

# Geology, Especially Geomorphology, of Northern Alaska

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## INTRODUCTION

Northern Alaska is considered here to include the geomorphic provinces of the Arctic Mountains, the Arctic Foothills, and the Arctic Coastal Plain (Wahrhaftig 1965). The Arctic Mountains are loosely synonymous with the Brooks Range in the usage of many; the combined provinces of the Arctic Foothills and Arctic Coastal Plain with the Arctic Slope (e.g., Gryc 1958). The gross topography and geologic features of the Arctic Mountains and Foothills may be compared with their counterparts in the Rocky Mountains and fronting plateaus of Canada and the United States.

The Arctic Slope and Brooks Range, for practical purposes, encompass the range of logistic support that is feasible from the Naval Arctic Research Laboratory at Point Barrow. Therefore, the geology with which we are concerned is confined to those provinces. The Coastal Plain, being closest to Point Barrow, is primary.

A field-oriented, isolated laboratory, such as NARL, is obliged to further primarily such research as is peculiar to its environs. Research not so related should be done closer to centres of civilization where costs are lower and where normal operational procedures permit greater efficiencies in the use of man's time. Moreover, federally sponsored research should supplement and complement that being done through private enterprise. It should not compete with nor duplicate unduly the privately funded research.

Because of the frantic exploration for oil at the present time, large sums of private money are being spent on various facets of the bedrock geology of the Arctic Slope and Brooks Range. In view of this, certain constraints should be placed on the immediate goals for geologic research supported by NARL in northern Alaska. This does not mean, of course, that NARL should back away from supporting basic geologic research. A certain amount of overlap is always healthy, especially when it is done for different purposes. Compilation of regional geologic reports and detailed areal mapping have long been the forte of the U.S. Geological Survey and should continue to be so. Nonetheless, the various companies are competing, and funds are too short to duplicate much of their normal, and very expensive, subsurface and geophysical research. Hence, a number of broad but rather well-defined avenues of geologic research assisted by NARL seem blocked out for immediate emphasis.

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For example, certain research in the general field of geomorphology, including glacial and Pleistocene geology, is geographically restricted or topically unique to northern Alaska. Topics in this category are less important to the petroleum companies whose major efforts are devoted to older portions of geologic time. Those portions of geologic history, such as the Precambrian, are also of less concern to the petroleum companies, although the position of the "basement" is of primary concern to them. Clearly, then, the most recent and oldest portions of geologic history fall especially into the domain of NARL at the present time and in the immediate future. So, too, do basic process-oriented studies with no immediate practical goal.

In the following pages a brief description of the provinces of the Arctic Coastal Plain, the Arctic Foothills, and the Arctic Mountains is presented for background. Some representative projects supported by NARL, as related to those provinces, are noted by literature citations. Most abstracts and unpublished manuscripts are omitted. A few general references needed to "round out the picture" are included. Many recent papers, especially on bedrock geology, are omitted, because acknowledgment to NARL specifically was not seen. A list of selected references on the geology of northern and northeastern Alaska is available (Brosgé *et al.* 1969). Finally, some conclusions on the future role of NARL in support of geologic research in northern Alaska are attempted.

#### GEOLOGIC SUMMARY

##### *Arctic Coastal Plain Province*

The Arctic Coastal Plain Province in which Barrow and NARL are located is roughly triangular in shape and extends almost 900 km. from Cape Beaufort on the west to the International Boundary on the east. It reaches its maximum width of about 175 km. due south of Barrow. The Coastal Plain is characterized by low topographic relief (Hussey and Michelson 1966), thousands of lakes and swamps (Black and Barksdale 1949; Carson and Hussey 1962 and 1963), and numerous meandering streams. Drainage is not integrated.

The Coastal Plain is a surface primarily of deposition. The surface sediments of unconsolidated silts and sands with some clays and gravels comprise the primarily marine Gubik Formation of Pleistocene age (Black 1964a). Those sediments rest with slight angular unconformity on marine shale, mudstone, and sandstone of Cretaceous age west of the Colville River and on clastics, particularly red beds, of Tertiary age east of that river (Payne *et al.* 1951). Older rocks underlie the Cretaceous and Tertiary rocks.

