed-meter basis, the ponds are fixing carbon at a rate 10 to 20 times faster than the lakes. Added nutrients increased productivity in the ponds while crude oil decreased it. Even the polluted Meretta Lake falls into the oligotrophic lake group, which covers the range from 0 to 100 gm of carbon per m^2 per year.

Algal photosynthesis rates are chiefly limited by the low amount of nutrients. Both Meretta Lake and Pond E near Barrow (Table 7) increased production after

fertilization. Artificial pools at Barrow in 1971 also showed increased photosynthesis as a result of phosphate addition, and there was even a response to nitrate addition but only when no sediments were present. Kalff's (1965, 1971) experiments with additions to samples in small bottles revealed that tundra ponds responded to phosphate, ammonia, and nitrate additions during times of high photosynthesis. At the end of the period of high photosynthesis, the phytoplankton responded to trace metal and vitamin additions, but they did not respond later during a period of low photosynthesis. Additional experiments in Lake Peters in 1968 (Kalff, unpublished) also indicated that low phosphorous concentrations were limiting the photosynthesis.

As noted, turbidity can limit light penetration (Lake Peters in Table 7, White Lake in Figure 12), but there is usually enough light beneath arctic ice covers in the spring so that large algal populations build up. In fact, there is so much light that the photosynthesis can be inhibited to a depth of 3 to 4 m below the ice sheet. Low production and algal growth in deep lakes during open water may be a result of constant circulation with accompanying transport of algae below the photic zone (Hobbie 1964). Thus, in contrast to the stable, calm conditions beneath the ice, the algae spend only a small fraction of each day in the upper part of the water column where photosynthesis is possible. (This is similar to the critical depth concept of oceanographers.)

Rodhe (1955) has suggested that arctic and subarctic algae might survive the winter by utilizing dissolved organic compounds for energy. Indeed, it can be shown that algae beneath the ice of arctic lakes do take up added radioactive organic compounds such as glycine, acetate, and leucine (Alexander 1970) or glucose (Kalff 1967a). It is difficult to interpret these experiments, however, as the natural levels of

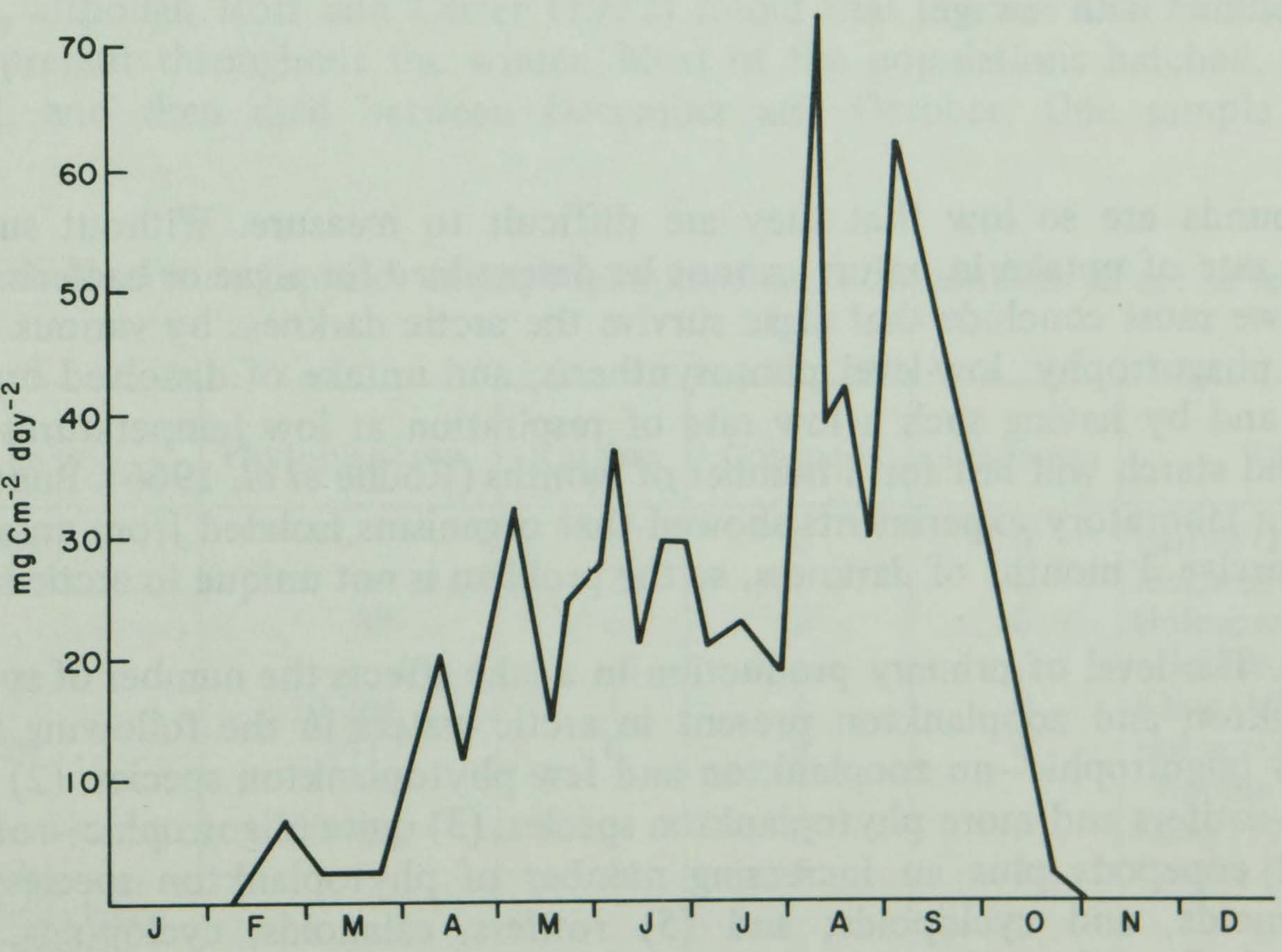


Figure 13. Primary production of phytoplankton (mg of carbon per m^2 per day) in Char Lake. (Kalff and Holmgren 1971)

Table 7. Maximum daily productivity and annual production of phytoplankton in arctic lakes and ponds.

Lake	Maximum mg C/m³ day	Year	Annual gm C/m²	Reference
Char Lake	–	1969	5.8	Kalff and Holmgren (1971)
	–	1970	6.3	
	–	1971	7.2	
Lake Peters	5.6	1961	0.9	Hobbie (1964)
Lake Schrader	14.0	1959	7.5	Hobbie (1964)
	5.4	1961	6.5	
Imikpuk Lake	60	1961	8.5	Kalff (1967b)
Tundra ponds II	[1]130	1963	0.7	Kalff (1967a)
	[1]260	1964	0.8	
III	[1] 60	1963	0.4	
	[1] 65	1964	0.8	
Tundra pond B	[1]200	1971	0.6	Alexander *et al.* (1972)
(Barrow) C	–	1971	0.5	
D	–	1971	[2]0.7	
E	–	1971	[3]0.3	
Meretta Lake	–	1969	[4]31.2	Kalff and Holmgren (1971)
	–	1970	[4]16.5	
	–	1971	[4]31.7	

[1] Production calculated from shallow pond (less than 30 cm).
[2] Pond fertilized in 1970 and 1971.
[3] Pond treated with crude oil in 1970.
[4] Lake polluted with sewage.

these compounds are so low that they are difficult to measure. Without such a measure, the rate of uptake in nature cannot be determined for algae or bacteria. For the present, we must conclude that algae survive the arctic darkness by various combinations of phagotrophy, low-level photosynthesis, and uptake of dissolved organic compounds, and by having such a low rate of respiration at low temperatures that stored fats and starch will last for a number of months (Rodhe *et al.* 1966). Bunt and Lee (1972) in laboratory experiments showed that organisms isolated from antarctic sea ice can survive 3 months of darkness, so the problem is not unique to arctic lakes.

Zooplankton. The level of primary production in a lake affects the number of species of phytoplankton and zooplankton present in arctic waters in the following way: (1) extremely oligotrophic–no zooplankton and few phytoplankton species; (2) very oligotrophic–rotifers and more phytoplankton species; (3) quite oligotrophic–rotifers and calanoid copepods plus an increasing number of phytoplankton species; (4) rotifers, calanoids, and cyclopoids; and (5) rotifers, calanoids, cyclopoids, and cladocera. A similar scheme has been proposed for Norwegian lakes by Hobbie and Langeland (in preparation). The theoretical basis is that there is not enough food (or algal nutrients) in very oligotrophic lakes to allow all the niches to be filled. Increasing eutrophication, while not enough at first to produce a eutrophic lake, allows more

niches to be filled; therefore, zooplankton and phytoplankton species numbers increase. Arctic lakes agree fairly well with this scheme (Table 8), since Angiussaq Lake, the most oliogotrophic, has no zooplankton while Lake Hazen, Char Lake, and Lake Peters have no cladocera. Angiussaq Lake was sampled throughout the summer with a relatively large mesh zooplankton net that may well have missed the rotifers. When Meretta Lake was fertilized, the number of algal species increased. A similar picture occurs in Lake Peters and Lake Schrader, although the glacial rock flour entering Lake Peters makes summer algal counts difficult to obtain.

The low number of zooplankton species in arctic lakes and ponds allows easy delineation of their growth stages and reproductive biology; for example, *Daphnia middendorffiana* (Edmondson 1955), *Limnocalanus johanseni* (Comita 1956), and *Limnocalanus macrurus* (Roff and Carter 1972). In ponds and shallow lakes the zooplankton usually hatch from resting eggs as soon as melting begins. The animals then grow to maturity and produce resting or resistant eggs which survive the winter on the bottom muds (may be frozen or unfrozen). The adults die when the lake freezes to the bottom or when salts in the water beneath the ice become concentrated. One exception is the cyclopoid copepods (Hobbie *et al.* 1972, and Stross and Kangas 1969) which overwinter in copepodid stage IV. When the ice melts in the spring, they quickly reproduce, and the young hatch and grow to the preadult stage. In this way there is always a good population of zooplankton throughout the summer in ponds, since the early population is made up of copepods (most of the June peak in Figure 14) and the late population peak is *Daphnia.* Temperature and ice conditions likely control the length of the reproduction cycle, since Tash and Armitage (1967) reported two generations of copepods in one summer at Cape Thompson while Barrow, 6° farther north, had only one. Still farther north, in a pond near Lake Hazen, a cyclopoid took 13 to 23 months to mature (McLaren 1964).

The zooplankton in deeper arctic lakes can pass the winter as free-swimming forms, although Roff and Carter (1972) found that in Char Lake only a few adults were present throughout the winter. Most of the populations hatched, grew, reproduced, and then died between December and October. One sample from Lake

Table 8. Number of species of phytoplankton and zooplankton in arctic lakes.

Lake	Phytoplankton	Rotifers	Copepods	Cladocera	Reference
Angiussaq	–	0	0	0	Barnes (1960)
Hazen	–	2	1	0	McLaren (1964)
Peters	89	6	2	0	Holmgren, Kalff, and Hobbie (unpubl.)
Char	10-20+	1	1	0	Kling (1972)
Schrader	147	6	3	4	Holmgren, Kalff, and Hobbie (unpubl.)
Meretta	20-40+	1	0	0	Kling (1972)
Imikpuk	–	4+	5	1	Comita (1956)
10 Colville lakes and Colville River	9-59 24-63	2-6 1-6	2 2	0 1-2	Coulon, Holmgren, and Alexander in Kinney *et al.* (1972)

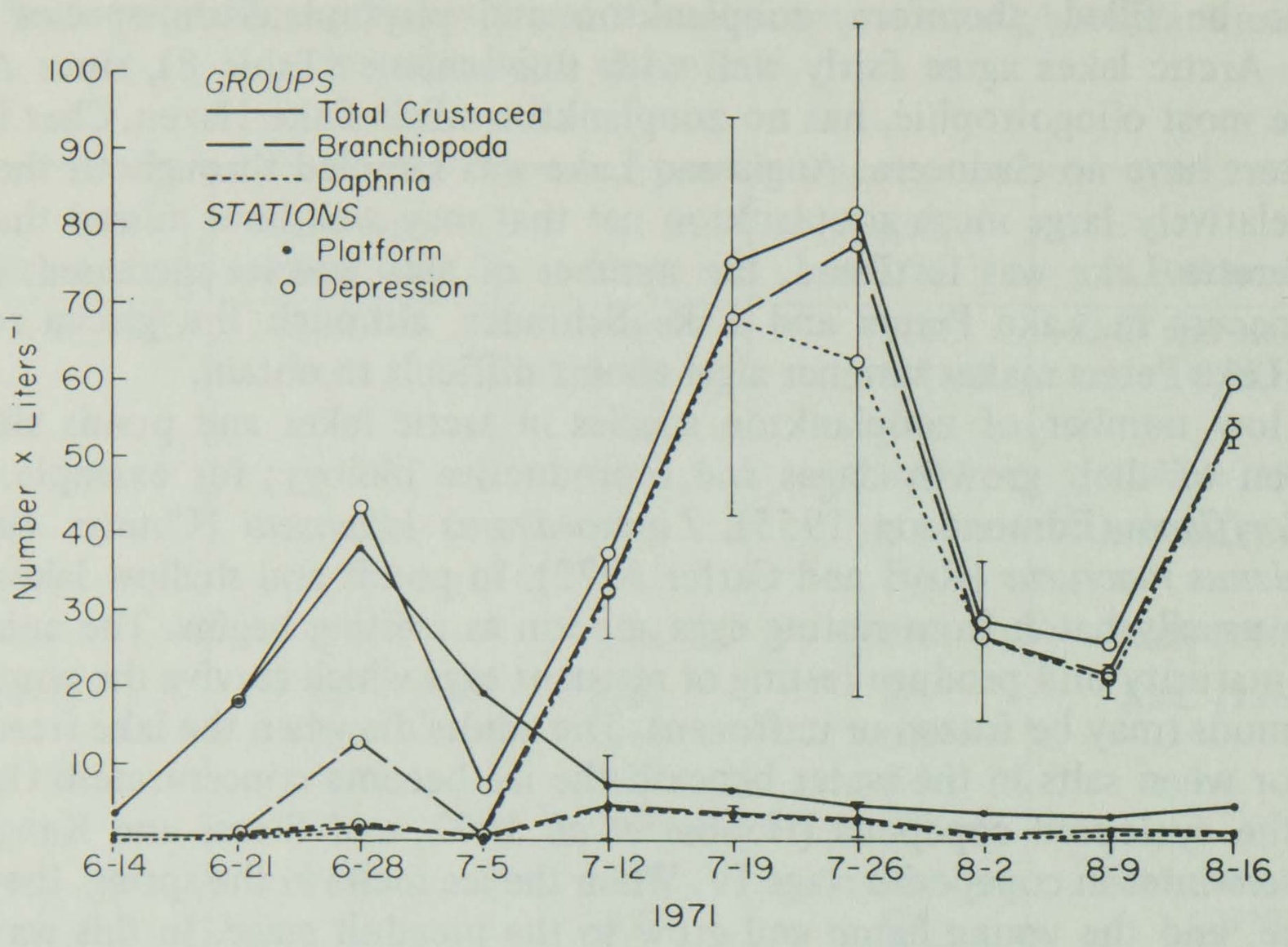


Figure 14. Crustacea and Branchiopoda (including *Daphnia*) in tundra pond near Barrow. (Redrawn from Hobbie *et al.* 1972)

Schrader (May 19, winter conditions) contained calanoid and cyclopoid copepods, cladocera, and rotifers (Holmgren, Kalff, and Hobbie, unpublished data), indicating overwintering populations of all these forms. Although the Char Lake study is the only adequate deep lake study, the presence of two modes in the *Cyclops* populations in Lake Hazen indicates that maturity takes 2 years (McLaren 1964).

The biomass of the zooplankton in arctic waters is low but comparable to winter zooplankton quantities in temperate lakes. In contrast to the values in Table 9, eutrophic Lake Erken and Lake Esrom had 2,000 to 25,000 and 3,000 to 80,000 mg per m^2 or roughly one order of magnitude more zooplankton (Jonasson 1972, and Nauwerck 1963). Lake Hazen, however, had 2 to 3 orders of magnitude less zooplankton than the eutrophic lakes. There are, of course, great seasonal changes in total biomass, but changes in number and in total biomass may have quite different annual patterns. For example, the total numbers of *Limnocalanus* in Char Lake went from an annual low in October or November to an annual high in March as the eggs hatched. The number then declined steadily until the next hatch (Roff and Carter 1972). In contrast, the total biomass of all forms increased sigmoidally from January until May, and then remained constant until a precipitous decline in October (Roff 1971).

The production rate of arctic zooplankton, while low, appears to be a high percentage of the phytoplankton production. Lake Hazen's annual production is extremely low, of course, and lies in the region of 0.5 gm wet weight per m^2 (McLaren (1964) converted to wet weight by assuming zooplankton equals 90-percent water). Stross (in Hobbie *et al.* 1972) calculated a production of 1.2 gm per m^2 for tundra ponds, but these ponds are only 10 cm deep. Data for Char Lake are not yet available, but production will likely lie in the 15 to 60 gm wet weight per m^2 per year range (calculated from data in Roff (1971)). In comparison, Lake Erken and Lake Esrom

produce 200 to 400 gm wet weight per m^2 per year (Jonasson 1972, and Nauwerck 1963). In spite of the low production, the biomass of zooplankton almost always far outweighs that of the phytoplankton (Table 9). The usual explanation is that phytoplankton have a high rate of production, so that zooplankton actually have more phytoplankton available than this ratio indicates. Nauwerck (1963) argues, however, that the zooplankton cannot eat a production rate but can graze only the standing crop available at any given time. The low biomass of zooplankton in arctic lakes means that they can filter out only a small percentage of the available phytoplankton and likely have little effect on the algal standing crop. This appears to be the case in Char Lake (Rigler and Kibby, quoted in Roff and Carter 1972) and in the Barrow ponds as well (Stross, in Hobbie *et al.* 1972).

While current studies at Char Lake may give some answers to this problem, it is possible that the phytoplankton are not the chief food source for most arctic zooplankton. Many lakes, such as Lake Schrader, gain dissolved and particulate organic matter from their watersheds. Other ponds and small lakes have higher plants in the littoral zone that will add fixed carbon to the planktonic areas (for example, *Carex aquatilis* in Barrow tundra ponds). Clear lakes, such as Char Lake, have extensive moss beds in deep water, and Kalff and Wetzel (1971) reported a large standing crop of moss extending from 3 or 4 to 16 m.

Arctic ponds and lakes without fish also contain fairy shrimp (Anostraca) and tadpole shrimp (Notostraca) as well as other large zooplankton. These are abundant throughout the Arctic from Cape Thompson, Alaska (Tash and Armitage 1967) to the Lake Hazen area (McLaren 1964), but they cannot coexist with fish. In Iceland, D.G. Frey (Personal Communication) could predict the absence of *Eurycercus* (a large cladoceran) by the presence of arctic terns feeding on sticklebacks. Although by far the most obvious part of the zooplankton, these forms tend to hug the bottom and probably are more benthic than planktonic. Certainly their low biomass suggests that they have little direct effect on the plankton as a whole. Thus, the *Daphnia* made up

Table 9. Biomass of zooplankton (mg wet weight per liter) in arctic lakes, and ratios (P:Z) of phytoplankton biomass to zooplankton biomass.[1]

Lake	Zooplankton biomass (mg/m^3)	P:Z	Reference
Char	[2] 1,000-1,500	0.13-0.5	Roff (1971) and Roff and Carter (1972)
Peters	400-500	6-10	Holmgren, Hobbie, and Kalff (unpubl.)
Schrader	700-1,300	0.3-1.7	Holmgren, Hobbie, and Kalff (unpubl.)
Tundra pond	600-800	0.05	Hobbie *et al.* (1972)
10 Colville lakes ...	500-13,500	0.001-0.35	Coulon, Holmgren, and Alexander in Kinney *et al.* (1972)
Hazen	[2] 30 (in top 32 m)	....	McLaren (1964)

[1] See also Table 6 and Figure 10.
[2] Approximation; not in original article.

46 to 93 percent of the total Branchiopoda (*Daphnia* plus fairy shrimp) biomass during July and August (Figure 14). On the other hand, these large animals may have important indirect effects on the plankton. Miller (1972b) suggests that the tadpole shrimp (*Lepidurus*) may be the chief agent for mixing sediment detritus and algae into the water column where they can be grazed by zooplankton. The shrimp may also stimulate benthic decomposition and production by stirring and mixing the sediment.

While we need to know more about life cycles, biomass, and production of arctic zooplankton, the basic questions still to be answered involve control mechanisms. One mechanism, the control of general types of zooplankton by extremely low productivities, has already been mentioned. Certainly low temperature is important in extending the duration of life cycles and in excluding certain forms, but arctic zooplankton do adapt to some extent. Rotifers on Spitsbergen, for example, have a more rapid embryonic development than would be expected from extrapolations from studies in temperate regions (Amren 1964a,b). *Daphnia middendorffiana* in Barrow ponds have a higher filtration rate than temperate *Daphnia* at the same temperature (Stross, in Hobbie *et al.* 1972). Populations can also be controlled by fish predation (the example of sticklebacks eliminating large forms has already been given). In Ikroavik Lake the sticklebacks feed on copepods *Daphnia* and *Eurycercus* (Penhale 1972). Whitefish also eat these forms as well as *Lepidurus* (Penhale, Personal Communication). In contrast, Roff and Carter (1972) mentioned that the arctic char does not feed on *Limnocalanus* to any extent. The continued mortality of the *Limnocalanus* was attributed to a combination of low food supply and a fungal infection.

Another mechanism controlling the population size in small pools was the tremendous flooding and scouring during the spring runoff that removed most of the resting eggs of *Daphnia* (Stross and Kangas 1969). Stross is presently developing models that include the effect of biological rhythms, as modified and triggered by daylength and temperature, on zooplankton production and the timing of resting egg formation. Distribution of rotifers may be controlled by water chemistry in some cases, since Amren (1964a,b) found three species of rotifers that were restricted to localities rich in chloride. Finally, McLaren (1964) posed an interesting question when he proposed that zooplankton production in Lake Hazen was strongly reduced in years when the ice did not completely leave the lake. It could be argued that the underice conditions are actually better for phytoplankton production, so there would be higher production with a year-round ice cover. On the other hand, the lake is so nutrient deficient that circulation of the deep waters may be necessary for algal production, even though the circulation takes place during late summer and the algal production takes place 7 to 9 months later beneath the ice cover.

Fish. Fish are present in all arctic waters deeper than 3 to 4 m. (See McPhail and Lindsay (1970) for distribution in the western Canadian Arctic.) Arctic char (*Salvelinus alpinus*) is the only species found in the most oligotrophic waters, such as Lake Hazen (McLaren 1964) and Angiussaq Lake (Barnes 1960). In Angiussaq Lake there are no zooplankton so the fish feed only on the benthic chironomid larvae. In other lakes the chironomids are the chief food, but small numbers of zooplankton are also taken; for example, Char Lake (Roff and Carter 1972). Growth is slow and is restricted to the summer months. Whitefish (*Coregonus*) in lakes near Barrow grow only in the 2- to 3-month summer period (Cohen 1954), while about half of the annual growth of whitefish in Great Slave Lake occurs during the first 2 weeks of August (Kennedy 1953).

Toward the southern part of the arctic region, whitefish, stickleback, blackfish, grayling, lake trout, and even pike occur. For example, Lake Schrader has arctic char, lake trout, and grayling; and Ikroavik Lake has two species of *Coregonus* plus the ninespined stickleback.

