Quaternary Geology of the Kenai Lowland and Glacial History of the Cook Inlet Region, Alaska

By THOR N. V. KARLSTROM

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A study of the Quaternary deposits of the Kenai Lowland, interpreted within the framework of the radiocarbon-dated regional drift sequence of Cook Inlet recording five Pleistocene glaciations and several smaller post-Pleistocene glacial advances

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QUATERNARY GEOLOGY OF THE KENAI LOWLAND AND GLACIAL HISTORY OF THE COOK INLET REGION, ALASKA

By Thor N. V. Karlstrom

ABSTRACT

The Kenai Lowland is part of the Cook Inlet Lowland physiographic subprovince that borders Cook Inlet, a major marine reentrant along the Pacific Ocean coastline of south-central Alaska. The Cook Inlet Lowland occupies a structural trough underlain by rocks of Tertiary age and mantled by Quaternary deposits of varying thicknesses. The bordering high alpine mountains—the Aleutian and Alaska Ranges to the northwest and north and the Talkeetna, Chugach, and Kenai Mountains to the northeast and southeast—are underlain by rocks of Mesozoic and older ages.

The present topography of the Kenai Lowland and adjoining areas is primarily the product of at least five major Pleistocene glaciations and two minor post-Pleistocene glacial advances. These are recorded by the distribution of moraines and ice-scoured landforms, by discordant drainage relations, and by stratigraphic evidence of multiple drift sheets separated by major unconformities and weathering profiles. The Pleistocene glaciations, named from the type localities of their respective deposits, are (from oldest to youngest) Mount Susitana, Caribou Hills, Eklutna, Knik, and Naptowne. The post-Pleistocene glacial events are named the Tustumena (oldest) and Tunnel advances of the Alaskan glaciation.

During the Mount Susitana, Caribou Hills, and Eklutna glaciations, ice lobes fed from multiple icecap areas in the surrounding mountains coalesced within the Cook Inlet trough and filled it to successively lower levels, as recorded by the altitudinal distribution of morainal deposits along the flanks of the bordering mountains. In the Knik and Naptowne glaciations, ice flowing from bordering mountains filled the Cook Inlet trough from valley wall to valley wall in its northern and southwestern constricted parts but did not coalesce in the middle, or widest, part where widely separate spatulate-shaped end-moraine complexes were deposited in the marginal lowlands. Proglacial-lake deposits and high-level strandlines associated with these end morainal deposits provide a clear record of proglacial-lake environments within the middle, wider part of the trough caused by ice damming the lower, constricted end of the trough during both the Knik and Naptowne glaciations. Comparable but more temporary lake environments probably existed in Cook Inlet during initial phases of advance and later phases of retreat of the earlier and more extensive glaciations.

Complete ice filling of the northern parts of the Cook Inlet trough during Naptowne and earlier times disrupted drainage connections between Cook Inlet and the adjoining Copper River basin; this provides the most direct and simplest explanation for the anomalous drainage course of the present Susitana River out of Copper River basin discordantly across the Talkeetna Mountains into Cook Inlet. The Susitana River canyon through the Talkeetna Mountains occupies an intermediate area that either remained ice free or was the last covered and first uncovered by ice during the repeated expansions and contractions of glacier ice from the bordering higher alpine areas of the Alaska Range and Talkeetna Mountains. Thus it lies in the most likely site for concentration of ice-diverted and ice-dammed melt waters and for consequent drainage superposition across bedrock structures.

Geomorphic subdivision of the moraines throughout Cook Inlet is primarily based on sequential position, differences in topographic expression, and angular morainal boundary relations suggesting significant intervals of weathering, erosion, and glacial retreat between advances. The main morainal discontinuity is marked by the outer boundary of the Eklutna glaciation, strongly suggesting that the major interglacial interval recorded in the region is between Caribou Hills and Eklutna in age. A statistical study of surface boulders on morainal deposits of Caribou Hills, Eklutna, Knik, and Naptowne ages mantling an upland surface near Skilak Lake on the Kenai Lowland indicates that Caribou Hills moraines may be about 7.7 times, Eklutna moraines 4.5 times, and Knik moraines 2.5 times as old as Naptowne moraines. Distinctive but less pronounced geomorphic differences between subordinate morainal belts of Naptowne age on the Kenai Lowland indicate at least four important glacial advances: the Moosehorn, Killey, Skilak, and Tanya. Near Skilak Lake, morainal remnants downvalley from Moosehorn moraines may represent a Naptowne advance of pre-Moosehorn age. Near Tustumena Lake the Moosehorn moraines mark the maximum extent of Naptowne ice; and still farther to the south, near Anchor Point, the younger Killey moraines are the outermost.

Two distinctly separate periods of post-Naptowne glacial advances are recorded by two sets of moraines lying well upvalley from Naptowne moraines and near fronts of existing glaciers in the Kenai Mountains. These represent the Tustumena I, II, and III, and Tunnel I and II advances of the Alaskan glaciation. The two sets of moraines of Alaskan age differ slightly in soil development, vegetation cover, and degree of dissection. Where observed, maximum soil profiles on the Tunnel moraines are a fraction of an inch thick; on Tustumena moraines, between 3 and 12 inches thick; and on the Naptowne moraines, between 2 and 10 feet thick. In contrast, weathering profiles observed in buried drifts of Knik and Eklutna ages have maximum thicknesses of between 10 and 20 feet and more than 40 feet, respectively. Natural exposures showing stratigraphic relations between Eklutna, Caribou Hills, and Mount Susitna drift sheets have not been found in the region.

Regional distribution of the moraines in Cook Inlet and adjoining areas indicates that the Pleistocene glaciers (1) flowed from the same high alpine areas that today hold the largest concentrations of glacial ice, (2) were larger near the Pacific

Coast and decreased progressively in size inland, and (3) were larger on the coastal sides of the mountain ranges and extended much farther onto marginal lowlands than those flowing inland from common ice centers. These regional relationships are consistent with the present distribution of glacial ice and with present orographically determined climatic zonation and coastward-inclined climatic snowlines resulting from prevailing inland migration across mountain barriers of precipitation supplies derived from the Pacific Ocean. They suggest that the main topographic and climatic elements which determine present distribution of glacial ice in the region have remained essentially the same throughout most, if not all, of Pleistocene time. Inasmuch as the regional inland decrease in precipitation is accompanied by a general decrease in mean annual temperatures, the importance of precipitation over temperature as the significant limiting factor on the distribution of past as well as present glacial ice in the region is strongly suggested.