The sediments extend northward under the Arctic Ocean with little or no topographic or geologic break. A broad regional arch plunging gently northward extends south from Barrow through the Coastal Plain and into the northern Foothills. Many structural warps lie east of the Colville River. The Precambrian basement near Barrow plunges southward, and the late Paleozoic and Mesozoic rocks on it thicken southward.

A characteristic tundra plant assemblage varies in composition from place to

place, depending on the composition, texture, and drainage of the sediments (Britton 1957; Spetzman 1959; Wiggins and Thomas 1962). Eolian features are widespread (Black 1951a).

Continuous permafrost and low relief result generally in poor drainage over large areas and in the development of striking patterned ground (Black 1952 and 1963; Tedrow 1962), of thermokarst phenomena (Anderson and Hussey 1963; Black 1969), and of various ice-cored mounds (Black 1951b). The lake area of some 65,000 sq. km. is perhaps the most unique feature of the Arctic Coastal Plain Province. Tens of thousands of lakes are unusually well oriented with their long axes a few degrees west of north. The lakes range in length from a few metres to 15 km. Shapes may be described as elliptical, triangular, ovoid, egg-shaped, rectangular, and irregular.

#### *Arctic Foothills Province*

The Arctic Foothills Province lies between the Arctic Coastal Plain to the north and the Arctic Mountains to the south. The province may be subdivided into northern and southern units, each with affinities closely related to the province it adjoins. It is bounded on the north in places with distinct topographic break. To the west of the Colville River that boundary is a marine notch that lies generally between 160 and 200 m. above sea level; to the east of the Colville River it reaches a maximum elevation above sea level of about 400 m. The boundary in places is a zone as much as 35 km. wide. On the south a major topographic break, commonly over 1,000 m. above sea level, occurs at the steep front of the Arctic Mountains.

The northern part of the Foothills is characterized by broad, rounded east-trending ridges, dominated only locally by mesa-like uplands. The higher southern part is characterized by much greater relief, as much as 800 m., and by numerous irregular buttes, mesas, and long linear ridges with intervening undulating plains and plateaus. The Foothills are dominated by erosional topography which emphasizes and is etched from the east-trending open folds of the Cretaceous sedimentary rocks in the northern part and of Devonian to Cretaceous sedimentary rocks and of intrusions all tightly folded and overthrust northward in the southern part. The lowlands are cut mostly in shale; the higher features are held up by more resistant sandstone, conglomerate, limestone, and chert. The Cretaceous-Tertiary rocks almost everywhere cross the north border without break except in degree of folding. They are very gently inclined in the Coastal Plain and broadly folded in the northern Foothills. At the south border the softer Mesozoic rocks, especially shales, generally lie within the Foothills Province and the older more resistant rocks form the steep front of the Arctic Mountains. The structural complexity is shared.

The drainage of the Foothills is integrated. Major streams originating in the Brooks Range are structurally controlled by and in part superposed on the bedrock. The Colville River, the largest, trends easterly for more than 300 km. in part along the somewhat arbitrary boundary between the northern and southern parts of the Province before turning abruptly north near Umiat. Most streams are swift yet portions are braided across gravel flats locally covered in winter with

thick river icings. Spring break-up is a time of flooding and channel shifting. Only a few thaw lakes and lakes of unknown origin exist.

### *Arctic Mountains Province*

The Arctic Mountains Province contains a variety of topographic forms which may be divided into several sections (Wahrhaftig 1965). Although lowlands exist along some major rivers, the gross topography can be called mountainous; it is rugged and complex. Several deeply dissected and glaciated mountain ranges represent the offset extension of the Rocky Mountains. Relief generally is 1,000 to 2,000 m. Elevations of 1,600 to 2,500 m. are common for peaks, and valleys are incised to elevations of 1,000 to 1,300 m. Both general elevation and relief increase eastward, but no low passes cross the eastern part. Accordant summit elevations differ in local ranges.