Despite their slow growth, arctic fish attain large size and may live for 40 years. Sticklebacks in Ikroavik, however, live for only a little more than 2 years (Penhale 1972), but whitefish in the same lake attain ages to 15 years (Cohen 1954). Landlocked char in most arctic lakes grow until about 16 to 18 years of age when the fish are 30 to 50 cm long and weigh 0.5 to 1 kg (Hunter 1968, and Thomson 1957, both quoted in Kalff 1970). Growth is much slower than this in Char Lake, and a 10- to 13-year-old fish is only 15 cm in length (MacCallum 1971). After growth ceases, the fish may live for 20 years more. Lake trout may also live for 40 years but will only reach 1 m in length.

The total populations of fish have only been estimated in a few arctic lakes (Wohlschlag 1953). The numbers and biomass are not too different from those in temperate oligotrophic lakes. Thus, Hunter (1968, quoted in Kalff 1970) estimated a biomass of 40 kg fish per ha in an unfished Victoria Island lake and MacCallum (1971, 1972) estimated 16 to 27 kg per ha in Char Lake (data recalculated).

An early study of the metabolism of arctic animals (Scholander *et al.* 1953) concluded that freshwater fish (stickleback and blackfish) had adapted to low temperatures by increasing their respiration rates at low temperatures. This finding was confirmed by Wohlschlag's (1957) measurements on whitefish whose respiration was much higher than that of the stickleback and blackfish. Two recent measurements, however, directly contradict these earlier findings. Cameron *et al.* (in press) measured stickleback respiration at Ikroavik Lake and found much lower values than did Scholander *et al.* (1953) for the same species. Arctic char from Char Lake (Holeton 1972, and Holeton in press) also have low respiration values, although slightly higher than those of the sticklebacks (the equations are so similar that the differences may well be due to error alone). The situation is complicated by the observation (Cameron *et al.* in press) that the sticklebacks move into the warm shallow water of the flooded tundra whenever possible, so they live a part of their lives at greater than 10°C.

Benthic algae and aquatic plants. Two IBP studies—at Char Lake and at Barrow ponds—have shown that primary production of aquatic plants is many times greater than production of the phytoplankton. The producers in the Barrow ponds, small algae living in the top 5 cm or so of the organic sediment, are being investigated by Stanley (1972). The sediment species, mostly cyanophytes and diatoms with some chlorophytes as well (Coulon, Personal Communication), contrast strongly with the chlorophytes and cryptophytes that dominate the plankton of this pond. The number of algae increased from 2×10^{10} to 4×10^{10} cells per m^2 (about 30 to 60 gm wet weight per m^2) over the summer. In contrast, the phytoplankton biomass peak was 0.02 gm per m^2 in the same pond. Total annual primary production was 14 gm of carbon per m^2 for benthic algae and 1 gm for phytoplankton. Even in the relatively nutrient-rich environment of sediments, algae are still nutrient limited, since fertilization of a pond doubled the productivity. Ikroavik Lake benthic algae are only one-third as productive as pond algae.

In Char Lake, benthic microalgae are also present, but the majority of the production is carried out by mosses. These cover about 30 percent of the lake's bottom (Rigler 1972) and may have a biomass of up to 1 kg per m^2 (Kalff and Wetzel 1971). Of this, less than 10 percent is living (Kalff and Wetzel 1972), but the mosses do fix

approximately twice as much carbon as the phytoplankton. On a whole lake basis, this is some 15 gm of carbon per m^2 per year. Note that these are preliminary numbers and that the production also includes epiphytic algae.

Vascular aquatic plants are common in the southern parts of the Arctic, although the flora is greatly reduced from that of the Subarctic. They are absent in the Far North. Ponds near Cape Thompson contain the emergent plants *Hippuris vulgaris* and *Arctophila fulva* (Watson *et al.* 1966). Submerged vascular plants (*Potamogeton, Ranunculus,* and *Sparganium*) grow in water up to 1.3 m deep on the Arctic Slope of Alaska, but they are rather rare (Spetzman 1959). In shallower water (0.3 to 1 m) and ponds, *Arctophila* and *Hippuris vulgaris* dominate (four other species are present), and in the pond margin *Carex aquatilis* is dominant (*Eriophorum, Caltha,* and *Alopecurus* are also present). In contrast, a pond near Lake Hazen contained only mosses (McLaren 1964). Big, turbid lakes have *Hippurus* but only in sheltered places (for example, Lake Peters), while clear lakes have a carpet of moss on the bottom. West Greenland lakes (Hansen 1967) are similar to those in Alaska, with *Potamogeton* and *Harpidium* in water deeper than 80 cm and *Batrachium, Callitriche, Hippurus,* and *Equisetum* in shallower water.

The only attempts to quantify the biomass and production of vascular aquatic plants were made by McRoy and Stanley (in Hobbie *et al.* 1972) in a Barrow pond. In this pond, 32 percent of the area was covered by *Carex aquatilis* (0.15 cm depth) and 13 percent by *Arctophila fulva* (15 to 25 cm depth). Over the summer, the above-sediment biomass within the plant stands of the *Carex* increased from 710 to 2,920 gm wet weight per m^2 and within the *Arctophila* from 42 to 230 gm. These are minimum values, however, since most of the biomass is in roots and rhizomes. Expressed as per-meter-square of the entire pond, the annual net primary productivity above the sediment was about 15 gm of carbon. The dead leaves decompose slowly over at least 5 years; as a result, the sediment in these ponds (77 kg wet weight per m^2 in the top 5 cm) is made up mostly of decaying *Carex* derived from washed-in leaves, as well as from roots and leaves grown in the pond. This detrital material provides food and shelter for the bacteria and benthic animals while the rate of nutrient release from the sediments controls phytoplankton productvity. Thus, the *Carex*-derived sediments dominate the energy and nutrient flow in this pond (also note the phosphorous pump effect of these plants which was discussed in the section on nutrients).

Benthic animals. The dominant group of benthic animals in arctic water is the chironomid larvae. They were the only form present in Angiussaq Lake (Barnes 1960), made up 95 percent of the benthos in Nettilling Lake (Oliver 1964), dominate northern Alaskan lakes (Livingstone *et al.* 1958), and make up 75 to 95 percent of total numbers and biomass in five pools at Barrow and five lakes at Prudhoe Bay (Bierle 1972). Chironomids are most abundant in shallow ponds with organic sediment; in the Barrow ponds their number may reach 9,000 per m^2 –36 gm wet weight (Bierle, unpublished). Shallow ponds near Cape Thompson contained up to 40,000 per m^2 (Watson *et al.* 1966). Deeper lakes have smaller amounts (for example, Chandler Lake has around 1.0 gm per m^2 (Livingstone *et al.* 1958) while lakes with a highly mineral sediment (Ikroavik) have small numbers). Char Lake has several thousand per square meter during the summer, but the detailed studies there have confirmed that three or four times more larvae are present immediately after hatching (Welch 1972).

The few detailed studies reveal that arctic chironomics have a 2-year life cycle in Barrow ponds (Bierle 1972) and in ponds near Lake Hazen (Oliver, Personal Communication as quoted in Bierle 1972). Thus, eggs deposited in the summer will develop to

2nd instars; then overwinter; then develop to 4th instars in the second summer; overwinter again; and finally emerge early in the third summer. In shallow ponds the larvae are frozen from October until June. Barnes (1960) and Oliver (1964) noted that emergence will take place through holes in an ice cover. Oliver suggested that the ability of the pupae of some species to move through the slightest crack in the ice was an adaptation for life in lakes with long-lasting ice covers. Production in a Barrow pond was calculated to be about 32 gm wet weight per m^2 per year (Bierle 1972). Only about 10 percent of this production was actual emergence. The rest was due to an increase in standing crop (16.5 gm), mortality (11.8 gm), and exuviae and secretions (1 gm).

Most of the chironomids are detritovores that feed on benthic algae, decaying plant parts, and bacteria. They continually mix and ingest the sediment, and some species may even selectively ingest particles richer in organic matter (Davies 1972). They are also the most important food for fish and shore birds.

One characteristic of the biota of arctic ponds and lakes is the great reduction in number of groups and of species within those groups. Tundra ponds, therefore, have about 10 species of chironomid larvae, while similar ponds and shallow lakes in temperate areas will have 60 to 160 different species. Livingstone *et al.* (1958) pointed out that there are no sponges, Notonectidae, Corixidae, Gyrinidae, Dytiscidae, or Amphibia north of the Brooks Range. Forms found in Barrow ponds include oligochaete worms (second most abundant taxon), Turbellaria, Plecoptera, Coleoptera, and Gastropoda. Nettilling Lake had lamellibranchs (*Psidium*), ostracods, caddis fly larvae, amphipods, and mites (Oliver 1964). Char Lake had benthic cyclopoids, nematodes, oligochaetes, a harpacticoid, an ostracod (*Mysis relicta*), a caddis fly, a tardigrad, and seven species of chironomids (Rigler 1972).

The organisms mentioned above are macrobenthos, but there is a group of smaller animals also present in the benthos (microbenthos). Although their biomass is small, they may be important in the cycling of nutrients. The only data come from Dillon's studies (in Hobbie *et al.* 1972) in the Barrow ponds where he found ciliates, flagellates, amoebae, nematodes, and rotifers. Their biomass ranged from 20 to 100 mg wet weight per m^2 near the shore to 0.4 to 20 mg in the center of the pond. In the same pond, the chironomids alone had a biomass of 36,000 mg wet weight per m^2.

Bacteria and decomposition. Little is known about the ecology of aquatic bacteria in arctic waters. Unfortunately, the same statement could also be made for temperate waters. Medically important bacteria, such as the indicator species *E. coli*, have been enumerated in a number of lakes (Boyd 1959, and Boyd and Boyd 1963), but these do not survive for long in arctic waters. Boyd and Boyd (1963) also made plate count measurements of heterotrophic bacteria in Imikpuk Lake where the number was low most of the year (less than 100 per ml), peaked during runoff (7,400 per ml), and then peaked again (2,000 per ml) in August. While the plate count method is useful for many purposes, direct counts of bacterial numbers always give 10 to 100 times higher numbers than the plate count (Sorokin and Kadota 1972). The method of staining and counting on membrane filters gave 0.1×10^5 to 2×10^5 bacteria per ml in Char Lake, and 2×10^5 to 80×10^5 in polluted Meretta Lake (Morgan and Kalff 1972). A slightly different technique employing acridine orange and an epi-illuminated fluorescent microscope gave 5×10^5 to 10×10^5 bacteria per ml in Ikroavik Lake (Hobbie, unpublished), and 1×10^5 to 30×10^5 in the Barrow IBP pond (Hobbie *et al.* 1972). Sediments in the pond contained 200×10^5 to $23{,}000 \times 10^5$ bacteria per ml. Both planktonic and

sediment bacteria increased regularly over the summer and reached a peak on August 1.

Bacterial numbers are not bacterial activity, but the relative heterotrophic activity of bacteria may be measured with radioisotopes of organic molecules. In Char Lake (Morgan and Kalff 1972), the maximum glucose uptake was fastest during July and early October with a range of 0.05 to 0.35 μg of glucose per liter per hour. In the Barrow pond (Hobbie *et al.* 1972), the maximum uptake was from 0.41 to 1.69 μg of glucose. Turnover times, or hours required to remove all of the organic substrate from the water, varied from 40 to 1,700 hours for glucose in Char Lake, and from 11 to 122 hours in the Barrow pond, thus confirming the higher activity of the Barrow plankton. In fact, the bacterial activity at Barrow is 2 to 3 orders of magnitude higher than expected from the maximum velocity versus phytoplankton production relationship of Morgan and Kalff (1972, their Figure 3). The dissolved organic carbon supporting this increased activity must come from the sediment.

Bacteria, as well as fungi, play important roles in breaking down detritus and recycling nutrients. Rates of breakdown can be roughly determined with litter bags, which are mesh bags containing pieces of leaves, blades of grass, and other organic material placed in the water. At Barrow the primary detritus source is *Carex aquatilis.* The loss of organic material from *Carex* in bags (0.02- and 1-mm mesh) is rapid at first (a 20-percent loss from fresh leaves in a week). After the blades of the sedge have overwintered on the plant, the rate falls to about 5 percent per week. After two winters the rate is 3 percent per week (data from Hobbie, unpublished).

Ecosystem analysis. The International Biological Program has provided the impetus to study all parts of a particular environment at the same time. In the Arctic–Char Lake and Barrow–the aquatic projects continued long enough for a number of goals to be realized. First, the systems were completely surveyed, and the type, number, and biomass of the plants and animals were measured throughout the annual cycle. Next, the flow of carbon, energy, or nutrients was measured, and the annual production or nutrient budgets for nitrogen or phosphorus were calculated. The next step was to carry out measurements and experiments designed to show what factors (physical, chemical, biological) were actually controlling the various rates of change; for example, growth, respiration, photosynthesis. Finally, the U.S. Tundra Biome is also constructing a mathematical model of an arctic pond that will incorporate the concentrations, biomasses, control mechanisms, and flow data.

The Barrow pond carbon flow chart (Figure 15) illustrates the insights to be gained through the second objective. The chart shows that most of the carbon is cycling through the emergent plants, to sediment detritus, to bacteria, to carbon dioxide. The plankton system is relatively unimportant in the carbon flow. In fact, some of the energy may be entering the plankton from dissolved organic carbon from the sediment. Although flow and biomass for only a single day are illustrated here, the magnitude of annual production is hinted at. A diagram such as this also points out some large gaps in our knowledge. For example, the rate of root production and transfer into detritus is unknown. Also, the rate of release of DOC from the submerged vascular plants is estimated from the literature and has not been measured. Finally, the benthic algae appear to be growing at the rate of 25 percent per day (Figure 15), but the actual growth rate was only 2 to 3 percent per week. Either the photosynthesis or the chironomid feeding rate must be in error.

Flowing Water Limnology

The hydrologic cycle and chemistry of streams and rivers have already been discussed (Tables 2, 3, and 5). A large project on the Colville River is gathering baseline data on chemistry and productivity (Kinney *et al.* 1972). Because of the high turbidity and constantly shifting channel of this river, there is no plankton and little, if any, bottom fauna.

The only detailed study of the fauna of a stream was carried out on Ogotoruk Creek near Cape Thompson (Watson *et al.* 1966). This creek was similar to temperate streams, although the number of organisms was somewhat smaller. Dominant groups were Chironomidae, Plecoptera, Ephemeroptera, and Oligochaeta in order of abundance. There was some evidence for decreasing numbers with increasing current (also a property of temperate streams). Most of the energy to support these populations

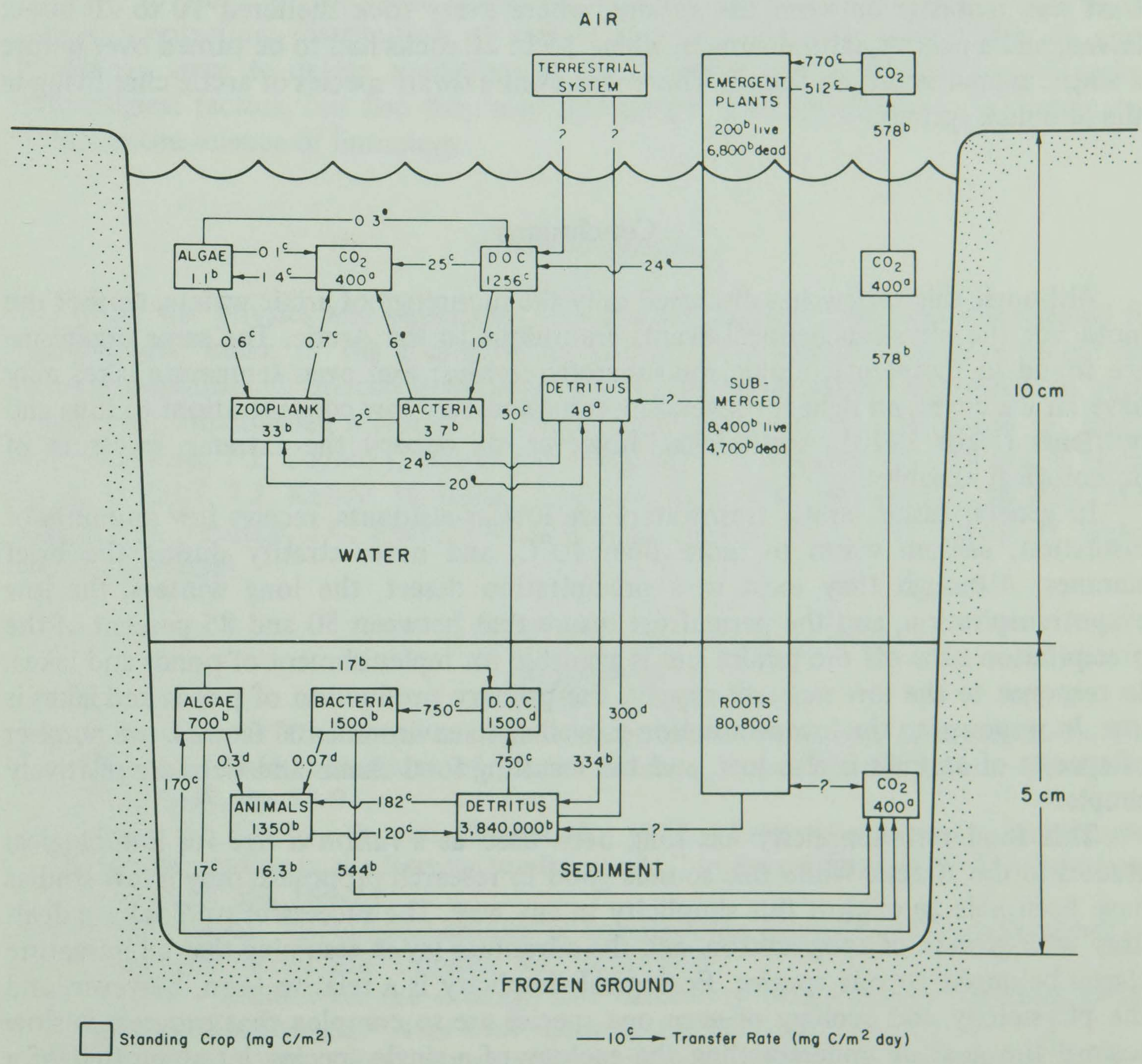


Figure 15. Standing crops and transfer of carbon between compartments of a tundra pond ecosystem near Barrow for July 12, 1971. (Superscripts refer to estimated error limits: *a* is 10%; *b* is 20%; *c* is 50%; *d* is normal magnitude; *e* is from literature. Redrawn from Hobbie *et al.* 1972.)

probably came from outside the stream, because the populations of attached algae were small.

Both springs and streams were investigated in west Greenland by Letteval (1962) who was studying Hydracarina (mites). In one valley system near Godhavn, the chemistry of spring water and of brook water varied only in the slightly higher concentration of oxygen in the brook. The spring flowed year-round at a temperature of 1° to 2°C.

Two other springs (Sadlerochit and Shublick in northern Alaska) were briefly investigated by Kalff and Hobbie (unpublished). The Sadlerochit springs were flowing at 12.5°C and the Shublick springs at 4° to 5.5°C. The total ionic composition (and conductivity) was high (Likens and Johnson 1968), in fact, higher than any other arctic water sampled by Kalff (1968) in his studies of northern Alaska and western Canada. Either because of the high ionic concentration (243 ppm total salts) or of the continually flowing water, the streams from the springs have an abundant growth of moss, diatoms, and Chrysophytes (*Hydrurus*) as well as a rich insect fauna. The contrast was fantastic between the springs, where every rock sheltered 10 to 20 insect larvae, and a nearby natural stream, where 15 to 20 rocks had to be turned over before a single animal could be found. There was even a dwarf species of arctic char living in the Shublick springs.

Conclusions

Although this review has discussed only the limnology of arctic waters, neither the biota nor the physical-chemical events are unique to the Arctic. The same organisms are found in temperate, alpine, or subarctic regions; and even temperate lakes may have an ice cover, no light for several months, and very low concentrations of ions and nutrients (Kalff 1970). Arctic lakes, however, do occupy the extreme spectrum of limnological variables.

In general terms, arctic freshwaters are low in nutrients, receive low amounts of insolation, seldom warm to more than 10°C, and never stratify during the brief summer. Although they exist in a precipitation desert, the long winters, the low evapotranspiration, and the permafrost insure that between 50 and 85 percent of the precipitation runs off the tundra and is available for replenishment of ponds and lakes. In response to the low nutrient supply, the primary production of ponds and lakes is low. In response to the low production as well as to environmental factors, the number of species of animals is also low, and the resulting food chains and webs are relatively simple.

This food web simplicity has long been used as a *raison d'être* for limnological studies in the Arctic. While this sounds good in research proposals, only a few studies have been able to exploit this simplicity in any way. The successful studies have dealt only with growth of zooplankton, and the advantage lay in assuming that all immature stages belonged to one species. Ecological simplicity is a relative term, however, and the physiology and ecology of even one species are so complex that progress is slow toward the goal of understanding the ecology of a single species, let alone that of a single ecosystem. On the other hand, two detailed studies have recently been carried out in an arctic pond and lake that will yield energy, carbon, and nutrient flows for the entire ecosystem. These undoubtedly have been helped by the simplicity of their systems, but it is possible that the simplicity has only reduced the number of elements to be investigated rather than simplified the interrelationships. Another point that is

more important than appears at first glance is that the arctic pond study has only a 2- to 3-month field season. Investigators need to devote only their summer vacations to the field work while the ecosystem is, in effect, put into cold storage for the other 9 to 10 months of the year.

At this stage in our progress toward understanding the limnology of arctic freshwaters, it appears that the biggest steps will come from detailed studies of whole systems utilizing every possible tool of modern research. This approach requires adequate arctic laboratories and a group of investigators from every possible discipline. Taxonomic and distributional studies should also continue, but it should be realized that only a small amount of usable information has ever come from the environmental measurements accompanying such studies. Most investigators seem to have a vague hope that some correlation will appear with some physical or chemical parameter that they have measured, but usually their hopes are not realized.

The two decades since Rawson's (1953) review have seen a remarkable increase in our knowledge of arctic limnology. Research during the next decades may see the answers to some of the basic questions, such as control of chemical cycles or the factors controlling distribution of certain species. Not only will studies of arctic limnology serve to define conditions at the extreme end of the spectrum of various limnological factors, but also they may well answer some questions that are important to the entire science of limnology.

Acknowledgments

While the physics and chemistry of arctic freshwaters have been investigated for many years, much of the biological work on processes and controls is recent and mostly unpublished. Special thanks are due to the following for permission to quote from their unpublished material: V. Alexander, R.J. Barsdate, D.A. Bierle, A. Bilgin, J.N. Cameron, P.I. Coyne, I. Davies, R.D. Dillon, L.A. Douglas, G. Holeton, S. Holmgren, J. Kalff, J.J. Kelley, H. Kling, J. Kostoris, W. MacCallum, C.P. McRoy, M.C. Miller, P.A. Penhale, J.C. Roff, D.W. Schindler, D.W. Stanley, R.G. Stross, H. Welch, and R.G. Wetzel.

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VEGETATIVE RESEARCH IN ARCTIC ALASKA

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During the last decade, ecology has emerged from the obscure ranks of biology departments to prominence in national and international "states of union" messages, and ecologists as critical observers of nature have become possessors of the keys to survival. This has been a decade of shifting perspectives, not only of social and ecological synthesis but also of attitudes and approaches to the study of arctic ecosystems.

In scientific expeditions to the Arctic it was once sufficient to observe or collect some new thing and then record it for scientific posterity somewhere. Today, there is pressure to tailor the pursuit of science to the needs of society. The problems of the Arctic pose great scientific challenges and are of considerable social significance. It is timely to examine some of our gleanings from the plant sciences.

Because we are anxious to synthesize and integrate the bounty from our intellectual resources, we shall adapt an ecological framework. It is perhaps no longer necessary to emphasize that the expansion of both the rate and the impact of man's well-oiled technology has made his concern and understanding of the entire biosphere relevant, indeed essential. The amounts of critical knowledge about himself as well as his environment and resource base have, unfortunately, not been man's prime concern nor is the amount of information required to operate "spaceship earth" readily attainable. We know neither the minimum number of kinds of organisms required for man's survival nor the orderly regeneration, regulation, and self-cleansing necessary to perpetuate any ecosystem. There are many examples of misbehaving systems with unstable, epidemic populations, declining productivity, and polluted or toxic environments.