The Pleistocene proglacial-lake history of Cook Inlet is complex and is known only in part. Multiple strandline levels and numerous unconformities, diastems, and buried organic layers in the proglacial-lake deposits of Knik and Naptowne ages record a complex sequence of high-lake-level fluctuations separated by intervals of partial or complete lake drainage. Insofar as the spillway threshold of the proglacial lakes was determined by a glacial-ice dam at the lower end of Cook Inlet, the sequence of lake-level fluctuations may be related directly to pulsations of ice advance and ice thickening and of ice retreat and ice stagnation experienced by the coalescent glacier lobes that made up the dam. The relations of strandlines to abandoned melt-water channels emanating from end moraines of different ages deposited above proglacial-lake levels provide geomorphic evidence for the following high-level lake phases: about 1,000-foot elevation or higher during the Knik maximum; during the Naptowne glaciation, about 750 feet at the Moosehorn maximum; about 500 feet at the Killey maximum; about 275 feet at the Skilak maximum; and about 125 and 50 feet, repectively, during two static lake-level intervals post-Skilak maximum and pre-Tanya maximum in age.

Complete drainage of proglacial-lake waters out of Cook Inlet between the Knik and Naptowne glaciations is recorded by buried paleosols and, locally, by buried marine sediments deposited in an interglacial sea that penetrated inland to the upper reaches of the present Cook Inlet. The marine sediments are exposed in coastal bluffs above storm beach levels, indicating that this interglacial sea may have risen higher than the present sea-level datum. Shells collected from the marine sediments are provisionally dated between 33,000 and 48,000 years old by the Potratz ionium/uranium ratio dating method. This date is consistent with the radiocarbon age of 37,000 B.C. obtained from wood collected from the stratigraphically higher proglacial-lake sediments of Naptowne age and, in combination with the radiocarbon results, indicates that the culmination of the Knik-Naptowne interglacial sea-level rise may have come sometime between 46,000 and 37,000 B.C. Radiocarbon dating of organic beds buried beneath surficial lake sediments exposed at different elevations in the lowland provide the following dates for late-Naptowne strandline levels: the about 275-foot strandline level, between 10,500 and 9000 B.C.; the about 125-foot strandline level, between 9000 and 8000 B.C.; and the about 50-foot strandline level, between 8000 and 7000 B.C. Final drainage of proglacial-lake waters from Cook Inlet was ca. 7000 B.C., or just before the Tanya maximum advance into the lowlands.

The majority of the more than 50 radiocarbon-dated organic samples now available from Cook Inlet deposits were collected from closed-depression, fresh-water coastal-bog deposits overlying proglacial-lake sediments in the lowlands; from low-lying tidal-bog deposits exposed above and below mean sea level along the coast; from upland closed-depression bog deposits; and from buried forest beds overridden by Tustumena and Tunnel advances of the Alaskan glaciation. The numerous widely spaced radiocarbon-dated coastal type bogs provide sensitive and continuous depositional sequences that stratigraphically record contemporaneous shifts in regional ground-water levels following final drainage of proglacial-lake waters from Cook Inlet and re-establishment of graded drainage connections with the sea. Cross-dating this continuous hydrologic record with the dated tidal-bog, upland-bog, and morainal sequences indicates the following geologic relations implying wetter and cooler climate: glacial advances contemporaneous with lowering regional ground-water levels (coastal-bog environments), also with lowering sea levels (tidal-bog environments), thus presumably glacioeustatically or thalasostatically controlled hydrologic shifts; with the reverse, or rising lake and ground-water levels in the uplands (upland-bog environments), thus presumably precipitation-controlled hydrologic shifts. In contrast, glacial retreats, implying somewhat dryer and warmer climate, coincide with rising water levels in tidal- and coastal-bog environments and with lowering water levels in upland-bog environments.

Combined with the radiocarbon-dated proglacial-lake strandline sequence and correlative moraines, and expressed in terms of glacial fluctuations, the integrated late Quaternary records of glacial and glaciohydrologic changes of Cook Inlet provide the following dated chronology in figures rounded off to the nearest 500 years:

- Culmination of Killey retreat, ca. 10,500 B.C.
- Skilak maximum (Skilak I), ca. 10,000 B.C.
- Two subordinate Skilak recessional readvances (Skilak II and III), ca. 8500 B.C. and 7500 B.C.
- Culmination of major retreat, ca. 7000 B.C.
- Tanya maximum (Tanya I), ca. 6500 B.C.
- Two subordinate recessional readvances (Tanya II and III), ca. 5000 B.C. and 4000 B.C.
- Culmination of two major retreats, ca. 4500 B.C. and 3500 B.C. (the latter considered to mark the boundary between the Naptowne glaciation and succeeding advances of the Alaskan glaciation).
- Trustumena maximum (Tustumena I), ca. 2000 B.C., preceded by a minor advance (pro-Tustumena), ca. 3000 B.C., and followed by recessional readvances (Tustumena II and III), ca. 1000 B.C. and at the beginning of the Christian Era.
- Important retreats, ca. 500 B.C. and A.D. 500. Tunnel glacial maximum (Tunnel I), ca. A.D. 1000, followed by recessional readvances (Tunnel II) after A.D. 1500 but before the historical record of general glacial retreat to the present, beginning ca. A.D. 1850.