Sedimentary rocks of Paleozoic and Mesozoic age are intricately folded, extensively faulted, intruded, and locally metamorphosed. East-striking Devonian and Mississippian rocks are exposed almost continuously through a sequence of over 3,500 m. A thick clastic sequence covers carbonates in the northern part of the province (Gryc *et al.* 1967); northward overthrust plates in imbricate arrangement are the major structural feature. These have been etched in strong relief by streams and glaciers. Limestone of Silurian age and metamorphic rocks of earlier Paleozoic and probable Precambrian age occupy the southern part of the province. The northern border broadly coincides with the boundary of the Mesozoic and Paleozoic rocks.

East of the 149th meridian the province bulges northward to within about 40 km. of the Arctic Ocean. Folds and thrust faults continue to trend eastward so greater uplift seems apparent. Major orogenies in early Cretaceous, Tertiary, and Quaternary times are recognized.

During the Pleistocene, glaciers enlarged at different times in the mountains and flowed northward onto the southern part of the Foothills and southward into the interior of Alaska. Drainage derangements are common. Drainage divides migrated markedly during the Pleistocene. Streams today flow outward from the mountains; the Noatak River bisects the western part of the Range. The major lowlands contain numerous small lakes. Larger rock-basin and morainal-dammed lakes are scattered throughout the province, but are more abundant in the eastern part. Small glaciers are still found in the higher areas.

### TOPICAL REVIEW OF NARL-SPONSORED RESEARCH

From the time of the earliest explorers up to 1944 only reconnaissance studies could be carried out along the coast and major rivers. Nonetheless, the gross framework of the geology of northern Alaska was established during the decades prior to the establishment of the Naval Arctic Research Laboratory. From 1944 to 1953 the Department of the Navy, through the Office of Naval Petroleum and Oil Shale Reserves, funded numerous United States Geological Survey parties in northern Alaska, with special emphasis on Naval Petroleum Reserve No. 4. Several of the parties received direct support from NARL. The reader is referred

especially to United States Geological Survey Professional Papers 302 to 305, in their many parts, for examples of the studies which Reed (1958) reviewed in considerable detail.

Results from some of the U.S. Geological Survey's studies are found also in publications other than those of the Survey, such as Brosgé *et al.* (1962); Tailleur and Sable (1963), and Gryc *et al.* (1967). Regretfully, it is not always clear what role the NARL played in furthering some of the basic geologic studies in northern Alaska from which numerous reports of the Geological Survey scientists were derived.

NARL-supported research on the bedrock geology of northern Alaska outside that of the Geological Survey has been limited. Two outstanding contributions on regional geology come quickly to mind — Porter (1966a) in the central Brooks Range and Reed (1968) in the northeastern Brooks Range. Each mapped and described the very thick Paleozoic and Paleozoic-Mesozoic sequence of rocks in his area and summarized the deformational history. In each report a review of the available literature provides an up-to-date source of information for representative portions of the Arctic Mountains. Langenheim *et al.* (1960) carried out a more specifically oriented study on Cretaceous amber from the Arctic Coastal Plain. Insect and floral remains embedded in the amber were stressed.

The various bedrock studies have done much to place that aspect of the geology of northern Alaska on firm ground and have provided the background that made possible the recent oil strikes in the Prudhoe area southeast of Barrow.

### *Geomorphology*

Most bedrock studies were focused largely on a resolution of the stratigraphy, sedimentation, paleontology, tectonics, and other facets of geology ultimately geared to assess the petroleum possibilities of northern Alaska; of necessity, surface morphology and surficial materials generally were relegated secondary roles by the scientists involved in those studies. Obviously all geologists use geomorphology in their surface mapping and to help in interpreting subsurface geology, but by only a few or in certain places could geomorphology be studied for its own sake. Furthermore, traverses were made primarily to locate bedrock outcrops, and surficial materials were hindrances. Nonetheless, all U.S. Geological Survey field parties made pertinent observations on the unconsolidated materials, as exemplified in part in the summary assembled by Black (1964a). Notes on the topography and morphology of various features also accompanied most regional reports.