What do we know and what do we need to know about the structure, function, and adaptive strategy of arctic tundra ecosystems? By ecosystem we refer to a unit of landscape, an ecological system composed of associated plants, animals, and microbes in their environment. Such systems are open, not closed; they are dynamic, not static. Their biota coexist and interact with the environment and with each other. The organisms have evolved various adaptations and the ecosystem has developed complex interdependencies for survival. In developing a perspective rather than a review, we shall concentrate on plants, the primary biological producers of any ecosystem.

Taxonomic Exploration and Vegetative Classification

The first reports from any little-known region are likely to be descriptions of the flora, fauna, and geography. Botanical studies on the North Slope have been part of the research activities sponsored by the Naval Arctic Research Laboratory since the facility was first funded. Recent botanical research projects have been evolutionary, from projects which have been mainly field oriented and which have resulted in excellent ecological assessments, community descriptions, and floral and taxonomic documentation to projects which have attempted to understand physiological processes in tundra plants.

Vegetative assemblages. Except for fungi, the arctic flora is now reasonably well known. We are fortunate to have the excellent flowering plant manuals of Hultén (1968), and Wiggins and Thomas (1962). Manuals by Anderson (1959), Polunin (1959), and Porsild (1964) contain particularly valuable comments on the site preference of most species. Hultén includes 1,559 species of vascular plants in 89 families and 412 genera for the Alaskan region. Spetzman (1959) lists 439 taxa in 53 families for the coastal plain, foothill, and mountain provinces of the Alaskan North Slope. There appear to be 104 vascular species at Barrow, 250 species at Umiat (Britton 1957), and 300 species at Cape Thompson (Johnson *et al.* 1966). Of 220 species at Meade River, at least 84 are also found at Barrow and 170 are common to Cape Thompson. The reduction in species diversity northward in Alaska is more likely related to a reduction of ecological niches pertaining to topographic and habitat diversity than to intensification of climatic parameters. The Lake Hazen area on Ellesmere Island has 115 vascular species (Savile 1964); Victoria Island, 207 (Packer 1969). In any case the arctic flora is of low species diversity when compared with lower latitudes.

Eurasian and Canadian arctic tundras are usefully distinguished as Low Arctic or High Arctic. High arctic tundra, mostly north of 75°N, has floras of 49 to 72 vascular species (Bliss 1971). For the Taimyr Peninsula at 75°N, 118 species were reported (Tikhomirov 1967), which is much lower than for the Siberian tundra farther south. In high arctic tundra, vegetation is generally less continuous and lichens are more prominent.

Krog (1968) provides an account of 348 species of macrolichens for Alaska. This compares with 375 species for Fennoscandia, although the list is certainly incomplete for Alaska. From existing records of lichen distribution, Krog concludes the following composition: circumpolar species, 61 percent; Eurasian and North American disjunct species, 14 percent; Asiatic-North American species, 15 percent; North American west coast species, 7 percent; and North American species with affinities in the southern hemisphere, 3 percent.

Steere (1965) points out that of some 500 known bryophyte species from the circumpolar Arctic, about 10 percent are considered restricted to the High Arctic, although far less endemism can be substantiated than formerly thought. At present, 70 bryophyte and 57 lichen species exist at Barrow (Murray 1972). The intriguing patterns of disjunct distribution of moss species hint of close relationships with tropical rather than with temperate flora. In combination with known unglaciated habitats that persisted throughout the glacial epoch, these disjunct relationships suggest that many arctic mosses have remained essentially unchanged since Tertiary time. In a recent review, Steere (1971) has summarized arctic bryology.

Redistribution and migration. Tundra landscapes comprise 5.5 million km^2 (23 percent of Canada and 15 percent of the USSR) (Bliss 1971). From geological and palynological interpretations (Colinvaux 1964a,b; and Hopkins 1967) as well as from present distributions of arctic and alpine floras (Love and Love 1963), there is general agreement that diverse tundra floras evolved in the late Miocene and early Pliocene in central Asia and the Rocky Mountains, and spread during cooler Pleistocene episodes. A circumpolar arctic flora originated in Pleistocene times (Hoffman and Taber 1967). The occurrence of coal and oil deposits on the Arctic Coastal Plain, as well as petrified trees in Antarctica, reminds us of earlier geological epochs and environments.

Modern vegetative assemblages began with topographic changes imposed by uplift and the resulting climatic shifts during the late Tertiary and Pleistocene. These vegetative patterns continued to shift and differentiate in response to repeated glaciation. Two major sources of floral migration are especially significant to Alaska: the Bering Land Bridge and unglaciated refugia. There is increasing evidence that major elements of today's biota, including man, crossed the broad land bridge that spanned Bering Strait during the Wisconsin glacial period until about 11,000 B.P. (Colinvaux 1964a,b; and Péwé *et al.* 1965).

Reconstruction (Heusser 1965) of late- and post-glacial pollen spectra (Figure 1) from the efforts of several investigators indicates that forested areas in Alaska contained about the same species as at present. Composition of arctic tundra evidently shifted from dominance by sedges, grasses, and composites to birch shrubs that were later invaded by alder at the thermal maximum.

Cytotaxonomic and genetic diversity. The distribution and migration of tundra floras continue to be objects of insight into Pleistocene events as well as evolutionary strategies. One clue is the frequency of polyploidy. These generalizations about multiple chromosomal complements have emerged:

(1) Arctic plants have partially substituted asexual for sexual reproduction, particularly among perennial herbs under environmental stress. Thus, polyploidy may not be limited to perpetuation of the genotype.

(2) The availability of new ecological niches, following deglaciation or gross climatic change, favors establishment of polyploid species.

(3) Polyploidy is generally thought to be a percentage of the flora inversely related to latitude in the northern hemisphere (Love and Love 1957).

(4) Polyploids are considered more successful in extreme environments than their diploid relatives. Thus, arctic diploid species are interpreted as ancient arctic-alpine genotypes occupying drier or more stable habitats including snowbed communities (Johnson *et al.* 1965). Polyploid species have spread over the Arctic during post-glacial times and occupy sites with greater cryoturbation.

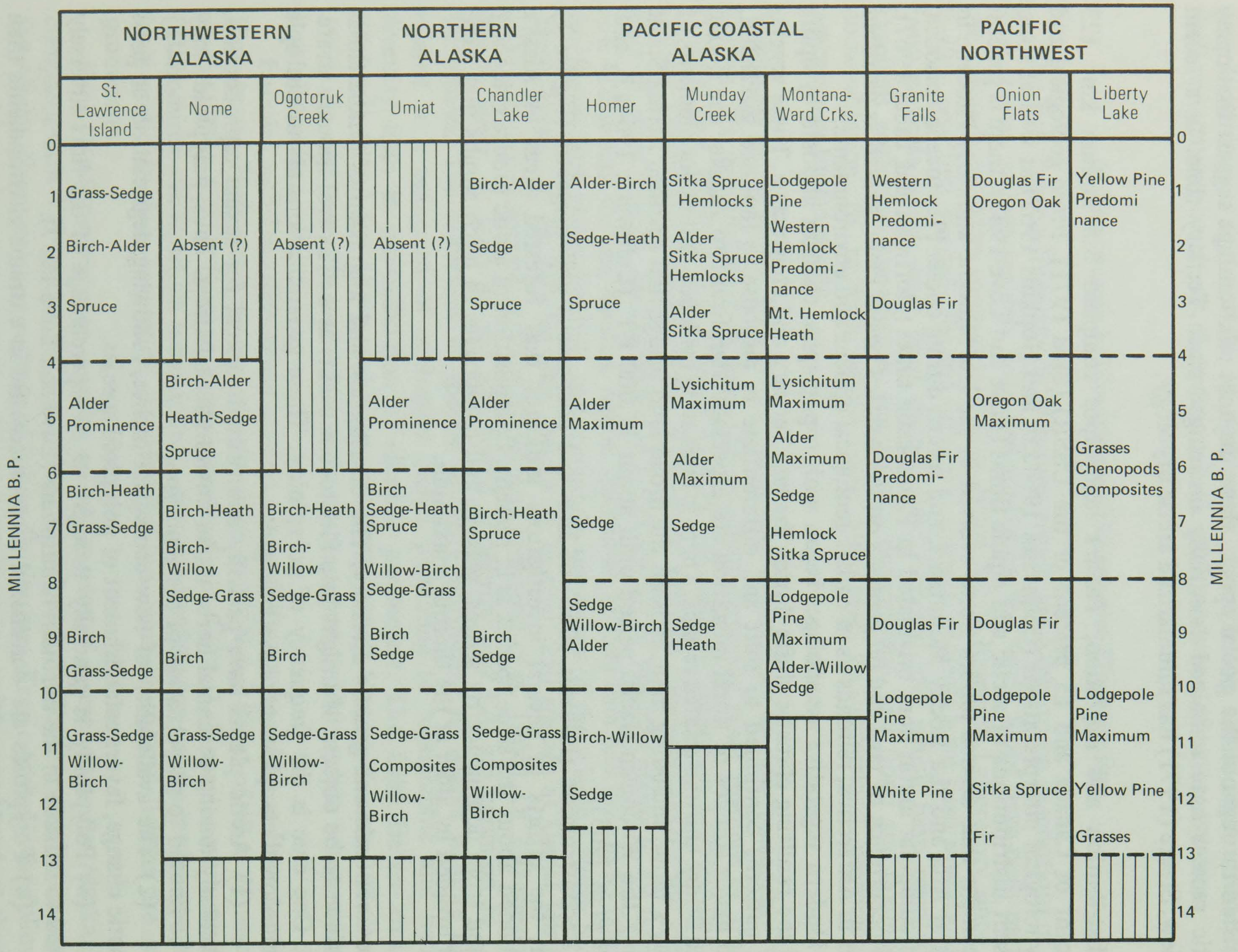


Figure 1. Summary of late- and post-glacial vegetation.

Johnson and Packer (1965) demonstrated for the Cape Thompson, Alaska flora a correlation of polyploidy with an edaphic gradient. The polyploid frequency was lowest in warmer, drier, more stable habitats and increased with greater soil disturbance. Clearly, a regional percentage represents an integrated flora existing over the range of habitats available. Polyploids are more successful than diploids in the disturbed periglacial habitats prevalent during glacial periods, as contrasted with the unglaciated condition of interior and northwestern Alaska in comparison with glaciated northern Europe. This fact is of major significance in accounting for the lower frequency of floras in Alaska (Johnson and Packer 1965, and Packer 1969).

The relationship of polyploid success to extreme environments is further supported by studies of the Canadian archipelago (Packer 1969). The frequency of polyploidy on 15 islands provides no evidence of a gradient controlled by latitude per se. Rather, the observed distribution is more nearly associated with summer isotherms; that is, temperatures ameliorate toward the northeast, southeast, and southwest from Prince of Wales Island, and polyploid frequency among dicots tends to decline accordingly from close to 70 percent on Prince of Wales Island to 50 percent on Southampton Island.

Mosquin (1966) advanced the view that self-pollination, apomixis, and polyploidy combine to produce relatively stable genetic systems, and hybridization is therefore minimal. In fact, though, the life cycle and reproductive biology are known for comparatively few arctic species.

As Böcher (1963) stated, ". . . it should not be forgotten that all species are more or less variable and that this variability also applies to their demands on habitat. In short, without an intimate collaboration between gene ecology, field ecology, and experimental ecology there will be no real progress."

Types and classification. Arctic vegetation has often been characterized by conspicuous and dominant species, by prominent life form, or by habitat and microtopography. Statistically based vegetative sampling has often permitted assessment of vegetative gradients or patchwork patterns in vegetative assemblages. Characterization by physiographic habitat has been the system of preference in Alaska, and among the first such reports for the Barrow area was Wiggins' (1951) study of polygonal ground.

Descriptive accounts of the vegetation of the Alaskan Arctic by Benninghoff (1952), Bliss (1956), Drury (1956), Hanson (1953), Hopkins and Sigafoos (1950), Johnson *et al.* (1966), Spetzman (1959), and Wiggins (1951) are particularly helpful. The classic on arctic vegetation on the North Slope of Alaska still continues to be Britton's (1957) eloquent description. Most of his observations and insights continue to be further documented and substantiated; that is, Cantlon (1961), Clebsch and Shanks (1968), and Pitelka and Schultz (1965). An elaboration (Table 1) of habitats and communities appropriate to coastal plain tundra with distinctive indicator species was developed from field studies at Meade River.

Kessel and Cade (1958), while studying bird populations along the Colville River, identified nine terrestrial habitats: (1) sedge-grass marsh, (2) tussock-heath tundra, (3) dwarf shrub, (4) tall brush, (5) tundra-lake edge, (6) dry tundra, (7) bluffs, slides, and outcrops, (8) alluvial deposits, and (9) riparian cutbanks.

Correlations with Environment

Webber (1972) has shown the value of gradient analysis, ordination, and principal component techniques in analyzing species groupings statistically and in correlating

Table 1. Physiographic habitats and ecological communities of arctic coastal plain tundra in Alaska.

Physiographic habitat	Community type
River bars	Open pioneer Riparian willow River bar tundra
River cutbanks	Bluff (a) Turf (b) Sandy Wet slump slope Dry slump slope Snowbed gullies
Sand dunes	Active Semistabilized Stabilized
Streamside	Stream margin Streambank Flood plain
Lakes and ponds	Open water Emergent grass Aquatic sedges Wet sedge bog String bog Sphagnum hummocks Pond margin
Low-centered polygons and ridges	Wet tundra Wet sandy flats Tussock tundra
Polygon troughs	Muddy Peat Wet moss Sedge
Upland tundra and ridges	Lichen barrens High-centered polygons Snowbed
Distributed sites (dry)	Recently drained lake sediments Squirrel burrows Abandoned dwelling sites (a) Moist (b) Dry
Disturbed sites (wet)	Airstrip and mine tailings Drainage ditches Excavation ponds Caribou and other carcasses Vehicle trails

the resulting species associations with various environmental gradients. His interpretation of 30 alpine stands on Niwot Ridge, Colorado suggests three controlling environmental complexes: soil moisture, snow cover, and substrate disturbance. Preliminary ordination of Barrow stands suggests that a topographic moisture gradient and a soil oxidation-reduction complex may account for distribution of species groupings. For plant communities in Spitsbergen, Rønning (1966) has also shown that the community spatial pattern is influenced mostly by permafrost through its effect on soil drainage.

Based on computer analysis of 400 m^2 quadrats at Barrow using an association analysis similar to Williams and Lambert (1959), nine homogeneous vascular species groupings were designated (Table 2). By including lichen, moss, and vascular species in the analysis, somewhat different groupings were indicated. To date, satisfactory statistical sorting of species association and meaningful correlation with environment have not emerged.

What emerges from the descriptions of arctic tundra is the impracticality of understanding tundra dynamics or even vegetative associations without a parallel examination of topographic microrelief soils and thaw depths that collectively constitute the substrate for plant life. Accepting the three physiographic units generally recognized for the North Slope (mountains, foothills, and coastal plain), Cantlon (1958) proposed that within major regions three scales of topographic relief were important: macro-, meso-, and micro-relief. Although he did not propose measurement units, these three scales are approximately on the order of hundreds to tens of meters, meters, and centimeters of vertical relief, respectively. Such a concept is supported by the development of different soil types along topographic gradients that primarily reflect drainage and snow cover (Brown 1966, and Tedrow and Cantlon 1958). Studies at Cape Thompson by Johnson *et al.* (1966) showed the relationship of the principal plant communities to relief, soil type, and permafrost (Figure 2).

Statistical attempts to correlate vegetative type with parameters of the atmosphere or lithosphere in local areas generally produce positive correlations with thaw depth

Table 2. Analysis of species associations in Barrow vegetation.

Group	No. of quadrats	Present	Absent
1	19	Alopecurus alpinus Petasites frigidus	. . . . .
2	11	Alopecurus alpinus	Petasites frigidus
3	44	Arctagrostis latifolia Dupontia fischeri	Alopecurus alpinus
4	14	Arctagrostis latifolia	Alopecurus alpinus Dupontia fischeri
5	57	Arctagrostis latifolia	Dupontia fischeri Saxifraga hieracifolia
6	30	Potentilla hyparctica	Alopecurus alpinus Arctagrostis latifolia
7	28	Cerastium beeringianum	Alopecurus alpinus Arctagrostis latifolia Potentilla hyparctica
8	130	Saxifraga cernua	Cerastium beeringianum Potentilla hyparctica Arctagrostis latifolia Alopecurus alpinus
9	66	. . . . .	All species in *Present* column

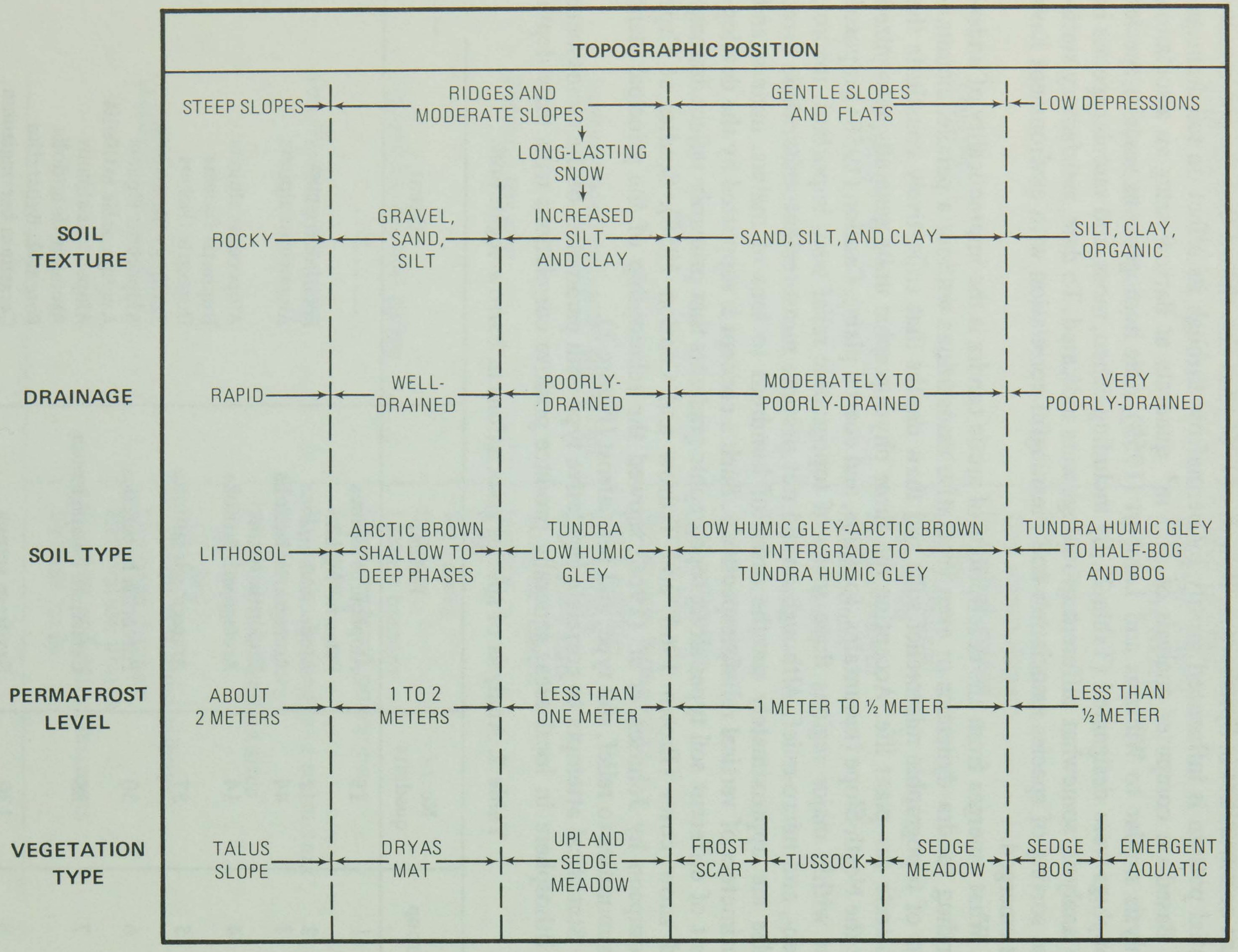


Figure 2. Relationship between soil characteristics and vegetation.

and soil moisture, but inconsistent results with other variables. Recent studies have attempted to examine complex relationships (Brown and Johnson 1965), but simple relationships probably do not exist. Most encouraging are the data being accumulated on arctic pedology and cryopedology (Brown 1965, 1966, 1967, 1969; Douglas and Tedrow 1959, 1961; Drew and Tedrow 1957; Hill and Tedrow 1961; and Tedrow *et al.* 1958), and on physiological cues and environmental controls. An integrated view of plant-soil interactions may soon solidify, thanks particularly to the efforts of IBP researchers.

Succession and Perturbation Experiments

Plant species and vegetative communities are arrayed in both time and space, and their evolution and migration over geologic time contribute to their present spatial distribution. Shorter term change in plant arrays, particularly following disturbance of the natural assemblage, is due to ecological succession. Succession is one of the more important concepts for ecosystem management and manipulation in temperate latitudes, but the phenomenon is poorly understood for tundra ecosystems (Churchill and Hanson 1958). Fragmentary evidence is accumulating that succession does occur as new habitats are colonized (Bliss and Cantlon 1957, Britton 1957, and Viereck 1966) or respond to freeze-thaw activity in tundra terrain (Benninghoff 1952, Hopkins and Sigafoos 1950, Johnson and Billings 1962, Sigafoos 1952, and Troll 1958).

Succession. We know little about the rates of vegetative recovery or succession in various types of tundra in response to disturbance. Observations at Barrow suggest reinvasion of some upland vehicle trails within 5 years, while other trails have remained unvegetated for 20 years. There are other examples of irreversible destruction of tundra in which albedo is lowered from an average of 20 percent to 10 percent or less, and the heat coefficient is altered so that thermokarst processes are activated and shallow ponds tend to replace meadows.

Britton's (1957) description of plant communities in the Barrow area and of the dependence of species arrays upon geomorphic processes remains valid. Plant populations are conspicuously related to drainage gradients, and the sequential pattern of *Arctophila→Eriophorum→Carex→Dupontia* stands from water 1 to 2 m deep to wet meadow is a successional series. Succession depends upon peat accumulation and the resulting changes in water and aeration. The distribution of such a sere seems to depend on the thaw lake cycle prevalent in the Arctic Coastal Plain.

In any case, surfaces of different ages are characteristic features, and older surfaces have greater microrelief as a direct result of ice-wedge formation. Thus, young surfaces support more uniform vegetation than older surfaces. Shifts in drainage may be subtle, and erosion from various thaw phenomena or stream action may juxtapose communities with no successional relationship. For this reason, more "mature" landscapes tend to have greater species diversity and complex patterns of plant array rather than convergence toward some relatively uniform climatic climax community. That *Dupontia* stands are more productive than dry meadow or peat hummocks is consistent with high rates of production in successional stages of temperate biomes.

Perturbation. Disturbances to arctic vegetation due to activities of man derive from both winter and summer roads, seismic lines, drill sites, crude oil spillage, tundra fires, living sites, and waste disposal. It is desirable to learn how to lessen such impacts and

to determine the best means to reestablish a vegetative cover as quickly as possible. The areal extents of such disturbances are still quite small, but they offer opportunities for examining processes and trends of vegetative behavior as well as for applying science.

Bliss and Wein (1972) examined 25 seismic trail sites in the Low Arctic. By using control plots in adjacent vegetation, they were able to characterize the disturbance (Table 3). They concluded that wherever viable roots and rhizomes of shrubs, sedges, or grasses remained in the disturbed substrate, a 30- to 50-percent recovery in natural plant cover will occur in 3 to 5 years. Subsidence will occur in areas of high ice content. To date, there is little evidence that immediate reseeding can prevent ground ice melt and subsidence. Less detrimental effects from surface rutting and scraping were measured in the High Arctic.