This independently dated and detailed glacial chronology of the past 14,000 years expresses a systematic pattern of glacial fluctuations, with major retreatal intervals recurring every 3,000 to 4,000 years and important but subordinate retreatal intervals recurring every 1,000 to 1,200 years. It is reasonable to assume that the pre-Skilak glacial oscillations of Naptowne age were subject to the same climatic regimen as that recorded by the post-Skilak events. Based on this assumption, the following extrapolated dates are obtained: ca. 13,500 B.C. for the

Moosehorn-Killey boundary; ca. 17,000 B.C. for the pre-Moosehorn boundary; and ca. 20,500 B.C., 24,000 B.C., and so forth for important retreatal culminations separating earlier pre-Moosehorn glacial advances. These figures, obtained by controlled extrapolations, for early and middle Naptowne events are compatible with the radiocarbon-dated samples which bracket deposits of comparable age between 37,000 B.C. and 10,500 B.C. near East Foreland on the Kenai Lowland. By assuming that maximum extension of Naptowne ice near East Foreland occurred halfway between these dated boundaries, a date of ca. 23,000 B.C., seemingly pre-Moosehorn, is obtained for the outermost Naptowne moraines in this area. Elsewhere on the Kenai Lowland, as interpreted from more complete morainal sequences, other ice lobes attained their Naptowne maxima somewhat later: during pre-Moosehorn or Moosehorn time near Skilak Lake; during Moosehorn time near Tustumena Lake; and during Killey time near Anchor point. By use of the surface-boulder counts made on the upland moraines near Skilak Lake, and by assuming that the Naptowne end moraines here are roughly 20,000 to 25,000 years old, the following provisional ages are obtained: between 50,000 and 65,000 years for the Knik moraines; between 90,000 and 110,000 years for the Eklutna moraines; and between 155,000 and 190,000 years for the Caribou Hills moraines. Although crude, the relative age differences suggested by the surface-boulder counts are probably of the right order of magnitude, and the derived ages in calendar years may be useful as a first approximation of the actual ages of the pre-Naptowne glaciations in Cook Inlet.

INTRODUCTION

PURPOSE AND SCOPE OF THE REPORT

In recent years the rapid settlement, increased commercial activity, and mineral prospecting on the Kenai Lowland have emphasized the necessity for general geologic information on the distribution and character of its surficial deposits. A glacial chronology has been summarized (Karlstrom, 1953, 1957; Krinsley, 1953) that is based on mapping of the glacial and associated surficial deposits of the Kenai Lowland and adjoining areas of the Cook Inlet, and field data are being recompiled on base maps recently made available (scale 1:63,360 and 1:125,000). Publication of the 1:250,000-scale landform map (pl. 3) is intended partly to fill the immediate need for knowledge of the area by providing a general picture of the major morainal pattern that largely determines the topography and surficial geology of the Kenai Lowland and by showing the distribution pattern of surficial deposits. The larger muskeg and swamp areas constitute the biggest single factor restricting land development. The landform map depicts an essentially complete morainal record of the Cook Inlet glacial sequence as well as some of the most significant morphologic relations used in reconstructing this chronology. This report includes the geomorphic, stratigraphic, and radiocarbon data that the author believes are essential to a general understanding of the geology of the Kenai Lowland and of the regional glacial history. More than 50 radiocarbon analyses are now available from organic samples collected by the author and others from the Cook Inlet glacial strata. These are discussed later in this report and, for convenience of critical assessment, are summarized in table 3.

PREVIOUS WORK

The author's work on the Kenai Peninsula is part of a Geological Survey project designed to map the regional distribution of unconsolidated deposits and to reconstruct the glacial history of the Cook Inlet region. Field reconnaissance and photointerpretation of the upper part of Cook Inlet in 1949 resulted in a preliminary map showing major morainal belts in the lower Matanuska Valley and the northern part of the Kenai Lowland; also shown were the results of site studies of the Pleistocene deposits in the Anchorage area, in the Susitna Valley near Kashwitna and Point MacKenzie, and on the Kenai Peninsula near Kenai.[1] Since 1950, field mapping has been concentrated in the northern parts of the Kenai Lowland and Kenai Mountains; photointerpretation and spot field checking of the morainal record in adjoining areas have continued as new photography and base maps became available.

Because of the lack of a more suitable base map for compilation of field data, the author in 1952 sketched a landform map (pl. 3), from aerial photographs, on parts of the 1:250,000-scale Kenai, Seldovia, and Tyonek U.S. Geological Survey Alaska reconnaissance topographic maps. This was done to permit more precise location of ground observation points and to assist in the regional interpretation of the morainal record of the Kenai Lowland. Photointerpretation of the glacial and associated deposits was controlled by field observations in the northern part of the lowland made by the author during the summers of 1949, 1950, and 1951, and by field observations in the adjoining southwestern part of the lowland made by D. B. Krinsley in the summers of 1950, and 1951. By 1952, sufficient data had been accumulated so that a broad breakdown of the upper Cook Inlet morainal record into at least four major glaciations could be proposed (Karlstrom, 1952). The last three of these are represented by deposits in the southwestern part of the Kenai Lowland (Krinsley, 1952). In a jointly written paper (Péwé and others, 1953), the Cook Inlet glacial sequence is described in the reports by Karlstrom and by Krinsley; the names "Mount Susitna" (oldest), "Caribou Hills," "Swan Lake,"[2] and "Naptowne" glaciations, and the "Nicolai

[1] Karlstrom, T. N. V., 1950, field check of airfield sites, Anchorage, Alaska: Rept. to Chief of Engineers, Dept. of the Army, Washington, D.C.

[2] This informal term is herein discarded from the Cook Inlet glacial nomenclature because more than one Swan Lake is present in the region and this could lead to confusion of the type section locality.

Creek" advance are applied to the Cook Inlet chronology; and tentative correlations are made with other glacial sequences in Alaska and with the type Pleistocene chronology of the conterminous United States. The distribution of the moraines of Naptowne and equivalent age described in that paper, along with the position of a fault cutting Naptowne deposits in the Cook Inlet region, as photointerpreted by the author, are shown on the Geologic Map of Alaska (Dutro and Payne, 1957). A brief description of the geology, hydrology, and vegetation of the Kenai Lowland was published in 1955 (Karlstrom, 1955a).

The general accuracy of the morainal boundaries and associated ice-marginal features on the 1952 landform map has been confirmed by field checks made in the northern part of the Kenai Lowland and adjoining areas since 1952 and by partial recompilation, in critical areas, of field data on the now available and more accurate U.S. Geological Survey 1:63,360-scale maps of Kenai, Alaska. New stratigraphic data, described later in this paper, have permitted subdivision of the originally proposed chronology and have required some revisions in correlation with type Pleistocene sections (Karlstrom, 1956; 1957). The "Swan Lake" glaciation is divided into 2 major glacial events: the Eklutna and the Knik glaciations; the Naptowne glaciation is subdivided into at least 4 subordinate glacial intervals, from oldest to youngest: Moosehorn, Killey, Skilak, and Tanya advances; and post-Naptowne time is subdivided into 2 main glacial intervals: the Tustumena and Tunnel advances of the Alaskan glaciation. These events are recognized in the southwestern part of the lowland, and their deposits shown in plate 4 are as mapped by D. B. Krinsley (written communication, 1955, 1959).