Without question a list of the most striking geomorphic features in northern Alaska would be headed either by the oriented lakes or by the ice-wedge polygons. Both features are a consequence of permafrost, or perennially frozen ground, that extends to depths of 400 m. in northern Alaska (Black 1954). Both phenomena were recognized and described prior to the inception of the Arctic Research Laboratory (e.g., Black and Barksdale 1949; Leffingwell 1919). However, the early descriptions only whetted the appetites of researchers who followed. I believe I am correct in saying that NARL has supported more research projects in earth science, including soils, that relate directly or indirectly to those two

phenomena than to any others. This is rightly so in the opinion of this writer, for those two phenomena reach their zenith in the vicinity of Barrow.

#### THE ORIENTED LAKES

In permafrost regions thaw of ground ice, which comprises more volume than pore space in unconsolidated sediments, results in thaw depressions that may become lakes. Both thaw depressions and thaw lakes are circum-Arctic and are exceedingly abundant. The oriented lakes of the Arctic Coastal Plain not only typify such thaw depressions with lakes, but they epitomize the orienting capabilities of the prevailing winds.

Black and Barksdale (1949) suggested that orientation was by wind oriented at right angles to that of today. None of the subsequent investigators has accepted that suggestion. Deevey (1953) thought it probable that elongation and migration of the lakes took place at right angles to the prevailing wind. Livingstone (1954) first called attention to a possible mechanism whereby currents account for the elongation of the lakes at right angles to the present winds. Rosenfeld and Hussey (1958) pointed out that the problem was more complicated than the simplified approach of Livingstone, and that his hypothesis could not apply equally to lakes only a few metres long and those many kilometres long. They suggested an elongation control by fault and joint patterns. Carson and Hussey (1959) reviewed five possible hypotheses for the lake orientation and concluded that each alone was not enough, but that a composite would suffice, namely: that oriented ice wedges might develop in a fracture system and maximum insolation would be more effective in melting the north-south trending wedges than the complementary set, and that the depressions so oriented would be perpetuated and enlarged by thaw and wind (wave) oriented sediments deposited on the east-west shores. Carlson *et al.* (1959) also suggested that preferentially oriented ice wedges play a role in the orientation of the lakes.

Carson and Hussey (1960a) reviewed the hypothesis of Livingstone (1954) and an unpublished one by R. W. Rex and then presented some current measurements from lakes near Barrow. Their field data suggested that Livingstone's hypothesis was not applicable but that the approach of Rex merited further study. Carson and Hussey (1960b) provided additional data on the hydrodynamics in three of the lakes near Barrow. Their measurements showed that erosion was going on at the ends of the elongated lakes by long-shore currents as predicted by the hypothesis later published by Rex (1961). Carson and Hussey (1962) summarized the results of their field studies on the lakes and supported with reservations on some aspects the circulation hypothesis of Rex (1961). Price (1963) raised the wind-resultant problem, but Carson and Hussey (1963) concluded that it would not change materially their earlier conclusions. Britton (1957) outlined a thaw lake cycle and its association or effects on vegetation on the Arctic Coastal Plain. Maps showing overlapping lake basins of different ages were prepared by many of the authors cited above and by Wahrhaftig (1965) and Brown and Johnson (1966).

Dating the lake basins, except in relation to each other, has been difficult. All observers of the lakes have witnessed shore erosion of several metres during single

storms. Lateral migration can be very rapid. The truncation of existing ice wedges by lateral migration demonstrates that some lakes or parts of them must only be some decades or a few centuries old. Livingstone *et al.* (1958) used the growth rings of small willows to show that the gentle shore of one oriented lake was exposed during the last 150 years. Radiocarbon dating of organic matter in two drained lakes near Barrow suggested ages of several thousand years (Brown 1965). Carson (1968) concluded that transgressive expansion reached a maximum between 4,000 and 8,000 years ago. Other lakes must be considerably older according to the great depth to which thaw of permafrost has penetrated.

Not all lakes have been derived by thaw of ground ice (Mohr *et al.* 1961) although the studies of Brown (1966a), Hussey and Michelson (1966), and Black (1969) indicated that thaw depressions 3 to 6 m. deep can be produced from the thaw of ice in the upper part of permafrost today. Livingstone *et al.* (1958) cited a particular instance of supposedly much greater thaw. The origins of the deep lake basins in the Arctic Coastal Plain and Arctic Foothills are not known.