Revegetative studies are underway in several locations. Bliss and Wein (1972) reported trials with 16 species seeded in 1970. At the rate of 20 kg per ha, *Festuca rubra, Poa pratensis, Poa compressa,* and *Phleum alpinum* gave the best results in establishment and winter survival on mineral and peat soils. *Alopecurus pratensis* grew better on mineral soil. Fertilizer treatment with 100 kg per ha actual N and P_2O_5 doubled culm height over nitrogen fertilizer alone. The authors recommend sowing seeds with snowmelt in the spring or before snowfall in the autumn.

Experiments with oil spillage on terrestrial vegetation are few. Bliss and Wein (1972) reported that oil poured directly on the foliage killed those leaves in contact with the oil in a few days. Some regrowth was evident in late summer from June treatment, but none from July treatment. Greater damage was evident in wet sedge and cotton grass tussock communities than in shrub communities. Microbial activity in the soil may increase tenfold, but the implications of this activity for the nutritional status of the community are not yet established. McCown and Brown (1971) applied oil to the soil surface (avoiding foliage contact) and observed little immediate damage. Shoot growth response of *Dupontia* through the summer was not suppressed, except at the heaviest treatment of 12 liters per square meter, but root biomass seems to have been reduced. Observations in the second growing season showed reductions in stems per plot and in growth per stem. *Carex aquatilis and Eriophorum angustifolium* seemed less sensitive than *Dupontia.* To the extent that effects of oil spillage are manifest through limited root growth, vegetative response may not be apparent in aboveground tissue for one or more years.

A study of the effect of an air cushion vehicle (SK-5) on tundra vegetation (Abele *et al.* 1972, and Rickard 1971) was measured quantitatively. The results clearly show

Table 3. Change in conditions caused by seismic lines and winter roads with paired control plots in 1970.*

Community type	Year disturbed	Increased active layer (cm)	Increased bare soil (%)	Decreased plant cover (%)
Shrub-sedge-heath hummock	1965	26	63	65
Hummocks	1967	8	25	34
Wet sedge meadows ..	1969	1	5	7
Spruce-alder	1969	10	98	169
Upland winter road ..	1969	7	100	99

*Adapted from Bliss and Wein (1972).

that the exhaust air blows the litter and loosens organic matter, but principal damage was caused by dragging of the vehicle skirt on the surface. Although such effects change the albedo, the direct visible damage by the air cushion vehicle after 25 passes was often less than that of a single weasel pass.

In general, any disturbance which eliminates or greatly reduces plant growth, vegetative cover, or the organic litter or peat layer by any cause will increase thaw depth as a result of increased solar heat flux (Brown *et al.* 1969). Greater understanding of response to disturbance in different landscape units is needed for regulating land use and for providing design criteria for land vehicles.

Structural Adaptation

The vegetation of arctic ecosystems is comparatively simple in both composition and structure, although far more complex than is suggested to the uninitiated observer. Herbaceous perennials and low shrubs are the most abundant forms, while annuals are rare or absent. Common morphological adaptations include (1) cushion or polster life form, (2) rosette life form, (3) leafy stemmed plants, (4) graminoid, including tussock formation, and (5) prostrate, diminutive woody shrubs.

Clearly these forms are a response (Bliss 1962c, and Tikhomirov 1963) to climatic moderation close to the ground, even beneath seasonal snow. Tussock formation may also be advantageous for maximum solar interception at the low sun angles characteristic of high latitudes. Caespitose or depressed growth form is a common feature of alpine vegetation, including the Andes above 4,800 m. Chabot and Billings (1972) observed that this growth morphology may be a response to wind or snow blasts, but it is also likely to be an adaptation to a high-energy environment close to the soil surface.

According to the life form classification of Raunkiaer, most arctic and alpine plants are chamaephytes and hemicryptophytes, with only a few therophytes. Vegetative reproduction is the usual means of propagation, especially among rhizomatous monocots; however, many species may set seed. In some species apomixis is high. By carefully examining the ratio of individual shoots per unit of reproductive structure, Dennis and Tieszen (1972) found less than 2.5 percent flowering shoots for two species of *Eriophorum,* about 10 percent for *Dupontia,* and about 7 percent for *Carex aquatilis* and *Saxifraga cernua.* This low percentage of live shoots bearing flowers is suggested by the authors to imply either that a given shoot requires 5 to 10 years of physiological maturity before flowering or that 5 to 10 vegetative shoots contribute resources to produce a single reproductive structure.

Greenhouse experiments from arctic seeds indicate some populations flower readily in nonarctic climates in the first year. Bliss (1971) reported that flowering primordia are formed and overwinter in 80 to 90 percent of arctic and alpine tundra species. Perennial species apparently have two advantages over annuals: (1) they can store greater amounts of food reserves for rapid growth in the spring, and (2) they can occupy a habitat and survive without producing seed each year.

Noting the similarity in life forms and physiological cues and thresholds for alpine plants, Chabot and Billings (1972) suggested strong, directed natural selection. Rapid growth over a limited number of days is a characteristic that incorporates most of the known physiological responses, such as efficient use of a low-energy environment, increased respiration rates, large carbohydrate reserves associated with starch degradation processes at low-temperature growth regimes, and vegetative reproduction. This

generalization would seem to be an evolutionary strategy of both arctic and alpine plant populations.

Physiological Processes

The functional responses of tundra species have been reviewed recently by Billings and Mooney (1968), Bliss (1962a, 1971), Johnson (1969), Savile (1972), and Warren-Wilson (1966). Most of our understanding of how arctic plants function has resulted from studies conducted in alpine regions or from comparative growth chamber responses, even though the need for basic physiological information from the Arctic has been apparent for some time (Porsild 1951, Steere 1960, and Wiggins 1952). Only within the last several years, however, have a number of plant physiologically oriented ecological projects been initiated at the Naval Arctic Research Laboratory.

Although our understanding of plant responses to a variety of specific environmental factors (such as wind, temperature, photoperiod, depth of thaw, nutrients, and soil moisture) is important, it is probably the low heat budget of northern Alaska which is ultimately most important. The net effect of this low heat budget is exerted on plants, not only through low air temperatures but also through the short growing season. Other considerations include permafrost, cold and generally wet soils, anaerobic conditions in the active layer, slow decomposition of organic matter and release of nutrients, increased viscosity of soil solution, and other physical factors. These must all be considered as well as the internal plant responses to low temperatures (for example, those involved with nutrient and water uptake, photosynthesis, respiration, and translocation) when we want to understand the function of tundra plants.

Pigment relationships. Knowledge of pigment concentrations in individual leaves and their changes through the season can be used as an indicator of the photosynthetic potential (Tieszen 1970) of that plant or plant part, and therefore provides valuable inferential information on the role of that plant in the seasonal kinetics of CO_2 uptake and production. Similarly, the distribution of chlorophyll in the species comprising the community and its vertical partitioning provides initial estimates of the relative roles of the species in the incorporation of carbon dioxide (Tieszen 1972c).

The distribution of chlorophyll in plant communities is one common parameter of diverse species and morphologies. Examination of chlorophyll per unit area at Meade River (Tieszen and Johnson 1968) showed that mosses in dry sedge stands might contain over a third of this vital pigment, whereas in wet sedge stands nearly all the pigment was contained in *Carex aquatilis.* The amount of pigment in different communities, including dry and wet sedges, low shrub willow, and cotton grass tussock tundra (0.32 to 0.77 g m^{-2}) was highly correlated with the production of plant biomass. On the other hand, chlorophyll concentrations varied among different communities from 1.5 mg g^{-1} in dry sedge tundra to 8.8 mg g^{-1} in wet sedge tundra on a dry weight basis. The opposite relationship for cellulose and other supporting tissues is suggested.

On a land areal basis, chlorophyll content is about the same in alpine (Bliss 1966) and arctic tundras as well as being similar to some temperate herbaceous communities (Bray 1960). Within the same species, growth chamber studies suggest there is more chlorophyll in the leaves of arctic populations than in alpine populations (Billings and Mooney 1968). While observing *Thalictrum alpinum* in growth chambers, Mooney and

Johnson (1965) found that the 25-percent higher pigment content in arctic populations was genetically controlled.

Associated with adjustment in pigment content are wider but thinner leaves in certain arctic-versus-alpine plants of *Deschampsia caespitosa* and *Trisetum spicatum* (Tieszen and Bonde 1967). Billings and Mooney (1968) concluded that green pigment content was both genetically and environmentally conditioned. Direct comparison (Tieszen 1970) of the pigments of arctic and alpine grasses *in situ,* on the other hand, showed a wide range among the species in both regions, although there were slightly higher chlorophyll concentrations on a dry weight basis in the arctic grasses.

On an areal basis, arctic and alpine plant populations possessed similar chlorophyll contents, and in each case chlorophyll was correlated with leaf thickness. In combination with less structural tissue (nonchlorophyllous cells) in the Arctic, we hypothesize lower light requirements for saturation and higher respiration rates in the arctic grasses. Both arctic and alpine tundras, however, should possess a variety of photosynthetic response surfaces.

At Barrow, peak standing crops of chlorophyll (Figure 3) precede by around 10 days the peak standing crops of current biomass (Tieszen 1972c), suggesting an early senescence of photosynthetic tissue would have significant effects on CO_2 uptake. The maximum chlorophyll concentrations (5.5 mg Chl g dry wt^{-1}) occur still earlier, and in dicotyledons they are apparently attained during leaf expansion immediately after growth has commenced (Figure 4). The generality of this hypothesized difference between the principal monocotyledons at Barrow and dicotyledons remains to be established, as does the significance for CO_2 incorporation. Current growth analysis indicates that, in a number of the grasses, the earliest produced leaves begin senescing within a few weeks, or before we would expect them to be below light compensation. Apparently, leaves which attained most of their growth during the previous season senesce rapidly after exsertion. This has been graphically shown in terms of a rapid loss in the ability to fix carbon dioxide in the oldest leaves of some plants (Figure 5).

One mechanism of maximizing conversion of light energy to organic compounds would be to minimize aboveground supporting of maintenance tissue. This may account for the apparent low density of shrubs and nongreen structures in other plants. A characteristic of tundra plants in wet meadows is that few structures are devoid of chlorophyll, suggesting that most plant parts may be active in CO_2 uptake.

Photosynthesis. Regardless of the origin of arctic flora, the net result is a collection of species with distinct phylogenetic affinities of some consequence for plant processes in general and for photosynthesis in particular. In the grass family, for example, all species at Barrow belong to temperate-derived as opposed to tropical-derived groups, and as such they would be expected to possess certain distinct characteristics of photosynthesis, including relatively low maximal rates, low-temperature optima, presence of photorespiration, and high CO_2 compensation points. In a survey of Barrow vascular plants (Tieszen 1972b), all species possessed high compensation points (around 50 ppm carbon dioxide at 15°C and 762 m) and are therefore characterized as inefficient. This is probably a generalization which can be used for tundras, and it is consistent with the low-to-average photosynthetic values reported for tundra grasses in the USSR (Shvetsova and Voznesenskii 1970).

In addition to this genetic and inherent physiological limitation, however, the low ambient temperatures (soil and air) result in a depression of CO_2 uptake, as has been reviewed by Warren-Wilson (1966). The use of agricultural phytometers in the Tundra

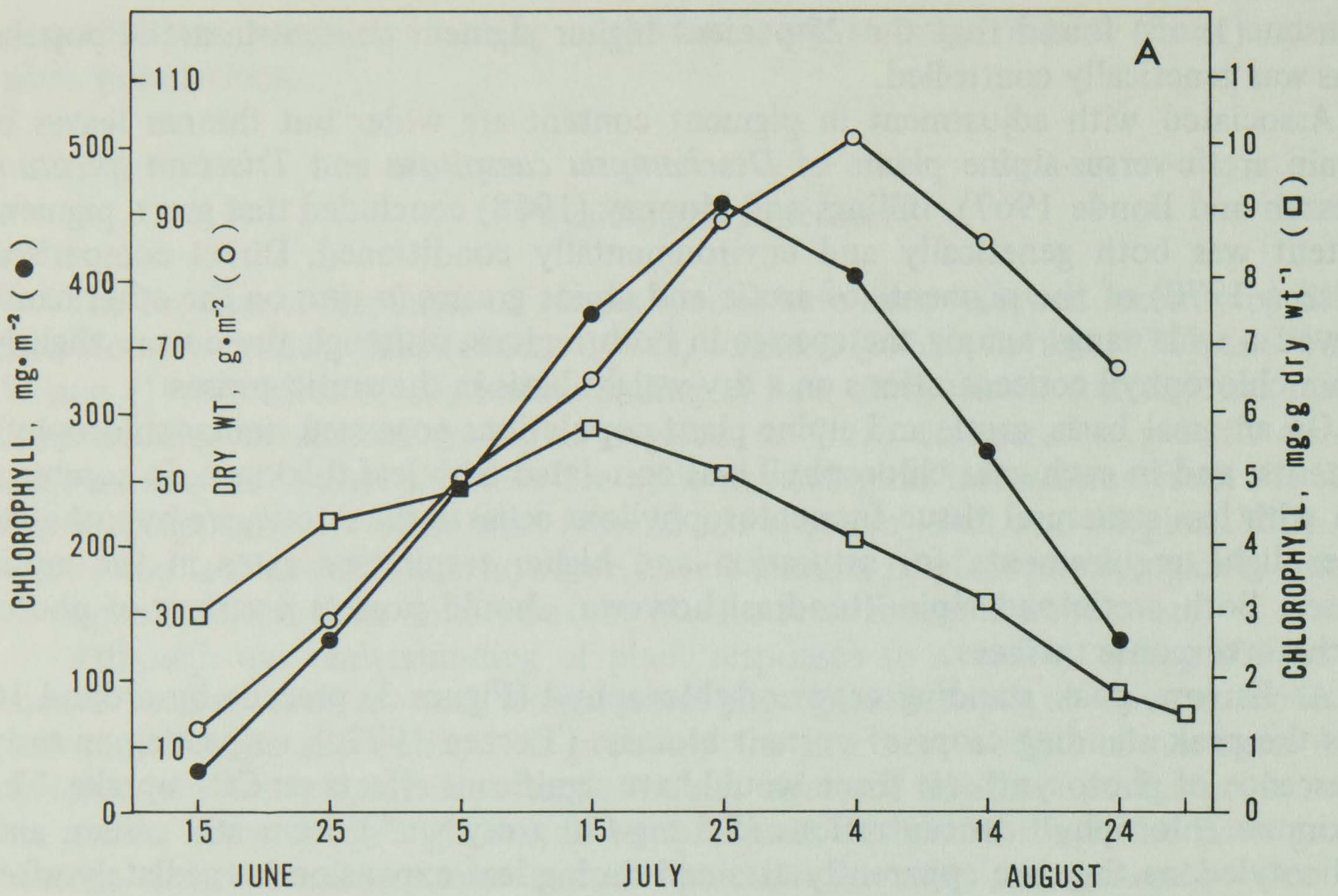


Figure 3. Progression of vascular biomass, chlorophyll standing crop, and concentration at IBP intensive site near Barrow.

Biome program has certainly shown a marked sensitivity to temperature (Figure 6), both for growth and for CO_2 exchange.

Studies recently completed by Tieszen (1972b) document the photosynthetic responses of grass leaves near midseason and confirm the variability of maximum rates that were previously suggested. Generally, species with rapid growth rates (for example, *Elymus arenarius* and *Arctophila fulva*) possessed the highest rate of light-saturated photosynthesis (31 and 20 mg CO_2 dm^{-2} $hour^{-1}$), whereas the other species ranged between 8 and 17 mg CO_2 dm^{-2} $hour^{-1}$. Saturation was approached at

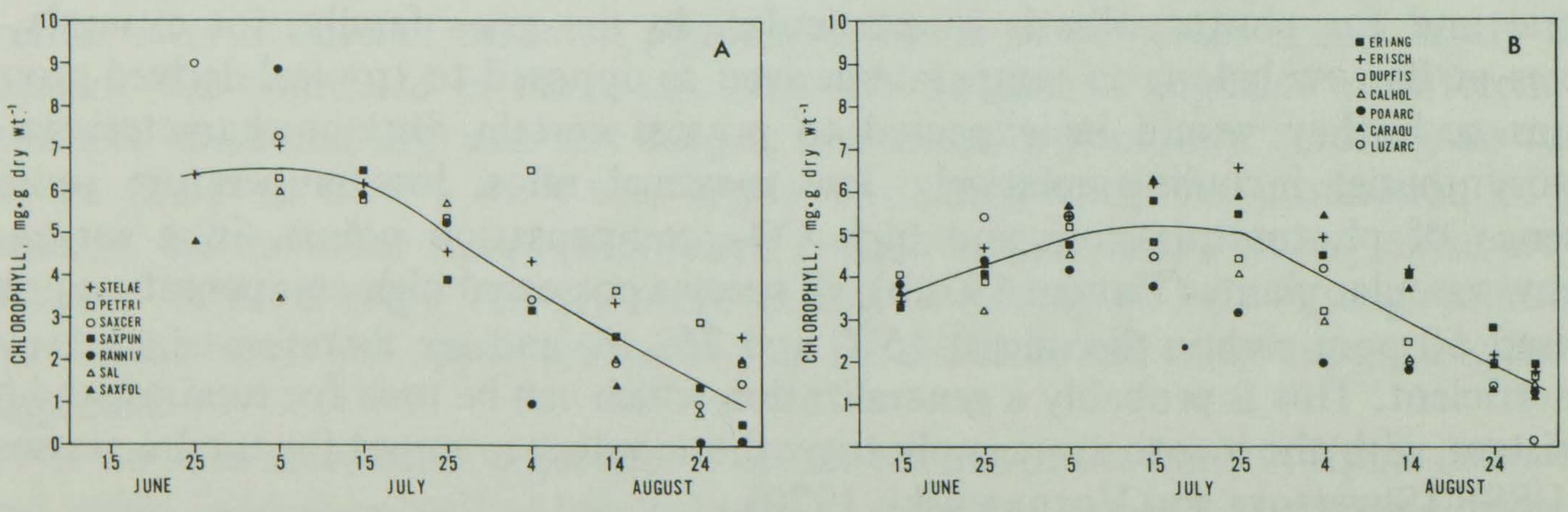


Figure 4. Progression of mean monocotyledon and dicotyledon chlorophyll concentrations.

incoming solar energy values of 0.4 ly minute^{-1}, suggesting that leaves would be light saturated only infrequently. All species tested were active at 0°C, but they possessed optima (15°C) well above mean ambient temperatures. Dark respiration rates showed a Q_{10} response between 1.8 and 2.4, which is high relative to temperate zone grasses.

The maximal photosynthetic rates appear more closely related to leaf carboxylation activity than to diffusion resistance. At temperatures above the optimum, however, the control over photosynthesis is not known, and an increased leaf resistance may be important. Certainly, the enzymes are stable to temperatures above 40°C (Tieszen and Sigurdson 1972), and the temperature optima are equally high. If the difference in photosynthesis between 2-percent and 20-percent oxygen is taken as a measure of photorespiration, the reduction above 15°C cannot be accounted for by an increase in respiration, since photorespiration is quite closely coupled to photosynthesis. Photorespiration (and/or oxygen inhibition) is significant in the Arctic and may account for an immediate return of 20 to 55 percent of the assimilated carbon dioxide.

The above responses may represent a biased set of data, since they do not include spatial and/or temporal variability. Acclimation has been shown to be important at subcellular levels (Tieszen and Helgager 1968) and at plant levels (Billings *et al.* 1971), and one could expect substantial changes in photosynthesis with experimental conditions. Spatial variability in water and minerals could also affect photosynthesis, although in ways not quantitatively known at this time. Nutrient enrichment could

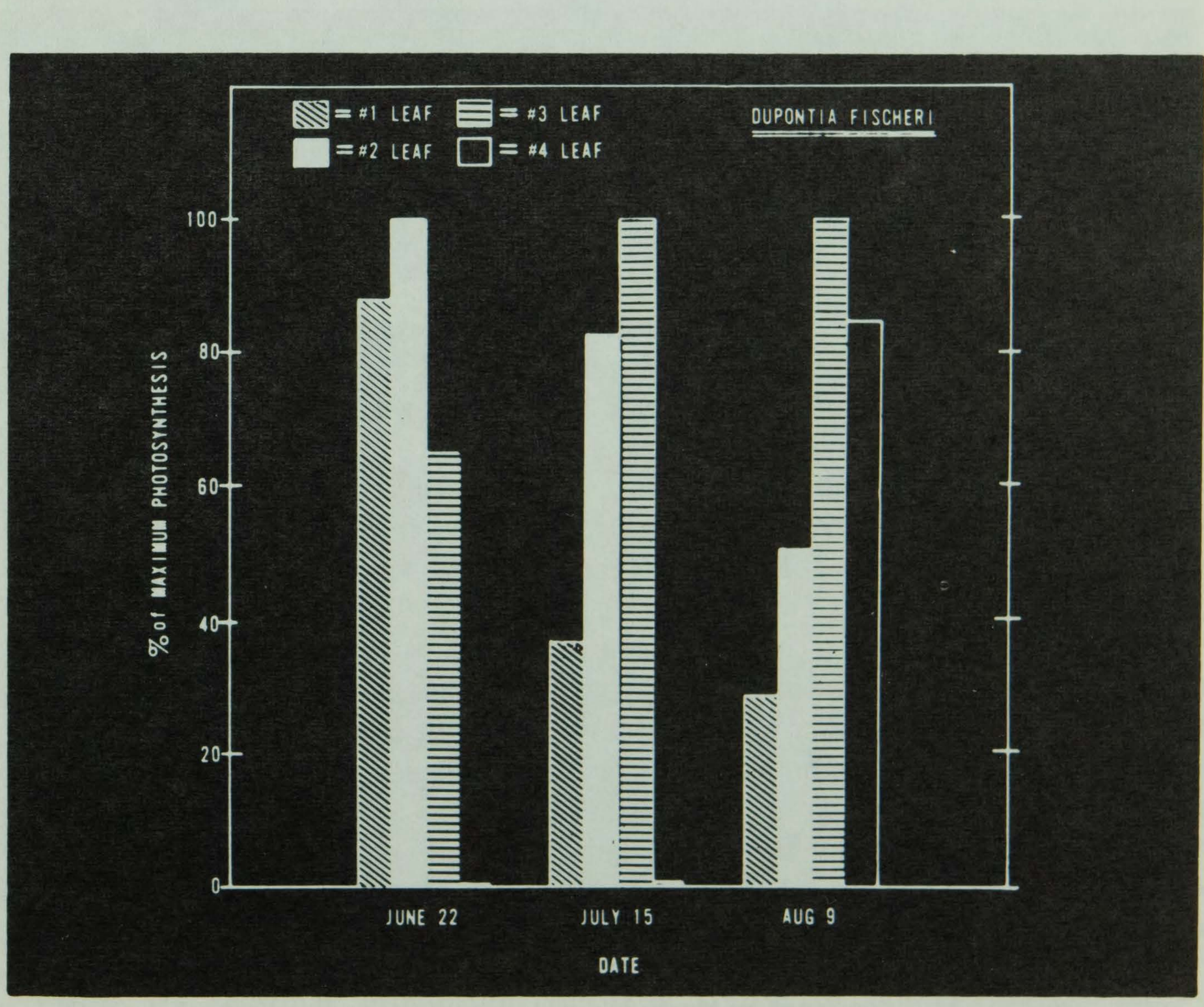


Figure 5. Seasonal progression of relative photosynthesis in leaves of *Dupontia fischeri.*



Figure 6. Response of ryegrass grown at laboratory, at field greenhouse, at Barrow, and at Prudhoe Bay.

increase photosynthetic efficiency or more likely, as suggested by preliminary data from fertilized plants at Barrow, could result in the production of more foliage. Control plants from fertilized plots showed similar chlorophyll concentration, photosynthetic rates, and carboxylation activities, but with a nutrient-induced increase in leaf area, canopy height, and plant density. This suggests that existing plant material functions at near optimal levels. It also suggests that as soil moisture and nutrients are altered, the plant adjusts its foliage to attain a new but comparable steady-state relationship.