ACKNOWLEDGMENTS

Geological Survey field mapping of the Kenai Lowland by D. B. Krinsley and the author, and of adjoining areas in the upper Cook Inlet region by the author, was supported largely by funds transferred by the Engineer Intelligence Division, Office of the Chief of Engineers, Department of the Army. Although the author must be held primarily responsible for the interpretations of the Kenai Lowland landforms shown on plate 3, and for the regional reconstruction of Pleistocene history, Krinsley's important contributions to the glacial geology and chronology of the Kenai Lowland are gratefully acknowledged.

Glacial deposits of the Kenai Lowland are of complex origin. They are derived from multiple ice sources in the mountains surrounding Cook Inlet; and their proper interpretation, therefore, requires a general consideration of the regional distribution of both bedrock and the major glacial deposits. In this regard the present work has been greatly facilitated by information, both published and unpublished, in previous reports about the Cook Inlet region. Particularly helpful have been reports by Capps (1931; 1935), Martin, Grant, and Johnson (1915), and more recent work by Trainer (1953, 1955) on the ground-water geology of the lower Matanuska Valley; by Dobrovolny and Miller (1950) and Miller and Dobrovolny (1959) on the engineering geology of the Anchorage area; by Bjørn Andersen (written communication, 1955) on the Pleistocene geology of the southwestern part of the Talkeetna Mountains; by Gordon Gastil (written communication, 1955) on the Pleistocene geology of the lower Matanuska Valley; and by Cobb (1951) on the Tertiary bedrock of the southwestern part of the Kenai Lowland. The author was fortunate in being able to to confer and discuss mutual field problems with Bjørn Andersen, Gordon Gastil, Robert Miller, and Ernest Dobrovólny during the course of their own field mapping in the upper Cook Inlet region.

Credit is due Ernest Marshall and Wallace Cropper, 1950; Robert Nelson and Donald R. Nichols, 1951; Lyman Taylor, 1953; and Joseph Durek, 1954, for their competent assistance in field mapping the Kenai Lowland and adjoining areas during the field seasons indicated.

The interest and cooperation of J. Lawrence Kulp, Wallace Broecker, and Edwin Olson of the Lamont Laboratory, and of Hans Suess and Meyer Rubin of the Geological Survey, were especially helpful. Their analyses and reanalyses of numerous radiocarbon samples collected from Cook Inlet have greatly facilitated the author's research, directed first toward testing the validity of the radiocarbon results as a tool in the geologic correlation of glacial events in Alaska, and then in the development of an independently dated glacial chronology of the Cook Inlet region.

REGIONAL SETTING

The Cook Inlet Lowland physiographic subprovince is an area that lies generally below an elevation of 1,000 feet. It is bordered to the west and north by the Alaska and Aleutian Ranges and to the northeast and east by the Talkeetna, Chugach, and Kenai Mountains (fig. 1). Cook Inlet and its extensions, Turnagain Arm and Knik Arm, form a major marine reentrant of the south-central Alaska coastline and subdivide the Cook Inlet Lowland into several natural subunits: (1) the Kenai Lowland, which fronts the Kenai Mountains to the east; (2) the Kustatan Lowland, a narrow coastal shelf fronting the Aleutian and Alaskan Ranges to the west; (3) the Susitna Lowland, a broad lowland between the Alaska Range and the Talkeetna Mountains that is drained by the Susitna River, which in turn flows into Cook Inlet from the north; and (4) the lower Matanuska Lowland, drained by Knik Arm, which lies between the Talkeetna and Chugach Mountains to the northeast. The Cook Inlet Lowland occupies a structural trough, is underlain at variable depths by rocks of Tertiary age and older, and is mantled by unconsolidated deposits of Pleistocene and Recent age. Semiconsolidated coal-bearing formations of Tertiary age crop out at the surface or occur at relatively shallow depth at the southwest end of the Kenai Lowland and along the flank of the Alaska Range between Tyonek and Peters Creek.

REGIONAL MORAINAL PATTERN

The present topography of the Kenai Lowland is primarily a product of repeated Pleistocene glaciations. Glaciers fed from multiple ice centers in the surrounding mountains and deposited a composite system of moraines in the lowland (pl. 1). The regional morainal pattern is the product of a series of single and compound ice lobes that advanced down major mountain valleys. These lobes advanced southeast across the Kustatan Lowlands from icefields in the Alaska and Aleutian Ranges (the Beluga Lake, Trading Bay, Tuxedni Bay, and Chinitna Bay lobes), southward into the Susitna Lowland from more northerly ice centers in the Alaska Range and Talkeetna Mountains (the Skwentna-Yentna, Kahiltna, Chulitna, and Susitna