Brown *et al.* (1968) discussed the hydrology of a drainage basin near Barrow. Brewer (1958) outlined the thermal regime of a lake near Barrow. The mineral compositions of some drainage waters from lakes, streams, and elsewhere in northern Alaska were reported by Brown *et al.* (1962). Effects of an arctic environment on the origin and development of freshwater lakes in northern Alaska were treated at some length by Livingstone *et al.* (1958) and the limnology of the arctic lakes was summarized by Livingstone (1963). Kalf (1967, 1968) added more limnological information. Black (1969) reviewed thaw depressions and thaw lakes of North America, especially those of northern Alaska.

#### PATTERNED GROUND

Patterned ground includes a variety of surface forms many of which are related to frost action and permafrost (Washburn 1956). A widespread pattern in part characteristic of continuous permafrost is produced by ice wedges in polygonal array as seen from above (Black 1952; Péwé 1966). The ice-wedge polygons of the Arctic Coastal Plain are ubiquitous and reach a climax of development in association with the oriented lakes. Only in a few restricted areas of the world have other polygons even begun to emulate those of the Arctic Coastal Plain.

The distribution, character, and origin of the ice wedges of the Arctic Slope were established decades ago with remarkable insight by Leffingwell (1919). Leffingwell's contraction theory for origin of ice wedges calls for present-day segregation of ice in ice wedges after the ground is frozen to considerable depth and for the moisture to come from the atmosphere. However, Taber (1943) working elsewhere in Alaska cast doubt on Leffingwell's findings. Taber's concept is that the ice wedges and other large masses of ice grew in the past when the permafrost was forming and that the moisture was drawn up from below the downward freezing layer. Black (1963) initiated a project at Barrow in 1945 to resolve the opposing theories of those men. He and his uncomplaining wife, Hernelda, at times under difficult and trying weather conditions, and with direct support from NARL in 1949-50 did the detailed laboratory and field studies

needed to establish the correctness and to quantify the theory of Leffingwell.

Black's studies involved observations in all parts of Alaska with ice wedges, but the critical laboratory studies of thin sections of ice and the detailed field measurements of thermal contraction and expansion of the ground were done at Barrow with support from the facilities of NARL. Ground ice collected at Fairbanks was even packed in dry ice and carried back to Barrow. Thermal measurements, meteorological records, moisture and textural determinations, and many other data were collected during the studies. A resumé of the studies and a list of the published results derived directly from them is included in Black (1963).

No one has repeated the detailed fabric studies of ground ice or the measurements of ground contraction and growth of ice wedges, although supplementary and partial confirmatory observations have been made by a number of investigators in the course of their studies. For example Lachenbruch (1962 and 1966) placed the mechanics of thermal contraction cracks and ice-wedge polygons on a firm mathematical-physical foundation; Brown (1966b) investigated the chemistry of ice wedges and related frozen ground; Drew and Tedrow (1962) proposed a classification of ice-wedge polygons; O'Sullivan (1966) expanded the chemical studies of permafrost in the Barrow area; and Walker and Arnborg (1966) related ice wedges and other ground ice to river-bank erosion. A large number of papers on the relationship of soils and vegetation to patterned ground in northern Alaska have appeared; Black (1964b) has reviewed a number of them. More recent papers include Brown and Johnson (1965) on pedoecological investigations at Barrow; MacNamara and Tedrow (1966) on an arctic equivalent of the Grumusol; Tedrow (1966) on arctic soils in general, but northern Alaska samples in particular; Brown (1966c) on soils of the Okpilak River region of northeast Alaska; Brown (1967) on tundra soils formed over ice wedges near Barrow; Tedrow and Brown (1968) on soils of arctic Alaska; Rickert and Tedrow (1967) on soils in aeolian deposits of the Arctic Coastal Plain; and Tedrow (1968) on the pedogenic gradients of the polar regions.