Photosynthesis data from the Arctic suggest that CO_2 intake *in situ* might be more closely coupled to radiation than to temperature. Grace and Woolhouse (1970) indicated that young shoots of *Calluna vulgaris* did not light saturate at intensities comparable to those received at noon on a clear day. In western Taimyr, Shvetsova and Voznesenskii (1970) documented strong diurnal curves in all species comparable to those recently attained from Barrow (Figure 7). Field photosynthesis was strongly dependent on light intensity, and values as high as 20 mg CO_2 dm^{-2} $hour^{-1}$ were not uncommon (Tieszen 1972a). Daily totals in the range of 200 to 300 mg CO_2 dm^{-2} day^{-1} were common in *Dupontia fischeri, Carex aquatilis, Eriophorum angustifolium,* and *Salix pulchra.* The seasonal pattern indicated maximum rates in July and early August, with a decrease in late August due to low radiation and well-developed senescence.

Growth and development. Growth is rapid immediately following snowmelt (Billings and Bliss 1959, Wager 1938, and Warren-Wilson 1960, 1966). This is apparently possible because of the large amount of carbohydrates stored in roots, rhizomes, and corms (Mooney and Billings 1960, and Russell 1940). It appears that the ratio of maximum live standing biomass aboveground to that belowground is about 1:5. Metabolism occurs at low growing season temperatures (near 0°C). The growing season is some 70 to 80 days, which requires that the yearly vital events be consummated in a short period. Thus, food storage underground in herbaceous plants as carbohydrates or as lipids (Bliss 1962b) in old leaves of evergreen shrubs is characteristic of arctic and alpine plants. Asexual reproduction, including apomixis and vivipary, replaces sexual reproduction as a response to a shortened growing season or an unfavorable climatic condition.

We know comparatively little, however, about events that condition flowering or seed growth in any given year. We do know that flower buds are usually preformed the previous growing season, but complete development and anthesis depend on the temperature of the flowering year, with some species possibly having a photoperiod requirement (Hodgson 1966). Seed dormancy is environmentally controlled, but seeds can remain viable for a long time at low temperature since they require temperatures well above freezing for germination (Amen 1966, and Bliss 1958). Optimum germination temperatures seem to be 20° to 30°C, but seedling establishment commonly

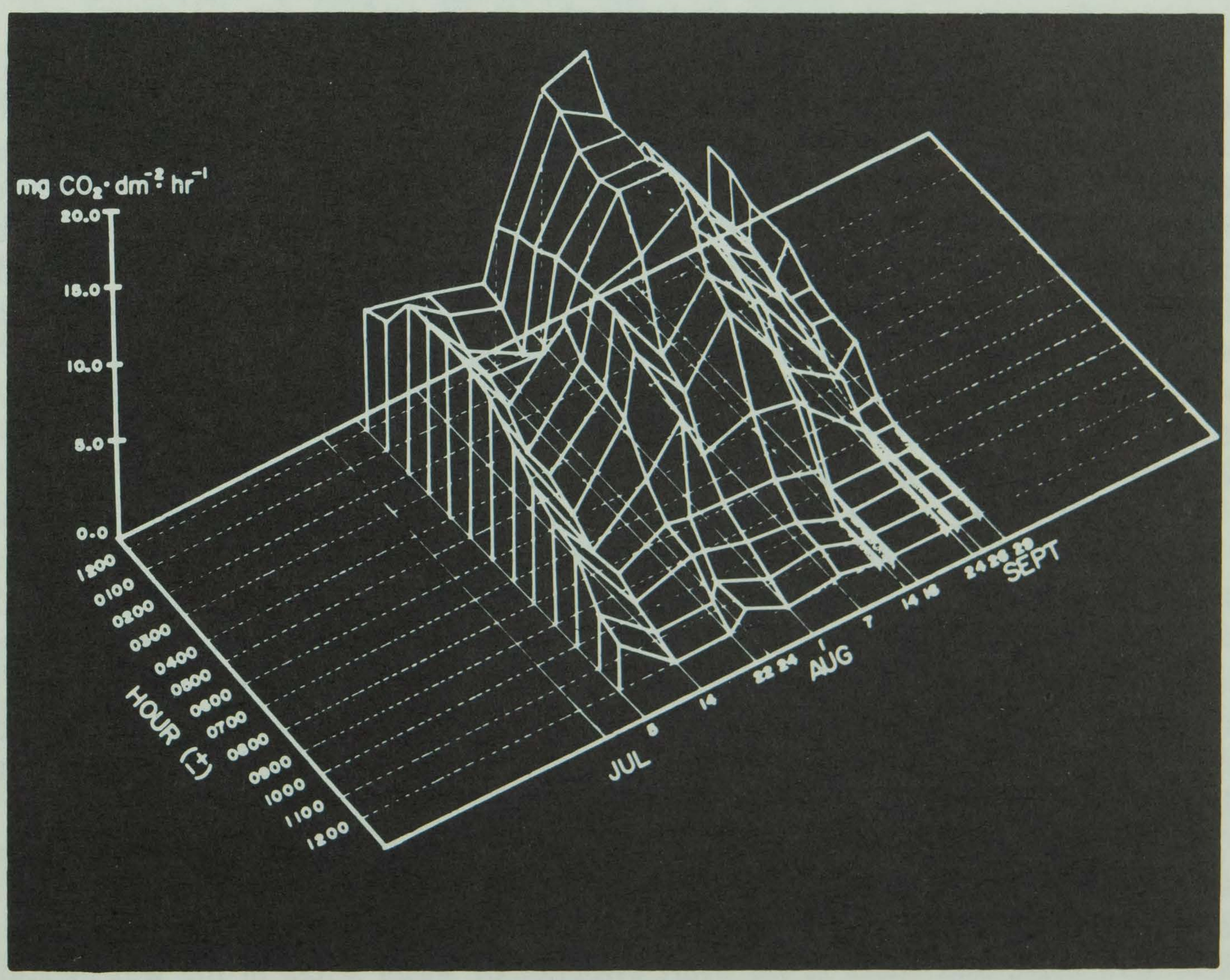


Figure 7. Seasonal progression of daily course of photosynthesis in *Dupontia fischeri.* (24-hour curves were obtained under ambient conditions and are represented by plotting the means for each hour's departure from 1200 hours.)

requires several years. Thus, sexual reproduction is opportunistic and vegetative propagation is more reliable.

A direct consequence of the lack of persistent chlorophyll and late meltoff at Barrow is the initiation of the growing season near the summer solstice with little photosynthetically active tissue available. Thus, in an environment where radiation intensity is low and the season is short to begin with, canopy development cannot maximize the absorption or utilization of radiation at a time when radiation is most available. An adaptive growth strategy involves an early expansion and exsertion of photosynthetic structures, a phenomenon commonly reported for tundra plants and closely associated with the utilization of biological reserves (Fonda and Bliss 1966, and Mooney and Billings 1960). At Barrow, this mobilization of reserves occurs at a time when some roots and rhizomes are in the still-frozen active layer. The restriction this places on translocation and uptake phenomena would seem great, although few studies have addressed themselves to this problem. Irving *et al.* (1965), however, indicated that rehydration of willow buds occurred before the spring thaw.

An estimate of the importance of early release from snow was obtained from the computer simulations of Miller and Tieszen (1972), which indicated that a doubling of the available leaf area index by June 25 resulted in nearly a twofold increase in the final leaf area index. It is not known if a similar response would be obtained *in situ* since a sufficient data base for validation is not available. Ecosystem experiments, involving increased snow accumulation and therefore delayed meltoff, are being conducted in the San Juan Mountains of Colorado which hopefully will provide direct field data to determine the effect of growing season on growth and production.

Tieszen (1972c) interprets his data to indicate that growth patterns for most monocotyledons may differ from dicotyledons in arctic wet meadow stands. The persistent standing dead leaves in the monocotyledons protect the partially expanded leaves, which survive the winter in this condition. In the spring, only a small amount of basipetal growth is needed to exsert these basal portions of leaves which appear to be photosynthetically active shortly after exposure. Presumably, this allows an early utilization of assimilates to produce more leaf material. Tieszen (1972c) suggests that the dicotyledons, in contrast, exsert leaves somewhat later but at a rapid rate, which is probably more dependent on the mobilization of belowground reserves. For most dicotyledons, leaf exsertion then decreases, whereas for the monocotyledons new leaves or portions thereof continue to be produced.

In contrast to the rather abrupt initiation of growth, the termination of the growing season is more difficult to define at Barrow. Peak standing crops (Figure 3) of live material are attained by around August 1 (Tieszen 1972c), or well before one would expect photosynthesis to decrease. The cause of the cessation of production at this time is of some interest. The photoperiod is continuous until August 2, but changes in light quality in early August seem insufficient to serve as cues. New details on this may emerge from studies of light quality and plant responses in the Arctic now being undertaken by Klein of the Smithsonian Institution.

The active layer also attains its greatest depth in early August, and if continued plant growth depends on nutrient or water release as the soil thaws, this could result in cessation of growth. Initial data of Dennis (1968), however, suggest that water potentials remain high, and there is no overt evidence of water stress in the wet meadow types at Barrow.

One characteristic of many Barrow species is the ability to cease growth during unfavorable conditions at virtually any stage of development, and then resume growth when conditions improve. The importance of this adaptation was shown by Sorenson

(1941) for reproductive structures, but it is equally important for vegetative structures, especially because of the short growing season and high probability of severe weather.

Dormancy and cold resistance have received comparatively little attention, but Bliss (1971) states that photoperiod is the triggering factor, perhaps in association with thermoperiods and lower soil moisture potential. As Bliss (1971) points out, the data presented by Weiser (1970) suggest that more than one mechanism induces cold hardiness and that three stages are involved in acclimation. Further, if there is more than one cue to induce cold hardiness, then such greater adaptive flexibility increases survival potential.

Canopy structure and environment. Attempts to relate photosynthetic responses of individual leaves to environmental factors require a thorough characterization of the canopy structure and environment (Miller and Tieszen 1972). Generally, reduced canopy height has characterized descriptions of tundra regions. As one proceeds north on the Arctic Coastal Plain, there is a progressive decrease in height as well as in tussock character as *Eriophorum vaginatum* becomes less important. Thus at Barrow, the canopy is generally less than 15 cm in height (Caldwell *et al.* 1972). The live leaf area index in the wet meadow attains values around 1.0 by August which, in combination with an equal or greater leaf area index of dead material, produces a rather high extinction coefficient for light (Weller and Cubley 1972). The leaf area is concentrated in the lower 10 cm (Figure 8) (Caldwell *et al.* 1972), and is generally vertical in orientation, although the dicots and monocots which compose the lower parts of the canopy are more horizontal.

Computer simulations to determine the sensitivity of the system to various canopy features (Miller and Tieszen 1972) indicated that vertical leaves had higher photosynthetic rates but lower water use efficiencies than those positioned more horizontally. This model has predicted that a canopy with horizontal leaves would obtain a maximum leaf area index of 0.5, and a canopy of vertical leaves would support leaf area indices at least as high as 1.3. It is also inferred from the model that production would be greatest in wet areas with ample nutrients and for species with strongly vertical leaves. In fact, in unusual circumstances, pure *Dupontia fischeri* swards approximate these conditions, and have been found to possess leaf area indices higher than 5.0. These and other data from Barrow support the hypothesis that the most productive areas are nearly monospecific; however, such stands are usually restricted to specific habitats.

In addition to the influence of the canopy on the light regime, equally important effects are exerted on the thermal radiation regimes. Nakano and Brown (1972) have related soil thaw to surface temperatures, and they have shown that an accumulation of foliage will alter surface temperatures by affecting convective, radiative, and evaporative energy exchange. A well-developed canopy results in air temperatures within the canopy which are elevated 2.5°C above those at the 0.5-m level (Weller and Cubley 1972), although it may very well result in lower soil surface temperatures.

Clip and mulch experiments at Barrow verified the canopy effect, since there was a decreased soil heat flux in mulched areas and an increase in clipped areas. The effect of litter is seen more graphically in exclosures where standing litter cannot be clipped by lemming activity and grazing. Schultz (1969) has shown a similar response upon nutrient enrichment. Removal of the canopy, therefore, influences not only the canopy environment but also the belowground environment. The effects of canopy

removal must be evaluated for tundra areas that will be subjected to increased surface activity.

Miller (1972) explored the interaction of thaw depth and vegetative canopy development. He coupled his model of canopy interdiction of solar radiation with a model by Nakano and Brown (1972) that used soil heat flux to predict seasonal thaw depth. As live and dead plant material accumulated during the growing season, solar radiation from the surface increased, with a resultant decrease in convectional exchange and evaporation. The combined model predicted the 1970 thaw rate within 1 cm. Using sensitivity analysis, the depth of thaw was partitioned among the contributing variables as shown in Table 4. Although canopy leaf area is less influential at a particular spot, this variable was the most significant contributor to spatial variation in thaw depth. Since leaf area and canopy structure are directly influenced by animal, human, and vehicular activity, vegetation is shown to have a significant relationship to perturbations that result in heat flux and permafrost alterations.

Physiological ecology of plant populations. The experimental approach to processes in arctic and alpine plants and ecotypes of the same species has yielded an important insight into adaptation to severe environments at the species population level. From reviews of work by Billings and Mooney (1968), by Bliss (1962a), and by Tieszen (1972a,b,c), the following conclusions seem justified:

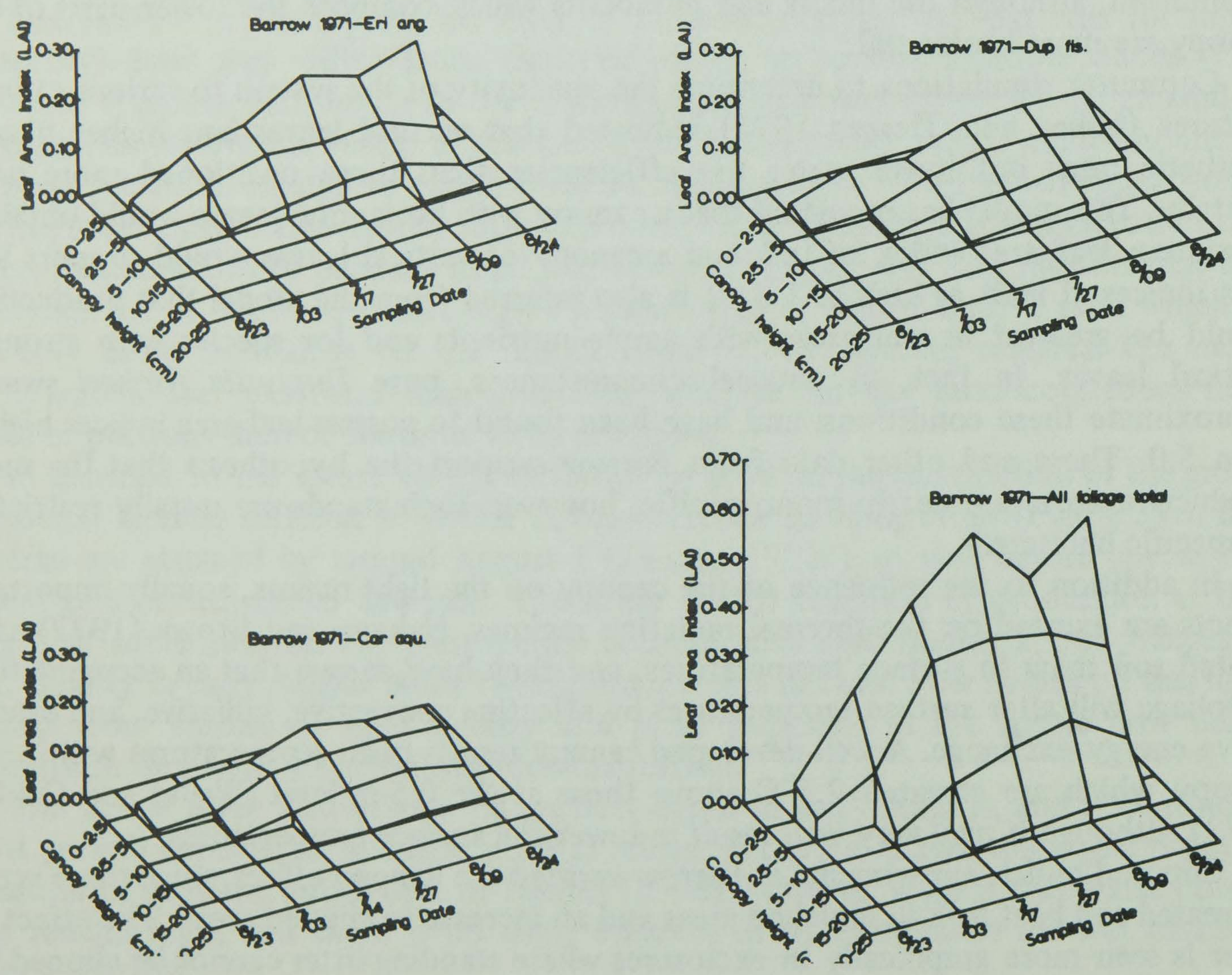


Figure 8. Vertical distribution of live leaf area index at IBP intensive site near Barrow.

Table 4. Relationship of maximum thaw depth to contributing variables at Barrow.*

Source	Change in variable (%)	Unit change in variable	Expected thaw variation with range (cm)
Sky infrared radiation	20	50 cm/1 cal cm/min	10
Soil thermal conductivity	16	110 cm/1 cal cm/°C	11
Solar radiation	12	30 cm/1 cal cm/min	6
Air temperature	11	2.2 cm/1°C	8.8
Leaf area index	8	8 cm/unit leaf area index	24

*From Miller (1972).

(1) Metabolism of the phenotypic plant is controlled both by genetic variation and by past and present environments. The diurnal and seasonal courses of photosynthesis and respiration are the result of complex interactions among genetic potentials, developmental plasticity, and environmental control.

(2) Plants of arctic populations have higher photosynthetic rates at lower temperatures and attain a maximum rate at lower temperatures than do temperate zone and possibly even alpine plants.

(3) Arctic and alpine plants have high respiration rates at all temperatures, and environmental acclimatization does occur. Dark respiration rates at Barrow showed Q_{10} responses between 1.8 and 2.4, and photorespiration is prevalent.

(4) Plants *in situ* will rarely be light saturated, but comparative studies suggest that light saturation for arctic plants is reached at lower light intensities than in alpine plants.

(5) There is a clinal increase in the photoperiodic requirements for flowering from southern to northern populations.

(6) Arctic plants are less tolerant of high temperatures than alpine plants, although the enzymes are stable to temperatures above 40°C (Tieszen and Sigurdson 1972). In demonstrating biochemical differences in the photosynthetic mechanism of the Hill reaction in *Deschampsia caespitosa,* Tieszen and Helgager (1968) support the same conclusions.

Thus, there is strong evidence that suggests evolutionary adaptation to the specific light climate by adjustments in growth and flowering response, perennating bud formation, and photosynthetic-respiratory balance. The close relationship between tissue temperature and rates of photosynthesis and respiration strongly suggests that maximum day-time temperature is the critical environmental factor distinguishing arctic and alpine gene pools from subarctic or subalpine populations (Billings and Mooney 1968). Although annual productivity is low, daily rates of carbon fixation during the peak growing season can be as high as most temperate herbaceous vegetation (Billings and Mooney 1968), ranging from 0.5 to 5.0 g m^{-2} day^{-1} for shoots, and perhaps up to 11 g m^{-2} day^{-1} if root productivity is included.

Community Production and Energy Flux

Primary production in tundra regions has been the subject of several reviews (Bliss 1962, and Wielgolaski 1972) which suggest that production is quite variable but generally increases as soil moisture increases (as does the relative proportion of below-

ground material). The spatial variability is causally related to certain factors, such as soil moisture and aeration. Arctic soils are generally nutrient poor, and production has been shown to increase upon the addition of mineral nutrients (Bliss 1966, 1971; and Schultz 1969). This increase in production can be accounted for mainly by an increase in more foliage area. Whether there is a corresponding increase in belowground biomass is not yet known. Dennis and Johnson (1970) related the belowground standing crop to other community parameters, including depth to permafrost, but they were unable to obtain accurate estimates of the seasonal dynamics or accretion in belowground structures. Future research projects must emphasize belowground dynamics.

An examination of the seasonal kinetics of aboveground live biomass substantiates the hypothesis that considerable carbon dioxide is stored in belowground structures. Biomass increases both rapidly (for example, 1.8 g m^{-2} day^{-1}) and linearly after meltoff until peak biomass is attained around August 1 (Tieszen 1972c). The dependence of the rate or the magnitude of vegetative production on climatic factors has not been established. Certainly, the magnitude is known to vary after lemming activity (Schultz 1969). If it did not vary as a result of different summer climates, the resiliency of the whole system would be of intriguing interest. The important point is that biomass production ceases perhaps 1 month before we would expect photosynthesis and other growth processes to be curtailed by the onset of fall. Thus, there is ample opportunity for a substantial incorporation of carbon in belowground reserves at this time. The utilization of these reserves and the establishment of allocation patterns remain to be further specified.

Similarly, the contribution of mosses to the productivity of the Alaskan Arctic is unknown, although the standing crops of dry matter and chlorophyll are occasionally large (Tieszen and Johnson 1968). Perhaps the best estimates we can provide of total production of organic matter are derived from the *in situ* photosynthetic studies, the aerodynamic assessment of CO_2 exchange, and computer simulations through the season with leaf physiological data.

Whole plant photosynthetic studies (Tieszen 1972a) indicate high rates of daily CO_2 uptake for three monocots *(Dupontia fischeri, Carex aquatilis, and Eriophorum angustifolium)* and one dicot *(Salix pulchra).* Incorporation of 200 to 300 mg CO_2 dm^{-2} day^{-1} was not uncommon, even on very cold days. Since these species accounted for more than 80 percent of the live biomass at the Barrow intensive study site and since concurrent leaf area indices were known, it was possible to calculate an estimated total vascular incorporation of carbon dioxide (Figure 9) for the entire summer season of 1971. These estimates reflect a limitation of energy incorporation for the first half of the season due to an incompletely developed canopy. Carbon incorporation by vascular plants is maximal at the time of peak living leaf area when as much as 16 g CO_2 m^{-2} day^{-1} are assimilated. Later in the summer, total incorporation decreases as radiation and temperatures drop, daylight shortens, and senescence ensues. Even after the period of peak uptake, however, enough carbon is fixed to account for one-third of the seasonal incorporation by vascular plants.

This method estimates a total unshaded vascular incorporation of over 750 g CO_2 m^{-2} $year^{-1}$. The use of the plant production model to provide estimates of reduction due to canopy shading suggests that this value may need to be reduced by about 50 percent. These photosynthetic studies have excluded mosses. Since mosses often form a rather complete understory for the canopy on moist sites, it is likely that their contribution would be great. For various reasons, including more moisture, more available radiation (sparser canopy), and persistent chlorophyll, we could expect

energy incorporation into moss to be greatest early in the season. The magnitude of moss CO_2 uptake is unknown, but for wet meadow stands it could easily approach 50 percent of that of vascular plants.