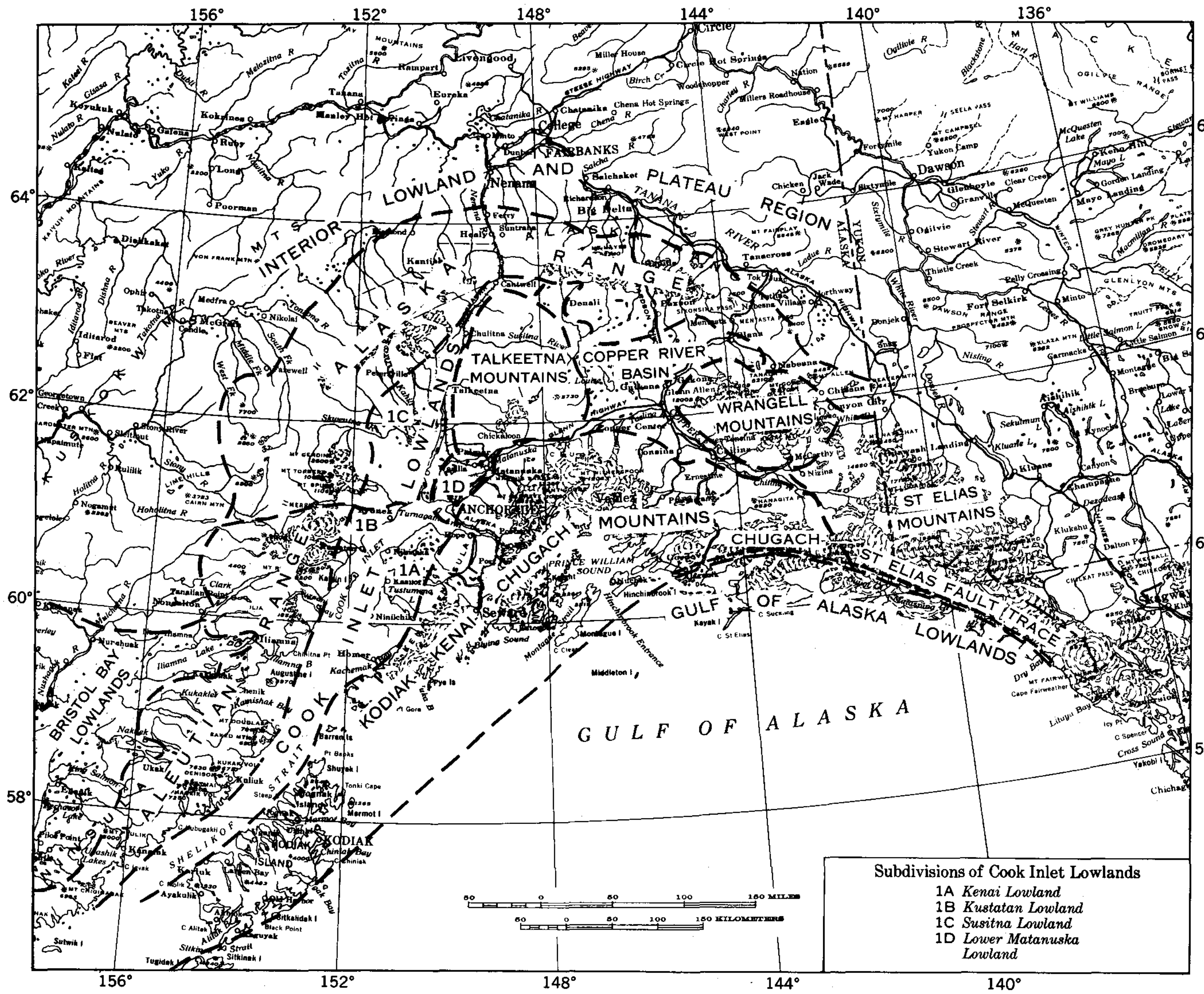

FIGURE 1.—Sketch map of major physiographic provinces of south-central Alaska and subdivisions of the Cook Inlet Lowland.

River lobes), westward across the lower Matanuska Lowland from Talkeetna and Chugach Mountain ice centers (the Matanuska-Knik River lobe), and northwestward and southwestward across the Kenai Lowland from Kenai Mountain ice centers (the Turnagain Arm, Skilak Lake, Killey River, Tustumena Lake, and Kachemak Bay lobes). Distribution of moraines indicates that the Pleistocene glaciers were repeatedly fed from the same high-level source areas that today contain the largest concentrations of alpine ice.

During the older and more extensive Pleistocene glaciations (the Mount Susitna, Caribou Hills, and Eklutna), ice from these alpine source centers coalesced and completely covered the floor of the Cook Inlet trough to progressively lower levels. Evidence for these glaciations is fragmentary; it is restricted to high-level glacial deposits and modified moraines in the surrounding mountains and to local exposures of drift in the lowland buried beneath younger deposits. In the later Pleistocene glaciations (the Knik and Naptowne), expanding ice lobes did not coalesce in the middle and upper part of the Cook Inlet trough but deposited separate spatulate-shaped end-moraine complexes in the lowlands. Below an elevation of about 750 feet these and the older moraines in the lowlands are conspicuously terraced and largely covered by sediments deposited in quiescent water. Stratigraphic and geomorphic evidence, discussed later in greater detail, records large proglacial lakes which occupied the upper ice-free part of Cook Inlet during the Knik and Naptowne glaciations and which presumably also came into temporary existence during advance and retreatal phases of the previous more extensive glaciations.

The boundary of Glacial Lake Cook of Naptowne age, shown in plate 1, roughly follows the approximately 750-foot strandline level, which is the highest but not the most conspicuously developed series of terraces in the Cook Inlet now recognized as Naptowne in age. The 500-foot strandline level provides the most continuous and well-developed strandline feature in Cook Inlet; is well developed throughout the Kenai Lowland; and is locally marked by terrace remnants cut into moraine-covered slopes, by hanging deltas, and by bars that partly divert the present drainage line. It is traceable along the western flanks of the Talkeetna Mountains between Willow and Talkeetna and is in all probability represented by one of the better developed strandline levels (precise elevations presently unknown) on the southern flank of Mount Susitna. A major topographic shelf underlain predominantly by water-laid sand and gravel at an elevation of about 500 feet along the Chugach Mountain front is considered by the author to mark this strandline level in the Anchorage area. Above this bench the mountain tributary streams flow in deep terraced valleys cut into terraced lateral-moraine deposits. Below this level the streams are incised in shallow broad channels cut below the irregularly terraced lowland surface. The 500-foot strandline and associated strandline levels appear to follow contours closely from the southeast tip of the Kenai Lowland to Talkeetna, a distance of about 200 miles. This suggests that if differential uplift has affected Cook Inlet since strandline development, it has been less than the present accuracy of mapping from aerial photography onto the 1:63,360 base maps. When more detailed ground mapping is completed it will be possible to assess this point more carefully. A subordinate glacial lake, Glacial Lake Talchulitna, was formed in the broad flat upland valley drained by Talchulitna River, between Mount Susitna and the Alaska Range. Here ice from the Skwentna–Yentna River and Beluga Lake lobes dammed the northern and southern ends of the valley during the Naptowne maximum. Contemporaneous glacial lakes were created in the middle course of Ayakulik and adjacent valleys in the Karlak quadrangle of Kodiak Island.