#### GLACIAL GEOLOGY

NARL supported a number of the U.S. Geological Survey geologists who made unusual efforts to record geomorphic data, including glacial geology, which were published in separate reports, e.g., MacCarthy (1958) on glacial boulders on the Arctic Coast; Sable (1961) on the Okpilak Glacier in the northeastern Arctic Mountains. Other projects supported by NARL on geomorphology and glacial geology entirely or at least as a major part of a field project include, for example, Hamilton (1965, 1969) on geomorphology and glacial geology in the Alatna River area of south-central Brooks Range; Porter (1966b) on the Pleistocene geology of Anaktuvuk Pass in the central Brooks Range; and Reed (1968) in northeastern Brooks Range. As our understanding of Pleistocene-Recent chronology of events has grown in North America, so too has our understanding of events in northern Alaska (Detterman *et al.* 1958). Each of the above authors recognized events not previously recorded and each revised the correlation of glaciations and other events from those of previous workers in their areas. Hamil-



ton (1969), Porter (1966b) and Reed (1968) provide correlation charts and literature citations for all previous glacial literature pertaining to the Arctic Mountains. General agreement on the gross framework of the Pleistocene-Recent events seems to have materialized rapidly over the past 15 years.

#### MISCELLANEOUS

In close association with the glacial studies are pollen-stratigraphic attempts to work out changes of vegetation which permit correlations with former climatic changes. Livingstone (1955) in particular established a three-zone pollen-stratigraphic record for the central Brooks Range, and later (1957) he extended the study northward onto the Arctic Foothills. The radiocarbon-dated stratigraphy and pollen sequence correlated well with the latter part of the glacial sequence. Colinvaux (1964), with samples supplied by others on NARL projects, showed that vegetation of 14,000 years ago reflected a climate colder than the present and that progressive warming extends to the present day. This record indicated that the Arctic Ocean has been covered with ice since the time of the Wisconsin glacial maximum. The Arctic Ocean ice cover apparently has been continuous for at least the last 1.5 million years according to Clark (see pp. 233-45).

Radiocarbon dating of buried peat and other organic matter in the upper part of permafrost has done much in the past few years to substantiate and also to revise our thinking of the rapidity of geomorphic events in northern Alaska. NARL has sponsored a number of studies which have yielded reports specifically on the dating of various events, for example, Péwé and Church (1962) on the age of the Point Barrow spit; Porter (1964) on the antiquity of man at Anaktuvuk Pass; Tedrow and Walton (1964) on the age of the glacial deposits of the upper Killik Valley; Hume (1965) on the sea-level changes during the last 2,000 years at Point Barrow; Brown and Sellmann (1966) on a buried peat from sea level at Barrow, and Faas (1966) on estuarine sediments at Barrow. Brown (1965) compiled a summary of all known dates from the vicinity of Barrow that were acquired in support of various studies in pedology, geology, and archeology. He draws a number of conclusions from the dated materials, e.g.: 1) the majority of soils and surficial features around Barrow are no older than 8,300 years and are perhaps considerably younger; 2) the present-day spit sediments are about 1,100 years old; 3) the upper section of the next inland raised beach is not older than 25,000 years and may be considerably younger; 4) a surface horizon of well-drained soil on that beach yields an average date of 3,000 years; and 5) buried organic materials at depths of 0.3 to 1.0 m. represent surface horizons of soils that existed some 8,700 to 10,700 years ago.

Other miscellaneous studies include MacCarthy (1953) on recent changes in the shoreline near Barrow; Hume and Schalk (1964) on the effects of ice-push on arctic beaches; Rex (1964) and Hume and Schalk (1967) on shoreline processes at Barrow; Black (1952), Hopkins *et al.* (1955) and Hussey (1962) on airphoto interpretation; Geist (unpublished manuscript) on collecting Pleistocene fossils and natural history material in arctic Alaska river basins; Hanna (1956) on the land and freshwater mollusks of the Arctic Slope; Schmidt and Sellmann (1966) on Pleistocene mummified ostracods near Barrow; Schalk and Hume (1962) on

shoreline investigations at Barrow; Hume (1964) on floating sand and pebbles near Barrow; Walker (1967) on dunes in the Colville Delta; and Walker and Morgan (1964) on weather and river bank erosion.