Coyne and Kelley (1972) have used an aerodynamic approach to measure net CO_2 exchange with the atmosphere. Their basic conclusions concerning light responses and dependence on leaf area agree with those of Tieszen (1972a). In late June, flux was negative, but quickly became positive and reached 8 g m^{-2} day^{-1} near peak season. They estimated that soil and plant respiratory sources contributed 6 to 8 g m^{-2} day^{-1}, thereby attaining a total estimated CO_2 uptake of 14 to 16 g m^{-2} day^{-1} during the peak season

With similar assumptions, they have calculated a seasonal budget which indicates that more than 140 g CO_2 m^{-2} were incorporated from the atmosphere, yielding a total incorporation from all sources of around 620 g CO_2 m^{-2} (somewhat higher than the corrected value for vascular plants estimated above of 600 g CO_2 m^{-2}). The discrepancy could be due to unknown sample errors, incorrect assumptions, or, as seems more likely, uptake by mosses. This seasonal incorporation of atmospheric carbon is equivalent to 380 g dry matter m^{-2} (substantially more than can be accounted for by just aboveground production). Johnson and Kelley (1970), however, have predicted a value of 344 g dry matter m^{-2} as part of a calculated carbon budget (Table 5).

Comparisons of primary production on a worldwide basis (Lieth 1972) indicate that tundra possesses a mean production of about 140 g m^{-2} $year^{-1}$, an amount

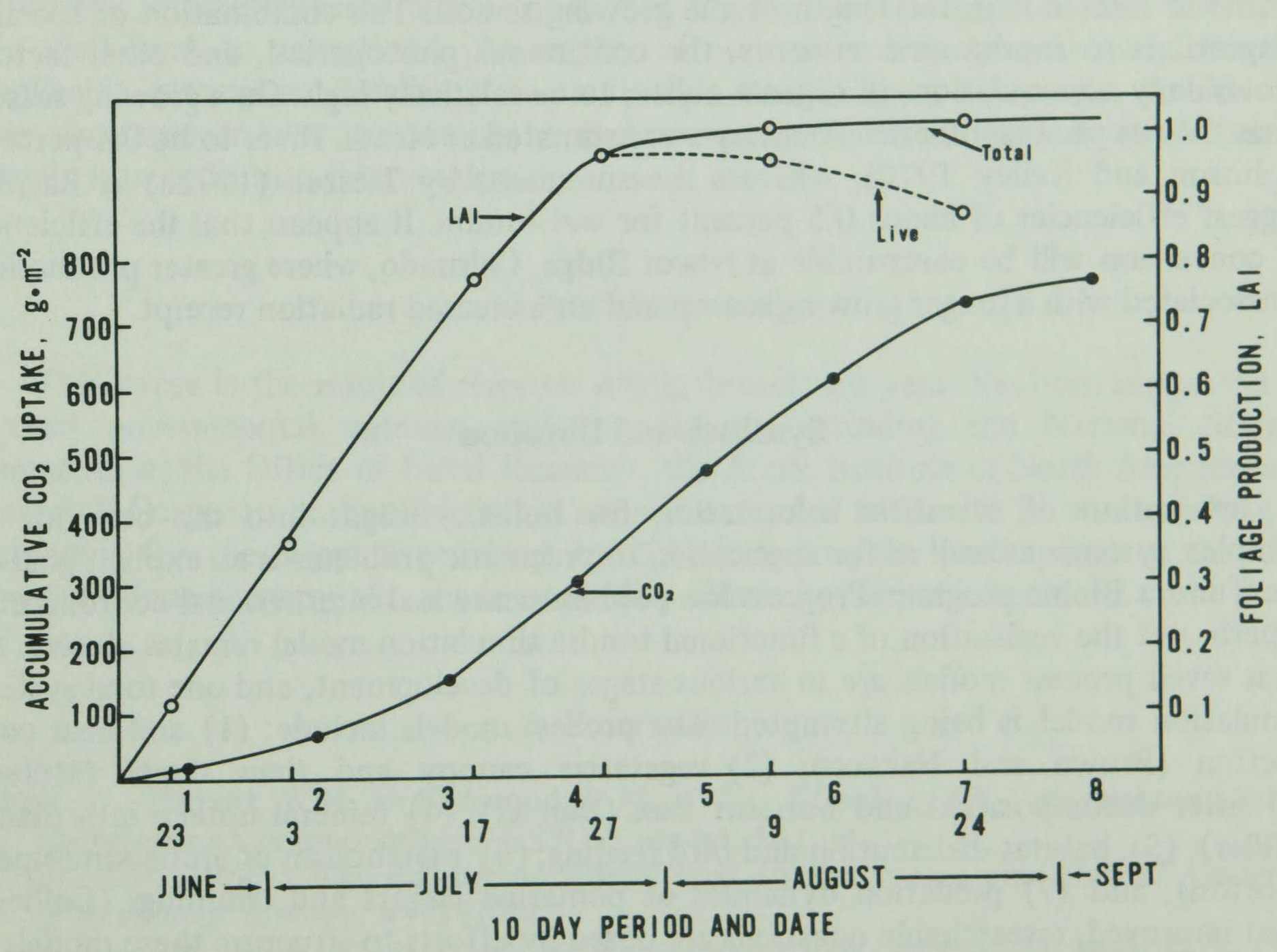


Figure 9. Estimated accumulative incorporation of carbon dioxide and production of total leaf area index of vascular plants at Barrow. (Accumulative CO_2 incorporation was calculated from mean photosynthesis data for four unshaded species in each period.)

Table 5. Dry matter production in a tundra ecosystem for a growing season.*

Type	g/m^{-2}	Source of data
Gross top production (GTP) (net assimilation)	109	Chamber measurements
Net top production (NTP)	82	Harvested plots
Net root production (NRP) (estimated)	100	Dennis (1968)
Estimated net production (NP)	182	NTP+NRP
Top respiration (TR)	27	GTP–NTP
Root respiration (RR)	135	Douglas and Tedrow (1959)
Primary respiration (R)	162	TR+RR
Gross primary production (GP)	344	NP+R
Litter (L)	273	Harvested plots

*From Johnson and Kelley (1970).

comparable to many arid ecosystems. In spite of this seemingly low input, productivity rates on a daily basis are only slightly less efficient than those of other ecosystems. Thus, the major reason for low annual productivity is due not to low photosynthetic rates but to the length of the growing season. The combination of specific adaptations to tundra environments, the continuous photoperiod, and other factors allows daily accumulations of organic matter to be relatively high. On a growing season basis the net photosynthetic efficiency was estimated at Meade River to be 0.4 percent (Johnson and Kelley 1970), whereas measurements by Tieszen (1972c) at Barrow suggest efficiencies of about 0.5 percent for wet tundra. It appears that the efficiency of conversion will be comparable at Niwot Ridge, Colorado, where greater production is associated with a longer growing season and an increased radiation receipt.

Synthesis and Direction

Integration of scientific information for holistic insight into the behavior of complex systems as well as for application to pragmatic problems is an explicit goal of the Tundra Biome program. Progress has been immense and international coordination superb, yet the realization of a functional tundra simulation model remains elusive. At least seven process models are in various stages of development, and one total system simulation model is being attempted. The process models include: (1) soil heat conduction (Brown and Nakano); (2) vegetative canopy and thaw depth (Miller); (3) litter decomposition and nutrient flux (Bunnel); (4) mineral uptake into plants (Miller); (5) habitat distribution and bird feeding; (6) metabolism of arctic sandpipers (Norton); and (7) predation dynamics of pomarine jaegers and lemmings (Collier). That improved, researchable questions are posed by efforts to structure these models is evidenced by the Tundra Biome activities.

It is still premature to judge the precision, reality, or generality of these models. Published models based on work in England (Gore and Olson 1967, and Jones *et al.* 1971) indicate that an important tool is emerging for ecosystem integration. A recent symposium edited by Jeffers (1972) on "Mathematical Models in Ecology" is an

important reference at a time of considerable interest in dynamic simulation modeling. Rather than believe the output of any particular computer simulation, however, it is useful to retain a perspective based on several decades, if not centuries, of scientific progress that is, in turn, based on reductionism which recognizes the need to develop tools of integration. In addition to computer models, technology assessment and remote sensing are also tools for integrative analysis.

To consider the past as prologue and to envision future trends in arctic research, we suggest that both ecological science and societal needs have already been well served by the 25 years of the Naval Arctic Research Laboratory. The discipline of ecology has gained in the following areas: (1) floristic evolution and dispersion, (2) physiological stresses, cues, and genetic elasticity, (3) population oscillations, (4) herbivorous and predator-prey relationships, (5) nutrient pools and cycling, (6) energy flow, and (7) biospheric coupling, especially via carbon dioxide and radioactive fallout.

Contributions to applications include: (1) identification of emergency food and water, (2) understanding terrain conditions for construction, (3) selection and consequences for surface mobility, (4) causes and location of erosion and landing sites, (5) tundra responses to disturbances, (6) remote sensing and terrain intelligence, and (7) behavioral response and psychological stress of arctic living.

Future ecological research will likely emphasize various mixtures of descriptive, experimental, and theoretical studies in accordance with the questions to be answered. Man's activities in the Arctic, as elsewhere, will intensify the need to understand ecological interactions and effects of human impact on the ecosystem, and vice versa. We shall have to accept the philosophy of ecosystem management and learn the applicable principles. Finally, it is predictable that in some areas man should consciously engineer new ecosystems as replacements for natural systems which cannot sustain intense human intervention.

Acknowledgments

This paper is the result of research which through the years has been supported by several governmental agencies and foundations, including the National Science Foundation, the Office of Naval Research, the Arctic Institute of North America, and Research Corporation. Special thanks are also extended to Max C. Brewer and John F. Schindler for the support provided by NARL and to the participants of the U.S. Tundra Biome program who made available preliminary, unpublished data.

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CYCLIC PATTERN IN LEMMING POPULATIONS NEAR BARROW, ALASKA

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The cyclic behavior of lemming populations at high latitudes, both in American and in Eurasian sectors of the Arctic, has attracted attention for many years. This attention has focused on two aspects of lemming populations: first, the nature of regulatory mechanisms for a cyclic small mammal belonging to a group, the microtines, which also cycle at lower latitudes in both temperate and Mediterranean climates; and second, the impact of lemmings as grazers on tundra, most immediately and directly on vegetation and soil substrate, but ultimately on the community as a whole. Ecological studies near Barrow, Alaska have addressed themselves to these matters with increasing scope and depth since the late 1940's.

By the mid-1950's, knowledge of lemming cycling, although advanced by pilot studies in northern Alaska from 1949 to 1953, was still too limited for analytic comparison with midlatitude microtines. The main objective of work reported here, then, has been the monitoring of a sequence of cycles to ascertain features of successive phases of cycling in a population of lemmings. This monitoring has proceeded with the hypothesis that regulation of numbers in a cyclic lemming population is really part of a nexus of regulatory interactions in tundra as an ecological system (Brown *et al.* 1970).

To anyone who has witnessed a strong fluctuation in a lemming population, the effect of massive grazing in the grass-sedge tundra of the coastal plain of northern Alaska clearly suggests a significant impact on the production potential of vegetation, on decomposition processes, and on cycling of nutrients. These aspects of tundra ecology have also been examined in northern Alaska since the mid-1950's. The expansion of studies on tundra ecology under the International Biological Program, beginning in 1969, marks a new, more intense level of effort in research on all these problems.

General background for the biology of cycles in mammals and birds is available from Chitty (1960, 1967), Elton (1942), Hewitt (1954), Keith (1963), Krebs (1964), and Krebs *et al.* (1973). For northern Alaskan lemmings, background comes from Maher (1970), Mullen and Pitelka (1972), Pitelka (1956, 1957a,b, 1964, 1969), Pitelka *et al.* (1955a,b), Rausch (1950), and Thompson (1953, 1955a,b,c). Recent physiological studies of brown lemmings in relation to population states include those

of Andrews (1968, 1970), Andrews and Ryan (1971), Andrews and Strohbehn (1971), and Mullen (1968). Pre-IBP studies on vegetation and nutrient cycling pertinent to the dynamics of both lemming population and the tundra ecosystem are those of Britton (1957), Douglas and Tedrow (1959), Drew *et al.* (1958), Pieper (1964), Schultz (1964, 1965, 1969), and Van Cleve (1967). Additional background is cited by Brown (1970), and by Monson and Sater (1969).

Near Barrow, two species of lemmings occur: the brown (*Lemmus trimucronatus*) and the collared (*Dicrostonyx groenlandicus*). Other mammalian grazers occur only sporadically. Avian and insect grazers of any consequence are absent. Of the two lemmings, the brown is the most important and the most prevalent in the grass-sedge tundra near Barrow.

Results of the long-term studies of the lemming population near Barrow may be divided into four topics, with each being considered in relation to cyclic phase and comparatively through a sequence of cycles: (1) the chronology of numerical fluctuations; (2) habitat distribution; (3) histories of reproductive performance and variation in body size, age distribution, sex ratio, and other characteristics; and (4) predation. Data for only the first topic are presented here, but reference is made to information on the other topics, especially predation. This paper has three objectives: (1) to enumerate the general features of a cycle, to the extent that present data permit; (2) to summarize the main events of successive cycles between 1949 and 1965; and (3) to examine events since 1965, with reference to the absence of a normal cyclic chronology and to the role predators may play in the occurrence of cycles.

Methods

Experience with lemmings near Barrow prior to 1955 indicated that the amplitude of variation in local densities was wide, that the relative use of different habitats changes with density and with season, and that home ranges can be small and localized. Consequently, to follow changes in population numbers, a suitable sampling scheme would have to be extensive; and for any one trapping site, traplines would have to be long with a high density of traps along each. For these reasons, it was considered that prior systematic trapline procedures (Calhoun 1948, and Thompson 1955a) would have to be expanded considerably.

The same arguments prevailed in a decision to use a procedure other than direct measurement of density by mark-and-recapture techniques. The latter method was out of the question due to excessive cost of the procedure in manpower and logistics, except in prehigh years or when the lemming population was in a cyclic high. Even then, we had difficulty because of concurrent interests in other aspects of tundra ecology.

Accordingly, in 1955, seven pairs of traplines (an eighth was added in 1960) were established in a sector southeast to southwest of (and 1.6 to 4.8 km from) the Naval Arctic Research Laboratory (Figure 1). Examples of all major terrestrial habitat types that are characteristic of the grass-sedge tundra near Barrow are traversed by the traplines.

Each line is 305 m long, with 51 trapping stations at 6-m intervals and with 3 snap traps (museum specials) placed at each station. Traps are placed within a 1.8-m radius of a stake in locations most likely to catch lemmings, but randomly in the absence of activity signs or suitable microtopographic features. The 153 traps of each line are checked twice daily over a 3-day period. In the early years, traps were baited at the

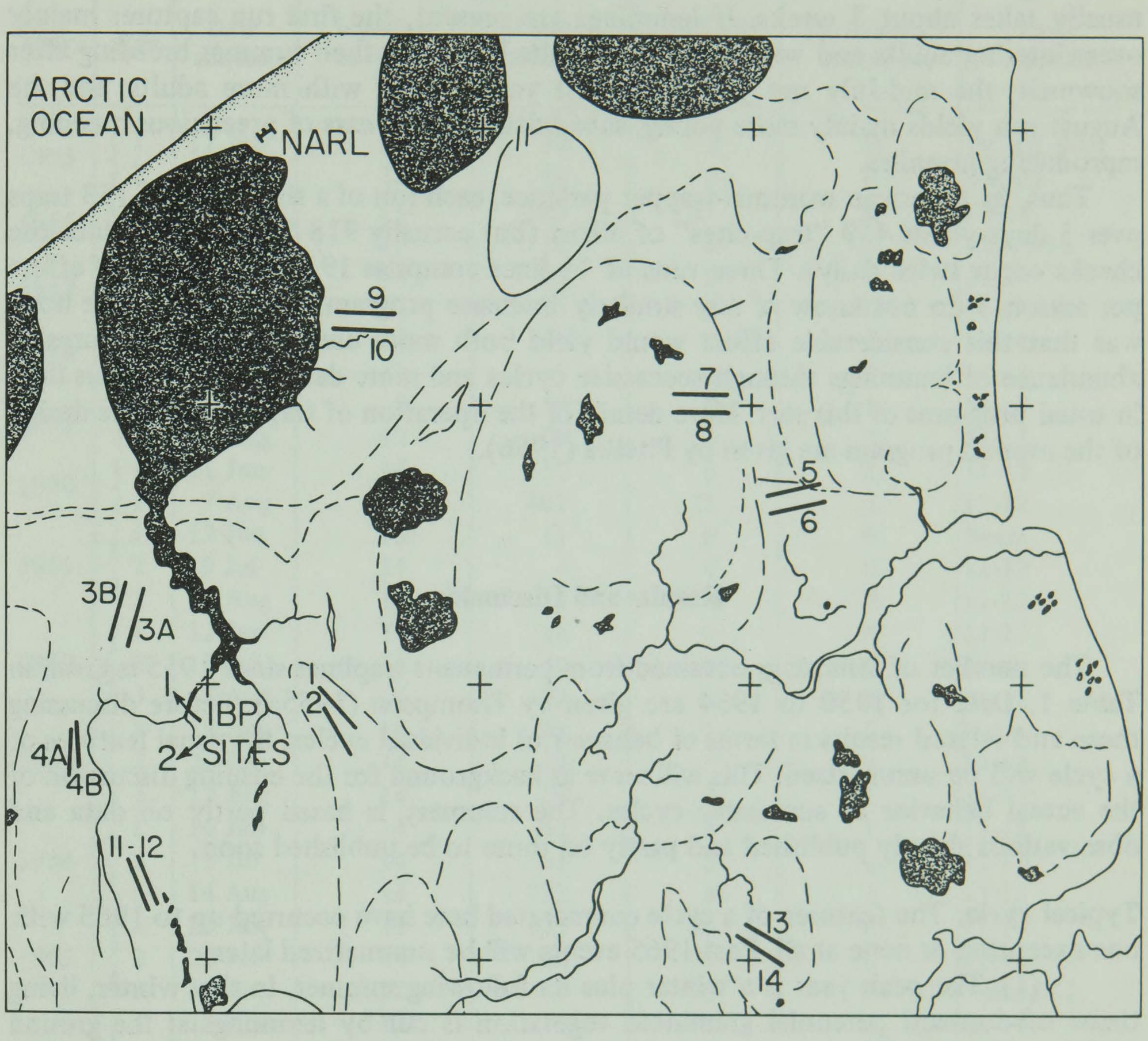


Figure 1. Map of area near NARL showing location of lemming traplines. (Crosses designate 1.6-km grids. North is up.)

beginning of the season by smearing the treadle with a mixture of bacon grease and peanut butter annointed with clove oil. But since 1960, traps have not been baited. New traps have been mixed into the supply as earlier ones were lost or transported for use elsewhere in northern Alaska. The supply of some 800 to 1,000 traps at NARL has been replaced twice in the 18 years of this study.

Most of the paired traplines are straight, parallel, and 30 to 120 m apart. Because of local topographic features, two pairs of lines are angled at certain points (never more than 30°), and some stations on neighboring lines are no more than 23 m apart. All traplines were run twice per season from 1955 to 1960, during which a considerable effort was also made to sample microtine populations at other northern Alaskan localities (Pitelka 1957a). This effort was phased out when it became evident there was no regional synchrony in the lemming cycle of a geographic scale such that this feature should continue to be considered as centrally critical to any explanation of cycles. Since 1960, Barrow traplines have been run three times per season, with the runs

occurring usually in late June, mid-July, and early August. (See Table 1.) A single run usually takes about 3 weeks. If lemmings are present, the first run captures mainly overwintering adults and winter-born subadults beginning their summer breeding after snowmelt; the mid-July run yields the first young along with more adults; and the August run yields mainly more young, subadults, and, in years of precocious breeding, reproducing juveniles.

Thus, in American mammal-trapper parlance, each run of a single line of 153 traps over 3 days yields 459 "trap-nites" of effort (but actually 918 "demi-nites" since the checks occur twice daily). Three runs of 14 lines comprise 19,278 trap-nites of effort per season. I do not know of any similarly intensive program in the Arctic. The hope was that this considerable effort would yield both more useful relative measures of abundance of lemmings through successive cycles and more data from specimens than in usual programs of this sort. More details of the operation of traplines and the design of the over-all program are given by Pitelka (1956).

Results and Discussion

The number of lemmings obtained from permanent traplines since 1955 is given in Table 1. Data for 1950 to 1954 are given by Thompson (1955a). Before discussing these and related results in terms of behavior of individual cycles, the usual features of a cycle will be summarized. This will serve as background for the ensuing discussion of the actual behavior of successive cycles. The summary is based partly on data and observations already published and partly on those to be published soon.

Typical cycle. The features of a cycle enumerated here have occurred up to 1965 with one exception or none at all. Post-1965 events will be summarized later.

(1) The peak year is a winter plus its following summer. In that winter, living tissue of dormant perennial graminoid vegetation is cut by lemmings at the ground surface and eaten. In that summer, a conspicuous layer of dead plant matter carpets the soil, and the amount of standing dead and/or living vegetation is reduced to the point where lemmings are easily exposed to predators.

(2) A cyclic rise in numbers of lemmings occurs in the prepeak year and in the peak year winter. Maximal densities are reached in the late spring, and exposure to avian predators begins at the onset of snowmelt.

(3) The main buildup in numbers toward a cyclic peak results from survival and recruitment in the peak year winter.

(4) In peak years, brown lemmings occur in all terrestrial habitats. In years between peaks, they occur chiefly or solely in areas of polygonal ground where the combination of microtopography and vegetation, both highly varying along micro-gradients, provides optimal habitat.

(5) Lemmings show variation in several body and reproductive characteristics that correlate with the phase of a cycle. Thus, lemmings attain highest body weights in the peak year (late winter and early summer). Precocious breeding occurs at highest rates among those born in the middle of the prepeak summer. Reproductive rates decline during peak summers. Other characteristics are similarly phasic.

(6) In prepeak summers, the upswing toward a peak can be evident first in late summer (for example, 1959 and 1964), or it can occur during the winter before the prepeak summer (for example, 1952).

Table 1. Number of lemmings obtained from permanent traplines near Barrow (1955-1972).

Year	Run	Date started	Number of lines*	*Lemmus* specimens	*Lemmus* remains and signs	*Dicrostonyx* specimens	Lines omitted
1955	1	17 Jun	8	50	2	0	3B, 4B, 9-14
	2	2 Aug	12	56	0	0	3B, 4B
1956	1	15 Jun	14	105	27	0	13-14
	2	10 Aug	13	12	2	0	11, 13-14
1957	1	27 Jun	14	22	0	0	13-14
	2	2 Aug	12	15	0	0	11-14
1958	1	19 Jun	12	0	0	0	11-14
	2	28 Jul	12	1	0	0	11-14
1959	1	28 Jun	12	19	0	2	11-14
	2	19 Aug	12	97	0	3	11-14
1960	1	21 Jun	14	612	6	1	11-12
	2	7 Aug	14	607	21	2	11-12
1961	1	12 Jun	16	11	0	0	None
	2	19 Jul	14	4	0	0	11-12
	3	13 Aug	14	1	0	0	11-12
1962	1	12 Jun	14	16	0	0	11-12
	2	13 Jul	16	42	0	0	None
	3	6 Aug	14	32	0	0	11-12
1963	1	18 Jun	16	21	1	2	None
	2	20 Jul	14	29	3	1	11-12
	3	12 Aug	14	26	2	1	11-12
1964	1	16 Jun	14	52	5	1	11-12
	2	13 Jul	14	61	5	0	11-12
	3	14 Aug	14	332	8	2	11-12
1965	1	28 Jun	12	433	25	0	11-14
	2	20 Jul	14	42	36	0	11-12
	3	5 Aug	12	9	0	0	7-8, 11-12
1966	1	18 Jun	12	16	0	1	11-14
	2	11 Jul	12	9	0	0	11-14
	3	11 Aug	14	27	1	0	11-12
1967	1	17 Jun	12	39	1	0	11-14
	2	11 Jul	12	14	3	1	11-14
	3	14 Aug	12	4	0	0	11-14
1968	1	23 Jun	12	21	0	2	11-14
	2	15 Jul	12	27	0	1	11-14
	3	10 Aug	14	40	0	2	13-14
1969	1	17 Jun	12	4	1	3	11-14
	2	19 Jul	14	2	0	0	13-14
	3	22 Aug	14	3	0	1	13-14
1970	1	22 Jun	14	1	0	16	13-14
	2	24 Jul	14	3	0	8	13-14
	3	25 Aug	14	2	0	9	13-14
1971	1	13 Jun	14	526	20	154	13-14
	2	17 Jul	14	127	10	7	13-14
	3	16 Aug	13	246	13	15	10, 13-14
1972	1	10 Jun	14	123	16	15	13-14
	2	8 Jul	14	60	9	0	13-14
	3	10 Aug	14	60	0	0	13-14

*Total number of lines is 16, numbered in pairs as follows: 1-2, 3A-3B, 4A-4B, 5-6, 7-8, 9-10, 11-12, 13-14.