Reconstruction of the morainal pattern of Cook Inlet and adjoining areas, as shown in plate 1, is primarily based on photogeology and compilation of field data on the 1:250,000-scale topographic series base maps. Experience gained in the Anchorage area, Kenai Lowland, Kenai Mountains, Mount Susitna, and near Beluga Lake by field checking preliminary photointerpretations has been used in drawing the morainal and other geomorphic boundaries elsewhere in the region. Remapping of the morainal and associated deposits in the northern part of the Kenai Lowland, on the western flanks of the Talkeetna Mountains, and on Kodiak Island by the author on 1:63,360-scale topographic maps; of the Eklutna and Naptowne moraines on the southern flank of the Talkeetna Mountains north of Palmer and Houston by Andersen (written communication, 1955); and of comparable morainal boundaries on the opposing Chugach Mountain front near Anchorage by Gastil (written communication, 1955) has permitted more precise location of morainal boundaries than is possible on the 1:250,000-scale base maps. Similar refinements in mapping will become possible as larger scale base maps become available in the adjoining areas west and north of Cook Inlet.

Geomorphic subdivision of the moraines throughout Cook Inlet is primarily based on differences in topographic expression and on angular morainal-boundary relations suggesting significant periods of weathering, erosion, and glacial retreat between advances. The moraines of Naptowne age record the youngest major glacial advance into the lowlands and are the most prominent and least modified of all the moraines with the exception of small moraines of post-Naptowne or Alaskan age that lie close to present glacier fronts throughout the region. Prominent moraines with less pronounced glacial construction form, attributed to the Knik glaciation, locally lie in front of, or above, the Naptowne morainal boundaries on the Kenai Lowland and northwest of Tyonek. Distinct but much more modified moraines, attributed to the Eklutna glaciation, lie in front of, or well above, the Knik and Naptowne boundaries and locally project into canyons and gullies cut into surfaces mantled by older glacial deposits. This Eklutna boundary marks the most distinctive geomorphic break in the morainal sequence and can be traced nearly continuously along the slopes of the Chugach and Kenai Mountain fronts southward from the Eagle River north of Anchorage to south of Tustumena Lake on the Kenai Lowland. Comparable moraines occur at approximately the same elevations on the southwest flank of the Talkeetna Mountains and across the Susitna Lowland on the slopes of the Alaska Range and Mount Susitna. Highly modified lateral moraines and associated drift, attributed to the Caribou Hills glaciation, are locally preserved above the Eklutna boundary along the southwest flank of the Talkeetna Mountains, on upper surfaces and slopes in the Chugach Mountains, and on Mount Susitna; near the Chickaloon River and between Skilak and Tustumena Lakes along the Kenai Mountain front; and on upper surfaces of the Caribou Hills south of Tustumena Lake. Scattered remnants of still older glacially scoured surfaces that only locally retain till or glacial erratics occur near the ice-rounded summit of Mount Susitna (fig. 2) near the Chickaloon River and south of Skilak Lake in the Kenai Mountains. Erratic material observed by Andersen (written communication, 1955) at an elevation above 4,000 feet in the western part of the Talkeetna Mountains appears to lie above the upper boundaries of the Caribou Hills moraines and is considered to be Mount Susitna in age. Erratic material on the highest surfaces in the eastern part of the Talkeetna Mountains, at elevations greater than 5,000 feet (John R. Williams and Oscar J. Ferrians, oral communication, 1958), may represent the Mount Susitna or later glaciations.

Factors such as lithology, topographic position, and morphologic environment that have a considerable effect on the rate and character of morainal modification have been considered in the interregional correlation of moraines. Judgments based on degree of modification have been tested against other geomorphic criteria such as morainal position, sequence, and boundary relations.

FIGURE 2.—Glacially rounded summit area of Mount Susitna dissected by younger cirque development. Glacial erratics of graywacke-argillite, basalt, sandstone, quartzite, and greenstone are locally present in pockets and fractures on the upland surface underlain by frost-fractured quartz diorite. Erratic material was found within 100 feet of the highest summit, elevation 4,396 feet, of the mountain. Type locality of the Mount Susitna glaciation, oldest recognized in Cook Inlet.

At best, these geomorphic criteria relating to age and correlations of moraines, though extremely useful, only suggest relative age differences; and stratigraphic and pedologic evidence is essentially required to demonstrate the existence, duration, and intensity of retreat between glacial advances. Local stratigraphic evidence, discussed later in this paper, supports the geomorphic suggestion of major age differences between the proposed glaciations and provides significant and additional information relating to the interglacial intervals.

The boundaries of the Pleistocene glaciations outside of Cook Inlet, shown in plates 1 and 2, are based on the distribution of moraines and glacial drift as mapped and intercorrelated by E. H. Muller and James Platt in the Bristol Bay region; by A. T. Fernald in the upper Kuskokwim area; by T. N. V. Karlstrom in the Tonsona River area; by J. C. Reed, Jr., in the McKinley Park quadrangle; by Clyde Wahrhaftig and T. L. Péwé in the central Alaska Range; by G. W. Holmes, H. R. Schmoll, A. T. Fernald, and T. L. Péwé in the eastern Alaska Range; by J. R. Williams, Oscar J. Ferrians, Jr., H. R. Schmoll, and D. R. Nichols, H. W. Coulter, and Lynn Yehle in the Copper River basin; by Harald Drewes in the Aleutian Islands; and by T. N. V. Karlstrom along the Alaska Peninsula south of Becharof Lake (Karlstrom and others, 1959). During the last two major glaciations, interior proglacial lakes comparable to those in Cook Inlet were created in the Copper River basin by ice damming of exterior drainage outlets (Ferrians and Schmoll, 1957; Ferrians, Nichols, Schmoll, and Williams, written communication, 1959; Ferrians and Schmoll, *in* Karlstrom and others, 1959). Despite inherent uncertainties of correlating moraines largely on the basis of topographic expression and sequential position, it is felt that the correlations are generally valid because of the regional evidence now available; and that the ice boundaries shown in plates 1 and 2 provide a reasonably accurate picture of the regional extensions of ice throughout central and coastal Alaska during Pleistocene time.

The reconstruction of the Naptowne ice boundary shown in plate 2 confirms in most respects Capps' (1931) early interpretation of the regional extent of Wisconsin ice in southwestern, central, and southeastern Alaska but differs from Capps' interpretation in that it is now known that Cook Inlet and Copper River basin were not completely filled with Wisconsin ice but were occupied largely by extensive interior proglacial lakes. Hopkins' (1959) generalized reconstruction of the Wisconsin ice boundary in the Bristol Bay area differs from the author's in that Hopkins' line is an extrapolation of the outer boundary of the Johnston Hill moraines. These moraines, as mapped by Muller (*in* Karlstrom, 1957), are much older and lie in front of both the Mak Hill (Knik) moraines and the younger Brooks Lake (Naptowne) moraines of Wisconsin age.