Near-shore, shallow-water studies off Barrow have provided information on various geomorphic processes e.g. Carsola (1954a) on the extent of glaciation on the continental shelf; Carsola (1954b) on the submarine canyons on the Arctic Slope; Carsola (1954c) on the microrelief on the upper continental slope in the Arctic Ocean; Carsola (1954d) on the Recent marine sediments on the continental shelf and slope; and Rex (1955) on microrelief produced by sea ice grounding near Barrow. Numerous raised beaches well inland and submerged topographic breaks, peat, and other submerged deposits attest to numerous fluctuations of land and sea and migrations of the strand line.

#### CONCLUSION

An attempt has been made to categorize the general geomorphic studies in northern Alaska. The artificial grouping does not permit the recording of numerous geomorphic observations included incidentally in many reports, nor does this review do justice to some major reports on file at the library of NARL but not published. Some have attempted to summarize all or at least many regional and topical aspects, including processes, of the geomorphology of northern Alaska.

#### STATUS OF GEOLOGIC RESEARCH AND FUTURE ROLE OF NARL

The titles of several papers presented elsewhere in this issue of *Arctic* overlap the general range of geology, especially geomorphology. Subjects such as pedology, botany, oceanography, archeology, permafrost, ecology, sedimentation, arctic engineering, heat flow, geophysics, and even zoology play a role in increasing our knowledge of the earth's surface and our understanding of earth history. Obviously, in the space available, it has been impossible to summarize fully all the major aspects of the subject. I have therefore limited my discussion arbitrarily to only a small part of the studies concerned with the bedrock of northern Alaska, and subsequently, at greater length, with the morphometry and evolution of the surface.

Since its inception in 1947, NARL has obviously played an important and enviable role in furthering geologic research in northern Alaska. Partly through its aid the general bedrock geology has been mapped on a small scale, and regional correlations of the various stratigraphic units have been completed. These and more specific studies of paleontology, texture and lithology, tectonics, paleogeography, and the like, have provided the understanding that has permitted the recent productive drilling for oil and gas.

It seems clear that for the immediate future various oil companies will dominate in the more detailed geologic studies needed to further oil exploration, and that NARL's role in that aspect will be minimal. However, the geologic history of northern Alaska is long and involved. Although they appear dissimilar, the Arctic Mountains are intimately related to the Arctic Slope. During the middle Paleozoic, northern Alaska was the site of a seaway that extended southward from the ancient

continent of "Arctica" in what is now the Arctic Ocean. That landmass until Jurassic time shed its wastes southward into the area of what is now northern Alaska. Then "Arctica" began to subside. The southern part of the seaway began to rise, and the ancestral Arctic Mountains were born. Repeated uplifts and folding affected the range and to a lesser extent the Arctic Slope throughout the remainder of the Mesozoic Era, still further restricting the ancient seaway. Meanwhile, thousands of metres of sand, mud, and coal were laid down in the shoaling water. Even volcanoes were active in the region at the beginning of later Cretaceous time.

Thus the landscape, as we see it today, is only the latest culmination of a long and complicated series of events. Working out all the fascinating details will be too much for practical-minded business men who have to have an immediate return on the invested dollar. Various areas of bedrock geology will still remain — for example, studies of paleontologic, mineralogic, and near-surface facies changes of the younger rocks in the Arctic Coastal Plain and the Arctic Plateaus will very likely need support. In the Arctic Mountains some detailed stratigraphic mapping, tectonics, metamorphism, and the like will go begging. A number of excellent Ph.D. thesis topics for the individualistic field-oriented geologist should be supported, perhaps in conjunction with funds from private companies. The regional compilations of the U.S. Geological Survey should continue along with their areal mapping.

NARL seems destined to emphasize geomorphic research with all its broad implications. Regional studies are still needed, but topically oriented and process-oriented research should lead. Such research can go on from its present base, on the oriented lakes, patterned ground, weathering and soil formation, pingos and other mounds, eolian activity, slope processes, glacial geology, etc. Almost no study made to date provides final answers: each has opened more possibilities. Only a few topics need be cited here.