(7) Cyclic decline begins with the onset of heavy avian predation on exposed lemmings in the peak summer; it continues through the summer and ends in the postpeak winter. Any recruitment in the peak summer merely slows the decline; it has never reversed a decline.

(8) The cyclic buildup of lemmings is paced by avian predators (especially breeding pomarine jaegers) in the prepeak summer. Their numbers then are highly variable and probably serve as the best single index of the level of cyclic buildup in the prepeak phase.

(9) The most massive predation occurs in the first 3 weeks of the summer of a peak year. The predation rate, however, remains high as the summer progresses.

(10) Predators of significance to the numerical dynamics of the cycle are three: the pomarine jaeger (*Stercorarius pomarinus*), the least weasel (*Mustela rixosa*), and the snowy owl (*Nyctea scandiaca*). The owl's share in peak years has varied (significant only in 1960, with densities of one to two breeding pairs per 1.6 km^2). The jaeger, on the other hand, occurs in peak years at a remarkably consistent breeding density, the ceiling being evidently set by territorial behavior which allows about 20 pairs per 1.6 km^2. An excess of jaegers scrambling for lemmings characterizes the onset of snowmelt. From these, successful contesters establish territories and sometimes exclude others numerically several times those remaining to breed. Weasels are at least as important as jaegers, mainly because they prey easily and directly on nestling as well as on adult lemmings, and their predation persists through the decline phase.

Among secondary predators, only the arctic fox (*Alopex lagopus*) is mentioned here. Near the coast it is rare as a summer resident, but it moves coastward in the fall and winter. In prepeak years and especially in postpeak winters, the impact of fox predation on lemmings is probably significant, but data are scant. Fox trappings by Eskimos and other factors now complicate assessment of the role of this predator in the lemming cycle near Barrow.

Cyclic patterns in trapline results. Patterns of successive cycles from 1949 to 1965 are diagramed in Figure 2. Differences in timing and relative abundance of brown lemmings are based on trapline results and also on field observations of both lemmings and their predators between late May and early September.

Since 1950, when Thompson began his studies, cyclic peaks have occurred in 1953, 1956, 1960, and 1965. From the data in Table 1, there is no doubt of the peaks in 1960 and 1965, nor in 1953 (Pitelka *et al.* 1955b, and Thompson 1955). Numbers seem too low to qualify 1956 as a peak year. Still, the first run yielded a number exceeding all years except 1960 and 1965 (and the unusual year 1971 to be considered later). More importantly, evidence of overwinter cutting of vegetation was extensive, as in the early summer of other peak years. Also, pomarine jaegers settled in densities characterizing other peak years (Maher 1970). In 1956, snowmelt was well under way by May 29 (first day in the field). Jaegers were not only present in numbers on that date, but also they were behaving territorially. Thus, exceptionally early and sustained exposure to avian predators resulted in a massive early decline in lemming densities. We do not know what the densities were when exposure to predators began. The variable and rapidly changing conditions of early summer preclude accurate density estimates (short of some new developments in radiotelemetry or infrared photography). Apart from the initial density level, onset of precipitous exposure to avian predators can vary by 2 weeks. The low take from the first run of traplines in 1956 thus reflects at least this latter variable—the exposure in that year having been unusually early.

This much is reviewed of events in 1956 simply to establish the fact that it was a peak year and that, in terms of winter impact on vegetation and early summer response of avian predators, it was similar to 1953, 1960, and 1965.

We also do not know the magnitude of variation in density levels between peak years for late spring just before heavy avian predation begins. But the peaks, as revealed by the onset of snowmelt, do vary in strength. Of those seen by us, 1956 was the weakest. Its prepeak summer (1955) was unimpressive; in the peak summer, the number of lemmings not only declined rapidly in June, but also summer reproduction was poor, with the result that nesting of jaegers, though initiated at ceiling densities, failed almost completely (Maher 1970). On the other hand, 1960 was the strongest peak,. with unusual nesting success by jaegers and owls. The peak years 1953 and 1965 were intermediate.

In addition to these four, 1946 and 1949 were also peak years (Rausch 1950). The five successive intervals (3, 4, 3, 4, and 5 years) average 3.8 years. The interval of 5 years is an exception (that is, it almost certainly would have been 4 years had not the

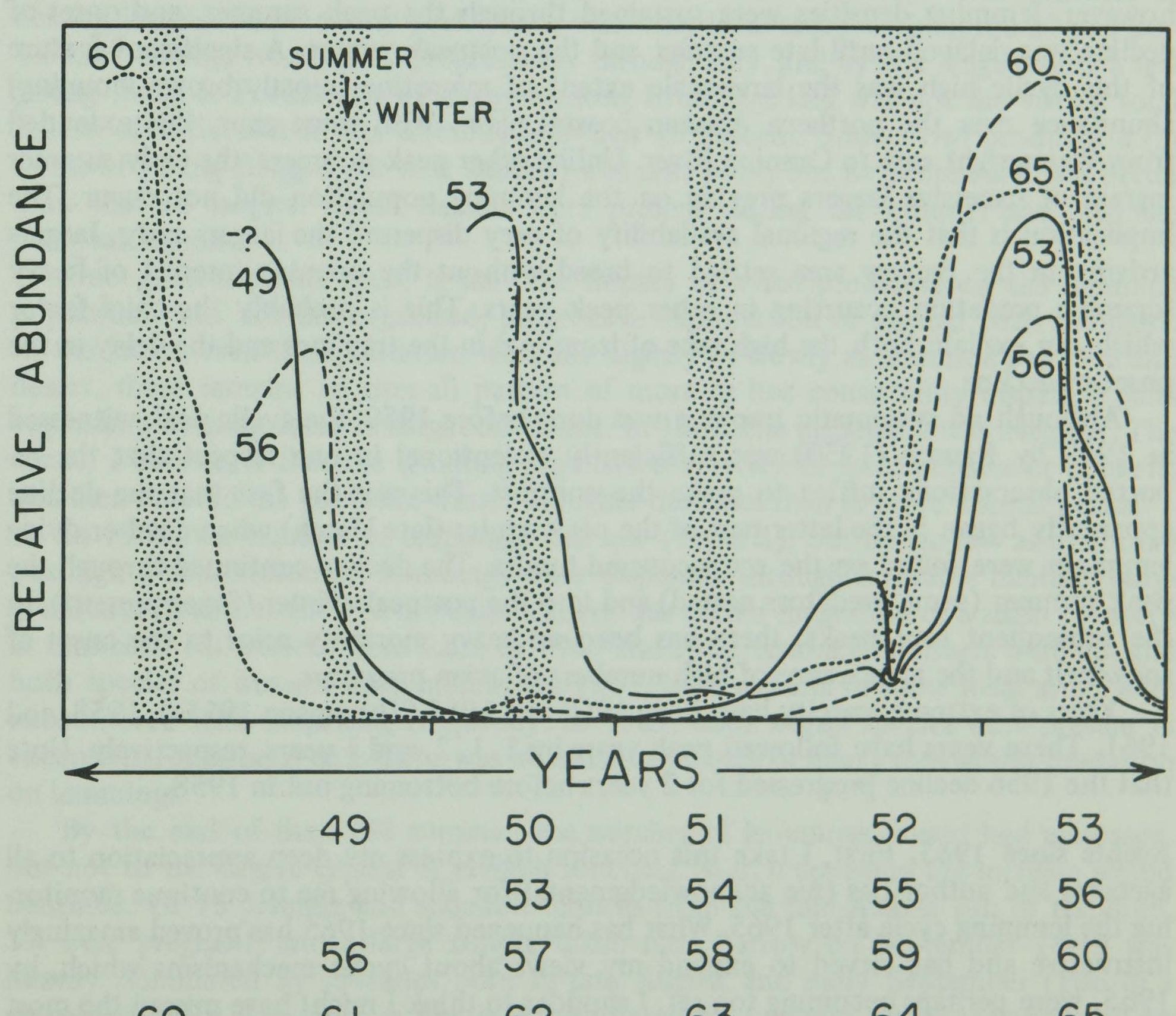


Figure 2. Time trends and relative amplitudes of four successive cycles of brown lemmings near Barrow, superimposed with peak years. (At cyclic peaks, densities are estimated at 50-100 per 0.4 ha; at cyclic lows, less than 1 per 4.0 ha.)

following events transpired). In the summer of 1963, which early showed signs of being a prepeak season, an early July storm left 15 cm of snow locally (less on higher ground but the mantle was continuous—officially at Barrow 9 cm). Following this, the summer was, so to speak, wiped out. Temperatures were subnormal for the remainder of the summer. More importantly, rainfall for July and August totaled 11 cm as opposed to a normal 4 cm (U.S. Weather Service 1963). Thus, protracted low temperatures, general wetness, and extensive surface water produced conditions unfavorable for lemming reproduction and indeed to plant production as well. Standing crop measurements in early August, at phenologically comparable times in successive years, were lower in 1963 than in either 1962 or 1964 (Schultz 1965).

Thus, the normal interval between cyclic peaks is 3 or 4 years. Longer intervals are probably the result of unusual events such as those illustrated by 1963. A second similar example is that recorded at Wainwright, Alaska in October 1955, when a warm spell with rains followed by freezing resulted in massive mortality in a population of brown lemmings then in a prepeak phase. Thus, the peak at Wainwright, which would have otherwise occurred in 1956, was delayed until 1957.

Declines from the cyclic peaks of 1953, 1956, and 1965 began with predator impact in the early part of the peak summer. This is considered typical. In 1960, however, lemming densities were sustained through the peak summer, and onset of decline was delayed until late summer and the postpeak winter. A significant feature of this cyclic high was the large-scale extent of microtine (mostly brown lemming) abundance over the northern Alaskan coastal plain. With some gaps, this extended from Wainwright east to Canning River. Unlike other peak summers, the early summer ingress of excessive jaegers preying on the lemming population did not occur. The implication is that the regional availability of prey dispersed the jaegers early. Jaegers arriving in the Barrow area settled to breed without the opening interval of heavy scramble predation occurring in other peak years. This is probably the chief factor which can explain both the high take of lemmings in the traplines and the delay in the onset of decline.

Although no systematic trapping was done before 1950, the cyclic peak witnessed in 1949 by Rausch (1950) was sufficiently exceptional in one respect that the reported observations suffice to make the contrast. This was the fact that the decline apparently began in the latter part of the peak winter (late March) when dead or dying lemmings were found on the snow-covered tundra. The decline continued through the peak summer (some predators nested) and into the postpeak winter (foxes present). In the subsequent four peaks, there has been no heavy mortality prior to the onset of snowmelt and the appearance of high numbers of avian predators.

Years of extreme scarcity have been 1950 and 1954 (Thompson 1955a), 1958, and 1961. These years have followed peak years by 1, 1, 2, and 1 years, respectively. Note that the 1956 decline progressed for 2 years before bottoming out in 1958.

Events since 1965. First, I take this occasion to express my deep appreciation to all agencies and authorities (see acknowledgments) for allowing me to continue monitoring the lemming cycle after 1965. What has happened since 1965 has proved amazingly instructive and has served to expand my views about cyclic mechanisms which, by 1965, were perhaps becoming too set. I shudder to think I might have missed the most recent years!

The main fact is that the Barrow area, notwithstanding the relative regularity of cyclic events since 1946, has not had a typical peak year since 1965. By peak year, I mean three early summer conditions in combination: (1) high numbers of brown

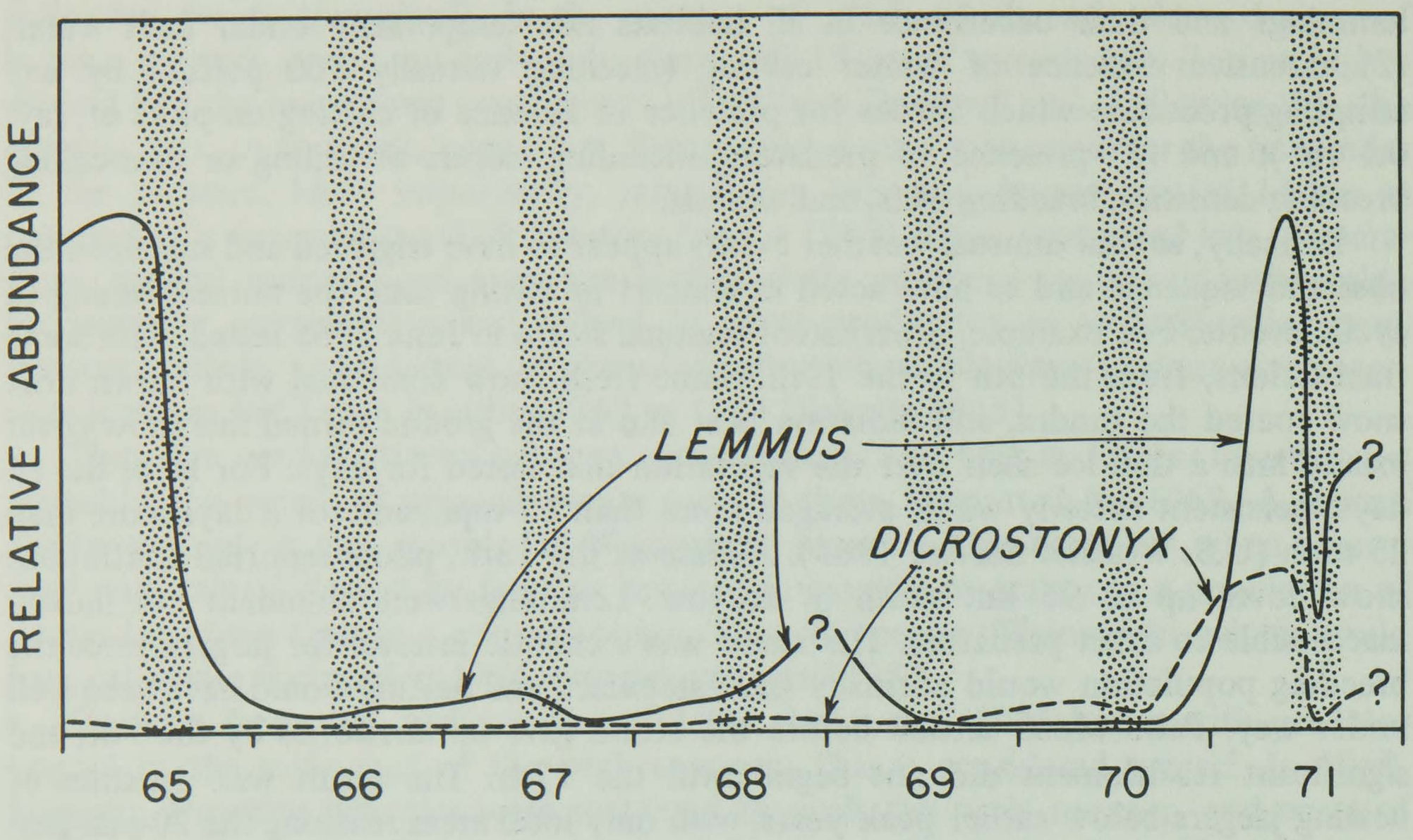


Figure 3. Time trend in populations of brown and collared lemmings near Barrow from 1965-1971.

mantle that appeared normal. This left a vegetation matrix for winter grazing which had not been cut by lemmings since 1965. Consequently, late 1968 and early 1969 samples of lemmings near Barrow revealed low overwinter growth and low reproductive rates. These conditions, impeding population growth in what might have been a peak winter, combined with exceptional numbers of weasels, resulted in a drop in lemmings by June 1969. Weasels, common that summer, preyed heavily on birds when lemmings became scarce, and were still present in early winter.

That winter, 1969-70, was severe. An October rain, with temperatures above freezing on the 10th, resulted in a subsequent ice glaze on the tundra. The winter's snow cover was also shallow which, when coupled with below-normal temperatures from January to May, finally reduced the number of lemmings to the extreme scarcity normally seen after posthigh summers. The presence of weasels after the 1965 peak (especially between 1967 and 1969, and probably in 1966 also) represents an unprecedented feature.

One is naturally curious to know what would have happened if winter weather (good October snowfall settling softly onto standing dead vegetation; continuous snow at least 30 cm deep through the winter) favorable to lemmings had occurred, and what effect weasels would have had then. It is tempting to suggest that patchy lemming numbers first generated under the peculiar circumstances of the 1965 peak year allowed weasels to persist in the area and slowly to build up (low reproductive rate is characteristic) while cropping a prey population impeded in its own growth not completely but considerably by unfavorable physical features of winter environment. Overcropping by weasels plus an extremely bad winter (1969-70) finally ended the decline. In 1970, lemmings were scarce and weasels absent.

One might argue that, in fact, lemmings in 1968-1969 showed a modified or suppressed peak coming a normal 4 years after the previous one. Features of prehigh

cyclic fluctuations in the brown lemming. A full discussion of this matter cannot be attempted here, but three aspects deserve comment now.

First, the impact of variable, unpredictable winter conditions on lemming numbers remains poorly understood, especially the degree to which such conditions can deflect normal phasing of cyclic change. Each year, we leave the Barrow area by early September, show up in late May or early June, and infer winter events using specimen samples on either side of winter, weather data, and the reports of staff and coworkers at NARL. Examples of important winter weather features include the amount of snow cover, extremes and atypical trends of temperature, wind-induced changes in the snow cover pattern, and especially the nature of conditions persisting at the ground surface after freezeup. Either individually or in combination, these are surely critical to winter survival and recruitment in the population.

We really know very little about all this, and can only make a few guesses as to ways in which and degrees to which winter conditions might have figured in the irregular behavior of the brown lemming population since 1965. That weather events can deflect the normal course of a cycle is illustrated by the events from 1963 to 1965 and by at least one other such occasion recorded near Wainwright from 1955 to 1957 (summarized above). My view now, however, is that for so long an interval as 7 years, it is unlikely that weather events alone would explain the observed irregularity, even if we had a full, first-hand knowledge for the successive winters since 1965 of both habitat conditions and population performance.

Second, the number of lemmings built up abruptly in 1971. This rise, to which local reproductive recruitment contributed only slightly (see above), demonstrates to a degree not witnessed (or detected) before the importance of dispersal in the local buildup of peak or near-peak numbers in a given area. In 1970, while the number of lemmings was low near Barrow, pilots and their passengers reported breeding jaegers and owls in the general vicinity of Peard Bay, about 95 km southwest of Barrow. This indicated that lemmings were then common there. None were reported from the south or southeast of Barrow (notwithstanding frequent flights by pilots alerted to note occurrences of lemming predators).

All that can be said now is that the Peard Bay area could have been the source of the lemmings which showed up near Barrow in late winter 1971. Given the year's time that transpired, given some reproduction during that interval, and given the known occasional predilection of brown lemmings for long-distance movement (Thompson 1955b), the suggestion of this source for the 1971 Barrow lemmings does not seem too farfetched. The reason for suggesting so distant a source is that, since first noted by Rausch (1950) and by Pitelka (1957a), the area of strong cycling in the brown lemming has been the triangular tip of northernmost Alaska southward from Barrow about 50 km to the Inaru River and east-west at this latitude over about 80 to 120 km. In all cyclic highs since 1949, this area has been consistently prominent. Over it, we have seen a persistence of local synchrony sufficiently impressive to lead one to ask if a population outside of it (for example, Peard Bay) might have been responsible for the ingress in 1971.

On the other hand, there is some probability, surely, that this local synchrony can break down occasionally. Thus, the severity of the 1969-70 winter in terms of ground-surface conditions and snow cover may not have been so unfavorable inland (say, 15 to 25 km) as at Barrow. Inland there is more upland and polygonal terrain, meaning more diverse and more favorable winter habitat conditions for brown lemmings than prevail at Barrow. An upsurge in an inland lemming population could have begun in

1970 while numbers near Barrow were low, with the result that dispersing lemmings moved into the Barrow area before the local population showed a significant increase.

Other than these suggestions, there is no evidence one way or the other. What we do have, however, is evidence that events elsewhere have contributed to the irregularity of lemming fluctuations at Barrow since 1965.

Third, to me, one of the more impressive lessons of the experience since 1965 is the increasing evidence of the importance of predators in the cyclic mechanism. Recall the summary of events in conjunction with the 1956 high, the failure of nesting avian predators, and the protracted 2-year decline with weasels present until lemming numbers bottomed out in 1958. Recall, also, the summary of events involving predators for 1965 through 1969. Recall, finally, the fact that winter predation by foxes, especially that in posthigh years when they tend to move to the coast in numbers, is interfered with by trapping. If summer predation by jaegers, owls, and weasels is sustained as breeding proceeds and free of disruptions by adverse weather, and if this impact continues effectively into the ensuing winter, then predation exerts a maximal depressing effect on prey. I suggest that given this summer punch to the population, any surviving lemmings in a posthigh fall and winter are then particularly vulnerable to weasels, and to foxes if they are present.

In the normal course of cyclic events, whether preying or scavenging, these efficient predators would wipe out most of the remaining lemmings. This impact in the 1965-1969 period was disorganized (as summarized above). In other highs (1953 and 1960), the impact and ensuing decline were abrupt. It now appears, therefore, that the regularity, strong amplitude, and relative timing of normal microtine cycles in the Arctic may be set more by predators collectively than by any other one component of the ecosystem. Together and serially, they slam the prey down and set a time Zero for the next cycle. Sometimes, as I believe the evidence of 1965-1972 shows, this co-adapted system fails. This interpretation of the role of predators supports views expressed by Maher (1967, 1970) and Pearson (1971). This is not to say, however (as Pearson does), that predator impact suffices to induce cycling. Recovery of food and cover, and pacing of population rise by these factors (that is, not merely by reduced predation) remain central points for any adequate hypothesis regarding the short-term cycle. Forthcoming evidence from the U.S. International Biome Program for tundra in northern Alaska; from analyses and modeling of pre-IBP data by A.M. Schultz and F. Bunnell; and from studies of the long-term snowshoe hare cycle by L. B. Keith will provide information critical to the continuing analysis of this entire problem.

Interaction of Lemmus **and** Dicrostonyx. An especially fascinating feature of events since the 1965 cyclic high of brown lemmings has been the unprecedented flareup in numbers of the collared lemming after 6 years of low numbers of brown lemmings. In all years prior to 1968 (Table 1) as well as in 1951-1953 (Pitelka 1957a) and earlier (Rausch 1950), collared lemmings were consistently uncommon. This was true for the area as a whole but also, more importantly, for their characteristic well-drained upland habitat (Pitelka 1957a), which near Barrow comprises a small fraction of the total land area. Before 1965, there is the barest suggestion (Table 1) that increases of collared lemmings, if at all, have occurred late in the cycle of the brown lemming. At such times, they would have been favored both by better food and cover conditions, and by protracted relief from any effects, direct or indirect, by the brown lemming (for example, 1959 and 1963-1964).

After 1965, a slight rise in the number of collared lemmings occurred in 1968, repeating the weak pattern of fluctuation of earlier years. A significant rise, however,

began in 1970, when collared lemmings occurred even in lowland wet habitats where they had never been trapped in the prior 15 years. In 1971, their numbers in June comprised 23 percent of the total catch. On well-drained ridge habitats, they were locally as numerous as brown lemmings and, on one such area, significantly more numerous (the 3-day catch at trapline 1 in June: 49 *Lemmus,* 79 *Dicrostonyx*). The winter ingress of brown lemmings into the area, however, evidently caused this situation to shift back to the more usual one, for by fall 1971 the number of collared lemmings declined markedly—and continued to decline in 1972.