CLIMATIC ZONATION IN THE COOK INLET REGION

The climate of the Cook Inlet region is, in general, intermediate between the dry, cold continental type of Interior Alaska and the relatively wet and mild maritime climate of the Gulf of Alaska coastal areas. Within the region, the orographic effect of bordering mountains determines a distinctive climatic zonation (Mitchell, 1958). The Kenai Lowland falls in the precipitation shadow of the Kenai Mountains and has lower mean annual precipitation than the Kenai Mountains to the east or the lowlands to the west and north (pl. 2). Available meteorological data from lowland station records indicate mean annual precipitation of 27 inches at Homer on the southern tip of the lowland, 18 to 19 inches in the central Kenai-Kasilof area, and 14.5 inches at Anchorage, just north of the Kenai Lowland. Mean annual temperature and snowfall show the same small but progressive northeastward decrease from 38° F and 61 inches, respectively, at Homer to 36° F and 59 inches at Anchorage. West and north of the Kenai Lowland, mean annual precipitation rises progressively from 23 inches at Tyonek on the west shore of Cook Inlet to 28 inches at Susitna, 30 inches at Talkeetna, and 45 inches at Curry. Eastward across the Kenai Mountains, mean annual precipitation increases progressively from 27 inches at Coopers Landing and 35 inches at Moose Pass to a maximum of 69 inches at Seward, which is at tidewater along the Gulf of Alaska coast. Kasilof on the Kenai Lowland has an average annual snowfall of 59.6 inches, and Seward has an average of 86.7 inches, or about half again as much.

RELATION OF VEGETATION AND PRESENT GLACIERS

The climatic zonation with a drier, more continental type climate restricted to the lee of the Kenai Mountains and centered near the head of the inlet is strikingly reflected in the distribution of both forest types and glaciers. The coastal rain forest of southeastern Alaska reaches its most northerly range along the coastal zone of the Kenai Mountains and in the most southerly part of the Kenai Lowland (Hopkins, Karlstrom, and others, 1955, p. 136). North of Ninilchik the coastal forest type characterized by hemlock and Sitka spruce is predominantly replaced by the interior forest type characterized by white spruce and white birch. A transitional zone between coastal and interior forest types on the Kenai Lowland near Ninilchik closely coincides with the mean-annual-temperature and precipitation line of 35° F and 20 inches. Similarly, the presence of larger and more abundant glaciers at lower elevations adjacent to the Gulf of Alaska than are found inland is consistent with the meteorological data of diminishing snowfall inland across the axis of the coastal range. Inasmuch as this decrease in precipitation inland is accompanied by a general decrease in mean annual temperatures, the importance of precipitation over temperature as the significant limiting factor on glacial intensity within the region is strongly suggested. In keeping with this meteorological evidence, the altitudinal distribution of snowfields and cirque glaciers records a regional snowline that is inclined steeply coastward across the axis of the Kenai Mountains. Large glaciers near the head of Turnagain Arm feed from icefields mostly below an elevation of 3,000 feet. Fourteen miles inland, minor cirque glaciers, present only on the insolation-protected north-facing slopes, occur at elevations of about 4,000 feet. Twenty-six miles farther inland, cirque glaciers are absent on peaks of comparable elevation that instead hold modified cirques formed during an earlier period (Naptowne) of depressed snowlines. Along this transect the present regional snowline therefore drops coastward much more than 1,000 feet in elevation in a horizontal distance of about 40 miles. Comparable coastward-inclined snowlines are recorded for the Chugach coastal mountains to the east, the interior Talkeetna Mountains to the north, and the Aleutian and Alaska Ranges to the west and northwest. According to Bjørn Andersen (written communication, 1956) the regional snowline across the coastal ranges immediately north of Turnagain Arm rises from an elevation of 2,700 feet near the head of Prince William Sound to over 7,000 feet in the interior part of the Talkeetna Mountains. The regional snowline at the southern tip of the Kenai Mountains lies between 4,000 and 5,000 feet in elevation, and on Kodiak Island it lies between 3,000 and 4,000 feet in elevation near the Pacific Ocean and above 4,000 feet inland. On the coastal side of the Aleutian Range northwest of Kodiak Island, the regional snowline lies, in general, above 4,000 feet in elevation and rises abruptly northward and northwestward across the axis of the range to more than 8,000 feet in elevation just north of Lake Clark. The approximate altitudinal distribution of the climatic snowline throughout south-central and southwestern Alaska is shown in plate 2.

RELATION TO PAST GLACIATION

The consistent relation between present glacial ice, peak elevations, and proximity to the Gulf of Alaska provides a direct and reasonable meteorological explanation for the distribution of glacial deposits throughout the region. The deposits record for past glaciations a comparable lower glacial intensity for the interior than for the coastal sides of the surrounding mountain ranges and a general decrease in glacial intensity with distance away from the Gulf of Alaska. This is particularly well illustrated by the progressive northward decrease in size of the ice lobes that fed from the Aleutian and Alaska Ranges during the last major glaciation and in the striking north-south asymmetry of opposite-flowing ice lobes fed from common fields in the central part of the Alaska Range (pl. 2). Whereas ice lobes draining the northern precipitation-starved flanks of the range extended onto the interior lowland margins for distances of less than 12 miles, those draining the precipitation-favored southern flanks pushed out appreciably greater distances (30–40 miles) and coalesced to form a continuous ice sheet. This ice sheet completely filled the northern part of the Susitna lowland to elevations above 3,000 feet and extended southward and eastward onto the Susitna lowland to a broad terminal position between Talkeetna and McDougal. Westward drainage from the Copper River interior basin was blocked by the ice fill in the northern part of the Susitna River lowland and by coalescence of ice from the Alaska Range and Talkeetna Mountain near Talkeetna. The distribution of Naptowne ice within the upper part of the Susitna River lowland thus created a persisting ice barrier that disrupted drainage patterns and raised exterior surface-drainage thresholds to elevations above 3,000 feet along the northwestern margin of the Copper River basin.