The general characteristics and distribution of the oriented lakes are recognized, but many details are not. Some or at least parts of the shallow shelves surrounding the deep central portion of some oriented lakes are depositional and some erosional. Truncated ice wedges are found under some shallow lakes and shallow shelves. They seem to reflect a recent development of those lakes and shelves. Some shallow lakes lack deep central basins. Are they the incipient lakes in contrast to the deeper ones that have thawed through the wedges? Are the shallow lakes all younger than the deeper ones? New wedges are growing on the floors of drained lakes and on the abandoned beaches of others. We seem to have a vast range in age of lakes and lake basins, but relatively little information is at hand.

Few definitive limnological studies on the oriented lakes have been attempted, and almost no bottom sediment studies. Even the lake orientation still poses problems although more effort possibly has gone into that facet than into any other. At present it is difficult to distinguish between cause and effect in the circulation patterns of the lakes. Fetch and water depth obviously determine what waves and currents can do. In many lakes the north and south ends have deep water and the banks are eroding. The two-cell circulation system demonstrated for

several elongate lakes may be the cause, but how can we make the transition from the very small equal-dimensional lake or from the large very shallow lake in which waves and currents are not effective transporting agents? The shallow shelves, whether erosional or depositional, seem mostly to be on the east and west sides; many lakes are enlarging also in those directions.

Timing of the formation of lakes in the past is essentially unknown. The overlapping basins show clearly a relative chronology, and buried deposits of former lakes are found at depths of many metres, some in association with buried fossil ice wedges. A long and complicated history of events can only be hinted at now.

Growth rates of ice wedges in northern Alaska have been measured for only one year and only at Barrow. The available radiocarbon dates support the dating of surfaces with ice wedges, but obviously a longer interval of time is needed to get average rates under present climates in different parts of northern Alaska. Relatively few wedges and samples of permafrost have been studied for their microscopic fabrics or their chemistry, and all these were from the immediate vicinity of Barrow. More regional coverage is needed. Quantification of the cryostatic processes in the active layer is desperately needed. Studies of weathering in association with the patterned ground and soil formation have been going on, but much more detailed quantification of the process with time is now required.

Although general agreement seems to have been reached in the glacial sequence in the Arctic Mountains, many areas remain to be mapped in detail. No comprehensive glaciological studies of individual glaciers have been attempted. Mis-correlations of deposits of relatively youthful age with pre-Wisconsinan events have been made. It seems unlikely that knobby moraine with undrained depressions and ponds in fine-grained deposits could survive from early Pleistocene times along the front of the Arctic Mountains as has been postulated. Eolian activity, mass wasting, frost processes, and vegetal growth should have destroyed them. Many more detailed studies specifically to do glacial geology and to resolve some of these problems are timely. If accompanied by quantified studies of slope processes, a better appreciation of the rate and manner of evolution of the landscape could be obtained.

To my knowledge no detailed study of river icings in northern Alaska has ever been made, yet that area has the "most" and the "best" in Alaska. The eolian deposits have largely been ignored. Marine erosion since the days of the early explorers has amounted to tens of kilometres in some places. Other than a few observations and some extrapolations from air photos and the like, few recent studies of its rate along the Arctic Coastal Plain have been attempted. Numerous raised beaches and submerged topographic breaks, peat, and other deposits attest to considerable migration of the shore line, not just in recent times, but extending back through the Pleistocene into still older chapters of earth history.

These are but a few examples in present processes and in earth history that NARL should support enthusiastically. It is true that alpine geomorphology can and is being studied in such places as Colorado which are much closer to centres of civilization than are the Arctic Mountains. Nonetheless, the 30° of latitude

intervening, the different rocks, and unlike histories of events make for differences in kinds or intensity of processes which only detailed measurements can document adequately.

The Arctic Mountains have been shedding their wastes across the Foothills and Coastal Plain at different rates for a long time. Most rocks in northern Alaska are marine. Vast changes in the elevation of land and sea are thus recorded in the deposits and features of northern Alaska, and only a glimpse of that fascinating history has been obtained to date. We must continue to study together those processes, features, and deposits on shore as much as those off shore — they are part of the same continuum of earth history. In other words, the United States Navy must continue to support research in its back yard while playing in its front yard.

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