No special study of behavioral interactions of the two species has been conducted near Barrow, but field observations certainly suggest that in usual circumstances the collared lemming is at a disadvantage with relation to the brown lemming. The collared lemming's habitat range is narrower, and the area of habitat suitable for this species is limited in the Barrow area. On the other hand, the brown lemming, when common, occurs in all habitats; moreover, it is the larger, more aggressive of the two species. Previous observations on diet (Thompson 1953) suggest only slight overlap between the two species near Barrow. In a food preference study of caged animals, collared lemmings took mainly dicot herbs and shrubs while brown lemmings took mainly sedges and grasses. While overlap in diet may be of some importance, the main competitive impact of the brown lemming on the collared lemming is more likely one of interference, direct and indirect, in use of runways and burrows, which maximizes when brown lemmings are common or during the snowmelt interval of early summer when lemmings are temporarily crowded into upland areas.

Whatever the mechanism, the events of 1965-1972 did provide an experiment that tested the response of the collared lemming in circumstances of sustained low densities of the brown lemming. The observations clearly suggest that the number of collared lemmings is suppressed by the brown lemming and that the former would be more numerous in the Barrow area in the absence of the latter.

Summary and Conclusions

Fluctuations in the populations of the brown lemming and the collared lemming have been followed near Barrow since 1955 using standard traplines. The main objective has been the monitoring of a sequence of cycles to ascertain the main features of successive phases of cycling in a population of lemmings and lemming predators, and to provide a basis for comparison of microtine cycling in the Arctic with better known examples of the same cycling at temperate latitudes. Four topics were considered: (1) the general features of a cycle, to the extent that available data permit such generalization; (2) variations, real or apparent, in patterns of cyclic fluctuations in lemmings since 1949; (3) the atypical fluctuational pattern of the lemming population since 1965; and (4) new evidence from this atypical interval regarding competitive interaction of brown and collared lemmings.

Of the two lemming species regularly occurring near Barrow, the brown lemming is overwhelmingly the more important. Cyclic peaks in numbers of this species have occurred in 1949, 1953, 1956, 1960, and 1965. In this time span collared lemmings have been consistently uncommon.

Since 1965, a potential for peaking in 1968 or 1969 apparently was effectively held back by weasels and by two successive harsh winters (1968-69 and 1969-70). Brown lemming numbers remained low through the 1970 summer. In 1971, the abundant brown lemmings were mainly immigrants, as shown by scarcity of winter

nests, limited areal extent of winter grazing, paucity of young in early summer samples, and low incidence of recently reproductive females. Lemming numbers were again low in 1972. Factors explaining the atypical fluctuational pattern witnessed near Barrow are (1) unusual winter weather, (2) events in neighboring populations not in phase with that of Barrow and promoting dispersal to it, and (3) breakdown of usual pattern in collective impact by predators on a declining lemming population and failure of this impact to set a regional time Zero for the ensuing cycle.

After brown lemmings had been uncommon for 5 years, a striking increase of collared lemmings occurred in 1970-1971. This strongly suggests that in its coexistence and interactions with the brown lemming, the collared lemming is normally at a competitive disadvantage.

Except for the brief interval in 1971, the number of brown lemmings has been relatively low near Barrow since 1965. Since then, the tundra vegetation there has not undergone the massive winter cutting by brown lemmings in normal cycling. Since, also, the usual cyclic interval is 3 to 4 years, it is suggested that cumulatively atypical conditions may be occurring currently. An example is the unprecedented buildup of *Dicrostonyx* numbers in 1970 and 1971. Such atypical conditions may also be occurring in vegetative production and decomposition, since the last massive cutting by grazers occurred 7 years ago.

Acknowledgments

From 1955 to 1969, support for the research reported here was provided by the Arctic Institute of North America under contractual arrangement with the Office of Naval Research. Since 1970, this research has been supported by the National Science Foundation under Grant GV-29349 to the University of California. It was performed under the joint NSF sponsorship of the International Biological Program and the Office of Polar Programs, and was directed under the auspices of the U.S. Tundra Biome Program. Field and laboratory activities at Barrow were supported by the Naval Arctic Research Laboratory. For assistance there, I am indebted to many persons, but especially to former NARL directors G. D. Hanna, I. L. Wiggins, and M. C. Brewer, and to the present director, J. F. Schindler, For comments on an earlier version of this paper, I express thanks to F. C. Dean, O. P. Pearson, and S. F. MacLean, Jr.

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NARL's CONTRIBUTION AND A LOOK AHEAD

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While drafting this talk in commemoration of our 25th anniversary, it came as a surprise to realize that I have been associated with the Laboratory at Barrow for a little over 12 years or nearly half its lifetime. Twenty-five years have witnessed the appointment of seven directors of which in sequence of service I must consider myself number eight since Dr. Wiggins served two separate periods. Twenty-five years have seen the conduct of hundreds of research projects and the presence of thousands of scientists and investigators. Since the greatest growth in projects has been during the second half of the 25 years, I have probably known a majority of the people who have pursued their research from NARL.

The product of NARL is research. How though does one measure the product? How can one apply the yardstick to measure the impact of an organization? These questions have never before been answered to the satisfaction of everyone. I will not likely answer them tonight, but I will make an attempt anyway.

A brief review of the "mileposts" in the past 25 years helps in assessing the historical impact of ARL (we did not become NARL until 1967). The Laboratory began in 1947 with the arrival of Dr. Larry Irving and a crew of six to do research in the biological sciences. The next year saw an increase in personnel to 30 scientists and technicians.

Dr. Irving served as Director until July 1949 when Dr. George MacGinitie took over. A year later in August 1950, the Director's position was assumed by Dr. Ira Wiggins. Both gentlemen coped with many difficult problems during the growing pains of a small but unique facility. In February 1954, Ted C. Matthews came on board as Director, the only nonscientist to hold the position. Those days were difficult times as the exploration of the Petroleum Reserve had been terminated a few months before and the ARL had been quite dependent on that operation. Ted Matthews, with his knowledge of the ARCON operation (Arctic Contractors), served the Laboratory well and with distinction.

In April 1955, Dr. G. Dallas Hanna relieved Ted Matthews. Dr. Hanna served until March 1956, when Dr. Wiggins returned and directed activities for the summer. In September 1956, Max C. Brewer took the helm and stayed on for the next 15 years (three-fifths of NARL's lifetime). This was a period of rapid growth for the Laboratory both in size and in direction. Dr. Brewer departed in 1971, but by then he had molded NARL into the dynamic and important facility it is today.

Three academic institutions–Swarthmore College, Johns Hopkins University, and the University of Alaska–have held ONR contracts for operation of the Laboratory. The University of Alaska has overseen administrative functions since 1953. The parent organization of NARL is the Arctic Program, in the Earth Sciences Division of the Office of Naval Research. The Director of the Arctic Program guides research efforts through contracts with both government laboratories and universities. In managing the program, ONR follows a policy of supporting the gathering of fundamental data which are oriented toward present and future navy needs. This general policy embraces a broad array of scientific inquiries.

The original research under Dr. Irving was mostly in biology. This emphasis slowly changed over the years. By the advent of IGY, a strong program in geophysics had been instituted. Since then an excellent balance of disciplines has been maintained so that now during any one calendar year a variety of investigations are supported out of NARL. These can range, as we like to say, from the extreme on the physical to the extreme on the biological, even including at times such things as anthropology and sociology of remote areas. It is this diversity that provides the vigor and stimulus researchers find so advantageous and unique at NARL.

Any listing of accomplishments of the Laboratory almost always includes the research that found immediate application. We often credit the early work of the Drs. MacGinitie with the discovery of the Barrow Canyon and its later importance to atomic submarines. The feasibility study of the Air Force Distant Early Warning Line–Project Lincoln–was an early NARL investigation. We have used and reused that wonderful quote by a knowledgeable Canadian that the results of the research from a single permafrost program at ARL saved more money in the construction of the DEW Line than the total ARL cost to that date. Certainly, the logistic methods pioneered by the Laboratory in pursuit of information have high applicability to others: the light aircraft operations, both over the ocean and inland, and the entire drift station experience from ARLIS I and T-3 to ARLIS VI and AIDJEX '72. A very strong case of accomplishment can be made for each of these areas of immediate application, but there are other equally important contributions.

Back in 1946, in correspondence which discussed the establishment of ARL, Dr. A. L. Washburn wrote a very prophetic letter in which he said: "An arctic laboratory for the pursuit of basic scientific research is one of the best ways to facilitate the acquirement of new information. It affords a base of operations for scientists, encourages cooperative observations in different fields of science, and is the only means of effecting some types of research requiring frequent observations at fixed points over a period of years . . . ." I think NARL can proudly claim to have lived up to that expectation.

The emphasis usually placed on applied benefits should not be allowed to eclipse the advances in our understanding of ecosystems within the rigorous parameters of the arctic climate. We have learned very basic things about arctic physiology and biology, about the fluctuations in animal populations, and about the natural history of polar bears, wolverines, whales, and other animals. Health, medicine, archaeology, and anthropology have also been productive. The archaeological site at Walakpa is estimated at 5,000 years old (the oldest Eskimo culture in North America). We have had advances in oceanography and limnology, gravity, physiography, geophysics, geomorphology, meteorology, and ionospheric physics. Simply because many of these increases in knowledge had no immediate dramatic application does not reduce their significance.

Recently, a member of the Department of the Interior, who was closely associated with the Pipeline Impact Statement, commented to me that the previous work done at NARL had given them at least a 2-year advantage on tackling the environmental statement. To equate that amount of time in dollar costs to the federal government and to the oil industry puts a very high monetary value on such information. But in the long run it is even more valuable because it simply exists in the encyclopedia of man's knowledge.

One of the unique features of the Laboratory is its remote position, although one can hardly call the service of two 737 jets every day the height of isolation. Most scientists live, work, and relax within the confines of the facility, and this situation produces an atmosphere where professors can talk with other professors, with graduate students, with local natives, and with arctic "veterans" to the benefit of all. The researcher is immersed in an arctic environment that of necessity forces a 24-hour attention to the problems at hand. This, in turn, provides an interaction and exchange between disciplines that is seldom found on the university campus with its schedule of classes and cloisters for separate groups of researchers.

In their book *Arctic Laboratory*, Reed and Ronhovde quote one graduate student who sums this up very well. He said "he valued particularly his contacts with other investigators" and added that "he had received a dinner-table education at ARL which could be described as a university in a quonset hut." In the present age of specialization we often lose track of the extreme importance of interdisciplinary exchange and the value of total immersion in a community that of necessity is oriented to discuss the research at hand. I wonder how many solutions to inquiries can be traced to just such an atmosphere—a university in a quonset hut with a dinner-table education.

Today, we have been commemorating a birthday, and from time to time we have been singing the praises of NARL. We must remember, however, that the Laboratory is not an impersonal entity. Rather, it is made up of many people, and so when we say the "Lab" we really mean the people who have worked there or who are now working there. I wish I had kept track of how many times I have heard the comment "We've really got a good crew this season, everyone is pitching right in and we're getting lots done." I always smile to myself when I hear it again, but it points out that the caliber of the people who work at NARL is consistently high. The sum is made up of its parts, and so it is with the Laboratory. We are fortunate in having had such a long history of dedicated, interested, and simply nice people. Without them, the interaction of disciplines could not have taken place and one of the unique values of the Laboratory would not have come about. I would like to publicly say "thank you" to all those who have lived and worked at NARL over the years.

Since the first summer of the Laboratory's operation, we have enjoyed a unique relationship with the natives of Barrow. For most of the lifetime of the Laboratory, about 60 percent of our employees have been hired locally. The difficulties that someone from the "South 48" can have trying to accomplish the simplest of chores in an arctic winter can only be appreciated fully by those who have learned the hard way. The people of Barrow have brought experience and knowledge to the Laboratory, and the value of these to the research effort can never be fully measured. Many overland trips, ice projects, boat projects, and ice stations owe their success to the presence and gentle suggestions of the local people. I now publicly express both my gratitude and the Laboratory's gratitude to the people of Barrow.

Another group of people who have had much to do with the success of NARL is often forgotten at times like this. These are the administrators, or the paper-pushers as we call them, who are not on the scene at Barrow but who make the decisions which

are far reaching or which affect the Laboratory's day-to-day operation. I refer to the people at the University of Alaska and at the Office of Naval Research. We all know how easier it is to take the short cut or to stick with the rules. Such action results in a "no we cannot do this because that's what the regulations say." One can go home at night with a clear conscience, but the job does not get done. The success of the Laboratory shows this has not been the case, for which we are grateful.

There are three people here tonight who should be singled out for special thanks. These include Dr. Wood, President of the University of Alaska; Max Britton, now with the Arctic Institute of North America; and Ron McGregor of the Office of Naval Research. In citing these people, I speak only for the years with which I am most familiar and hopefully offend no one with omissions. Both my predecessor and I have stated many times that the job at Barrow would be untenable without these men in Fairbanks and Washington. It seems inadequate, but I don't know how else one can express his feelings. Thank you gentlemen and God bless you.

It is also appropriate at times like this to look ahead and attempt to foretell what the next years hold for NARL. One could devote an entire evening to such speculation, but we do not have that kind of time so I will make only one prediction. I have mentioned previously the balanced research program that ONR has diligently maintained. I think this has been fortunate and will continue to be important for the future of the Laboratory. All those years of work on everything from lemmings to permafrost to underwater sound have produced a background of experience and knowledge on which the future research of the Laboratory can grow.

This broad base coupled with that unique capability of the Laboratory to produce interdisciplinary exchange is being reflected in programs that have already begun and should be more prevalent in the future. I refer to the Tundra Biome and AIDJEX (Arctic Ice Dynamics Joint Experiment) projects. In these projects many investigators in quite separate yet distinct disciplines, and usually from different universities or government laboratories, pursue their research in a "pool" effort in which the interactions of the parameters of each discipline are constantly discussed. It seems to me that this is a type of research "whose time has come." We have done most of the taxonomic inventorying that is necessary when beginning research in new areas, and indeed there is still some of this to be done. But there comes a point where the inventory becomes the tool for research, and we are now at that point. The current trend for these combined efforts on total systems is growing, and NARL has a unique capability in a vibrant and invigorating way to foster and promote such programs. The next 25 years will perhaps witness a different kind of growth, but they promise to be every bit as exciting as the previous 25 years.

ARCTIC RESEARCH: FOR WHAT PURPOSE AND FOR WHAT END?

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Anniversary celebrations provide the opportunity to join with old friends, colleagues, peers, and neighbors to review past events, to crow a bit about successes, to lament the missed opportunities, and hopefully to plan for an even greater future. Today, we are celebrating the silver anniversary of NARL (or ARL as many of us still remember it). Silver anniversaries are always special junctures in our lives, whether for a quarter century of marriage or for the research life of an institution.

I like to think that NARL has much to crow about on its silver anniversary. Twenty-five years ago it started most humbly, as aptly shown by the picture of Dr. Laurence Irving's pioneering group posed in front of its extremely modest laboratory. Twenty-five years later NARL has gained international recognition for the work that has emanated from the efforts of its researchers. Additionally, and what is of far greater importance, the results of their efforts have provided the background data and reasoning for numerous decisions at both the state and national levels.

As in the case of the government's space program, there also has been a spinoff of results into the private sector. Even as benefits continue to accrue, research at NARL is both increasing in scope and expanding in depth. Perhaps it might be of interest to examine why this is so when there has been a marked trend for research programs and institutions such as NARL to fade away, to become technical institutions, or at least to reach advanced middle age by the time of their silver anniversary.

Despite the vast amount of work done in the Arctic in recent years, it still remains largely an unknown environment to the general public. Because it is unknown, it retains a certain romantic interest for many people. But, because of man's appetite for raw materials and because of the potential for finding these raw materials in the Arctic, there exist national and international pressures for exploring the Arctic, for developing methods of economically retrieving the raw materials to be found there, and for finding better ways to live and work in its harsh environment. Thus, the circumstances existed and continue to exist for a research laboratory to grow with continuing vitality, provided it is properly organized to escape the doldrums of old age, often symbolized by repeated reorganization or contentment with past accomplishments.

In my opinion, NARL was properly organized to escape the pitfalls of old age and liquidation. It was established in 1947 for the support of arctic research without restrictive definition or programing as to what research would be conducted or how it would be supported. Therein lies the strength and continuing vitality of NARL. Had NARL been organized for the support of lemming research on the North Slope, it would have been dead long ago; had it been organized for the support of geological studies, it would have died in 1953; had it been organized for the support of permafrost studies, it would not have been organized by the Navy because they thought they already had their answers prior to 1950, not anticipating the problems of 1970; had it been organized for the support of ice studies, it probably would not have been created until the *Manhattan* tanker experiment and might have faded almost as rapidly; had it been organized for the support of auroral studies, it would likely have had the same limited life that the National Bureau of Standards' auroral station at Barrow experienced; had it been organized for the support of micrometeorological studies, it would long ago have been absorbed into the National Weather Service and operated by a technician; had it been organized for the support of naval communications, the Navy need might have evaporated before the facility was completed.

The operational task for NARL, in retrospect, really boiled down to one of supporting broad environmental research in a particular area—the Arctic—20 years before the word environment became a household word. Yet NARL still has the resilience to continue on after people could become tired of the word environment, and it will keep on growing so long as someone does not change its task by inserting the word "environment." The flexibility of NARL's programs has allowed modification with changing times, including those involving social environment, political environment, fiscal environment, and occasionally the biological and physical environments. The programs have tended to retain freedom from mission orientation, with the often ensuing prejudiced results and blinders as regards associated impingements from other aspects of the environment. Innovation in research has been encouraged rather than impeded, as often happens in the bureaucracy inherent in many well-organized programs. At the same time coordination of projects for balance has brought together complementary studies in such a way as to insure a large amount of interaction and critical examination of the results. This has tended to keep the scientific investigators from getting hung up on the swords of their own ignorance and has provided for quality scientific results.

The quality results and the nonmission orientation of the program are the assets that allowed NARL to develop its national and international reputation while at the same time providing information of much value to Department of Defense missions and to other national interests. For example, Dr. George MacGinitie, the second director of NARL, was not seeking submarine canyons for the *Nautilus* to enter the Arctic Basin when he discovered the Barrow Sea Canyon in 1949 while using an old dory to collect marine specimens. Also, Dr. MacGinitie was not thinking about ice islands when he photographed and described, from the ice, a part of what is now believed to have been Ice Island T-3 off the coast northeast of Barrow in the spring of 1950.

The Navy thought it would have no need for further studies of permafrost in 1950 when it agreed to continue the support of a U.S. Geological Survey permafrost project. A few years later, however, a Canadian government representative credited the Navy for this NARL-supported permafrost project by stating that it had saved the U.S. Air Force far more during construction of the DEW Line than had ever been spent on the NARL from its inception until that time. The sea ice study, begun in 1957, provided information and training for the designer of monopods and other supports used for oil

well platforms in Cook Inlet. These studies, coupled with results from some of the permafrost information obtained near Barrow, have formed the basis for several tentative designs for offshore oilfield platforms along the north Alaskan coast.

The results from an earth heat-flow study in northern Alaska provided the differentiation of parameters needed for earth heat-flow studies undertaken in areas ranging from the depths of the Arctic Basin to the southern 48 states, in Iceland, in Turkey, and in other parts of the world. In this regard, the Arctic often has been found to provide a less complex area for study, from which can be developed the basic parameters in both biological and physical studies for application to more complex studies in the southern latitudes.

Admittedly, the United States is facing an energy crisis, and the North Slope oil and natural gas reserves offer a partial solution. The problems of permafrost and tundra, which basically boil down to a problem of erosion, have been identified as two of the major obstacles in bringing this energy source to market. In the solution of these problems, the results from NARL-sponsored projects have been heavily utilized. In addition, many of the men trained at NARL over the past two decades are either directing or participating in additional research for industry. Such efforts extend into resolution of many other environmental problems for industry, the construction of facilities, and the solution of logistic difficulties.

Information obtained at NARL has aided in solving communication problems for all branches of government and industry in northern latitudes. In fact, NARL has even provided information for the Apollo missions. Little known is the fact that, of the dozen significant northings of surface vessels since 1849, five have occurred during the establishment and support of ice stations operated by NARL. During one such support operation, an icebreaker reached 79°30′ North by following a zone of weakness in the ice between two major ocean currents in the Arctic Basin. The same information used in this endeavor also was used by the Wally Herbert expedition in its successful dog team trek from Barrow to Spitsbergen by way of the North Pole.

As a sideline, NARL even trained an environmental commissioner for the State of Alaska. In so doing, it provided him with the insight to understand that the problems of waste disposal in the Arctic and in Harlem, New York were similar and that much of the problem in both cases was rooted in the psychology of impermanence for individuals and agencies in both locations.

Today, the United States has embarked on a housing program for natives in Alaska. Six thousand units are scheduled to be built during the next 5 years. At a conservative estimated cost of $40,000 per unit, the total expenditure would amount to $240 million. The information developed at NARL concerning water supply, sewage disposal, and the use of insulation in arctic structures could save many millions of dollars for this project. Yet, only one NARL project has been aimed at water supply, one at sewage disposal, and part of one at construction of this type of housing.

Many other examples could be cited, but the point is this: The research supported by NARL has provided practical solutions to many problems without ever having been pointed toward the solution of these problems or having such solutions as the goal. The search has been for knowledge of the environment and of man's interaction with the environment, not a narrow search for data to prove preconceived notions or expectations, although there have been exceptions.

For the most part, NARL-supported contract research has attracted topnotch, talented investigators who have not always been able to make a more or less permanent commitment to either living or working in the Arctic. In so doing, NARL has tended to escape the entrenched bureaucracy that inevitably results in any organiza-

tion, be it government or private. Such bureaucracies tend to drift toward a concentration on facilities, toward a concentration in developing personal comforts, toward a concentration for protocol whereby one does only those things that apply to his immediate job.

In the northern and/or remote stations, this tends to concentrate people's time toward providing such auxiliary services as commissaries, nurseries, private car plug-ins for winter use, and other comforts of a bureaucratic heirarchy. Not only does this dilute the scientific effort, but also it can, in time, push up costs (particularly in a logistically difficult area) to such fantastic figures that research is priced out of the market. In addition, it can so entrench a group that research suffers badly, sometimes actually changing from a status of scientific research to one of technical data gathering.

NARL has supported a quarter century of lean and hungry investigators, and independent and generally unfettered scientific research. The quality of the research has attracted an international reputation to the Laboratory. The results have so thoroughly interfaced with the various disciplines that the picture has often been complete and the results have had wide application to many government and private projects. The unplanned-for results have saved millions of dollars and have often seen surprisingly early practical application.

Arctic research: for what purpose? We might say to increase man's knowledge and economical use of arctic areas for his welfare, without destroying or unduly wasting its resources. Often, because of cost or remoteness, the benefits accrue to the government.

Arctic research: for what end? We can only speculate on this by using other areas and other research laboratories and their operations as a guide. We do know, however, that our knowledge of arctic areas is still meager and that our understanding of the environmental interplay and of man's influence on this interplay is just beginning to be developed. We also can speculate that lean and hungry investigators combined with independent and unfettered scientific research that is balanced in disciplinary approach and priority will maintain and enhance the scientific and nationally useful value of NARL's efforts. We can further speculate that organized, stylized, and bureaucratic operations could lead to more comfortable facilities, to more entrenched personnel, to greater expenditures with lessened quality and quantity of scientific output, and to perhaps the closing of another overaged and outdated laboratory. Hopefully, in 1997, NARL will still be able to crow about its accomplishments of the then past quarter century.

(Continued from back cover.)

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