The Susitna River flows into Cook Inlet from the Copper River basin through a deep canyon cut across structure in the northern part of the Talkeetna Mountains. The author believes the most direct and simplest explanation for this discordant drainage course is that of drainage disarrangement and superposition which would inevitably result from the pattern of intense and repeated glaciations recorded for the region. The Susitna River canyon crosses a relatively low glaciated mountain area that either remained ice free or was the last covered and the first uncovered by ice during the Naptowne and earlier more extensive expansions and contractions of icecaps developed on bordering much higher alpine areas. Thus the canyon occupies the most likely site for repeated concentrations of ice-diverted and ice-dammed melt waters and for consequent drainage superposition across topographic and structural grain. This interpretation differs from that of Wahrhaftig (1950), who believes that the discordant drainage pattern can be most reasonably explained by superposition from an inferred ancient postmature erosional surface (peneplane?) uplifted in late Tertiary or early Quaternary time.

Marginal to Cook Inlet, the position of the moraines of Naptowne, Knik, Eklutna, and Caribou Hills age indicates that glacial ice from the coastal side of the higher Aleutian and Alaska Ranges was predominant over ice that fed from the interior side of the Kenai Mountains and advanced much farther into the Cook Inlet trough. During Naptowne and Knik time the Skilak Lake and Tustumena ice lobes pushed out from 30 to 40 miles into Cook Inlet from ice centers on the interior side of the Kenai Mountains, whereas the Trading Bay lobe advanced 50 to 60 miles from icefields concentrated on the margins of the Aleutian and Alaska Ranges. During Eklutna time, ice from these ranges, as marked by the position of the interlobate moraine on the Kenai Lowland, pushed eastward more than two-thirds of the distance across the Cook Inlet trough to the boundary of coalescence with the ice flowing westward from the Kenai Mountains.

As recorded by the southwestward increase in the elevations of the lateral moraines of Naptowne age and fresh ice-scoured slopes along the front of the Aleutian Range, glacial intensity in Cook Inlet increased downvalley, and a large icecap area covered the Aleutian Range in the vicinity of Tuxedni Bay and southward during the Naptowne time. Ice flowing eastward from this icecap coalesced with ice flowing westward out of Kachemak Bay. This coalescing ice completely filled the floor of the lower part of Cook Inlet and was coextensive with ice that spilled westward across the glacially scoured low divide in the Aleutian Range as a major ice lobe of Brooks Lake (Naptowne) age in the Iliamna Lake basin of the Bristol Bay Lowland (Muller, 1953; Karlstrom, 1953; Krinsley,1953). The ice barrier formed in the lower part of Cook Inlet during the Naptowne and previous glaciations created interior proglacial-lake environments that are recorded geomorphologically and stratigraphically in the upper part of Cook Inlet.

Support for the existence of an ice plug in the lower Cook Inlet drainage during the last major glaciation in the region is provided by geomorphic and stratigraphic evidence from Kodiak Island. Because of the distribution and freshness of surface till and glacial-erosion forms on the island, Capps (1937) early speculated that Kodiak Island was covered during the last major glaciation (Wisconsin) by a local icecap that merged with ice from the Cook Inlet region and Aleutian Range, filling Shelikof Straits to the west and Barren Straits to the north, and pushing out some 50 miles into the sea southeast of the island. He suggested that the great eastward bulge of the underwater platform east of the mouth of Cook Inlet, the Portlock Banks, marks the seaward extent of the Cook Inlet ice lobe that was diverted through Barran Straits. This interpretation is consistent with the character and regional distribution of the glacial deposits of Naptowne and Brooks Lake age in the adjoining Cook Inlet and Bristol Bay regions. It is also consistent with the distribution pattern of the moraines, which indicates that ice in Shelikof Straits was sufficiently high along its northern margin to spill northward across the low ice-sculptured divide of the Aleutian chain at the head of Becharof Lake, and along its southern margin to surround completely the ice-free area at the southwest tip of Kodiak Island. Capps (1937) reported the presence of foreign rock types in the drift near Ayakulik at the southern tip of the island and considered that this erratic material was most probably derived from Aleutian Range sources. This evidence conforms with the morainal evidence, which records a southward-inclined ice-surface gradient in this section of Shelikof Straits from more than 2,000 feet in elevation near the head of Becharof Lake to 1,000 feet and less at the southwest tip of Kodiak Island.

Moraines, comparable in topographic expression and sequence to those of the Brooks Lake and Naptowne moraines, have been traced nearly continuously on areal photographs and topographic maps from Becharof Lake southwestward to Unimak Island. Here, as in the region to the northeast, the largest morainal loops deposited on the Bristol Bay lowlands do not lie north of the higher nearby mountain ice sources but directly in line with low ice-scoured gaps or passes (some below present sea level). This indicates derivation from main ice sources somewhat seaward and south of the axis of the Aleutian Range. The nearby Pacific Ocean island groups, Sutwik, Semidi, Chirikof, Shumagin, Sanak, and Kremtzin, show topographic characteristics and, locally, fiordlike indentations characteristic of the Kodiak Island group that suggest similar modification under icecap conditions during Naptowne time. Most of the islands are low lying and appear to have been buried completely by ice. Sharp arêtelike peaks and jagged slopes rising above glacially scoured topography on Unga Island suggest burial to an elevation of about 1,000 feet by ice derived in part from sources to the north and in part from the higher fiord-indented Koniuji Islands to the south. Thus, it seems evident that during Naptowne time a marginal ice sheet, formed by coalescence of seaward-flowing ice from the Aleutian Range with local island icecaps, was coextensive with ice in Shelikof Straits and extended westward along the coast to, and probably beyond, Unimak Island.

Maximum accumulation of ice along the coastal precipitation-favored side of the Aleutian Range provides a reasonable explanation, consistent with present climatic zonation, of the northward-flowing outlet glaciers that spilled through low gaps in the range and deposited the spatulate morainal complexes on the Bristol Bay and Bering Sea lowlands. South of Stepovitch Bay, major outlet glaciers eroded below present sea level and determined the present bays of Pavlof, Morzhovoi, and Bechevin. These bays constitute northward reentrants of the Pacific Ocean extending through the Aleutian Range and separated from the Bering Sea in whole or in large part by wide end-morainal deposits laid down by the outlet glaciers during their retreat southward from the Bering Sea coast. On the west shore of Pavlof Bay the morainal drift contains coarsely crystalline igneous rock whose source is unknown (Kennedy and Waldron, 1955, p. 14). According to the author's reconstruction of regional ice movements, the most likely source for these lithologically foreign materials would be the geologically unmapped offshore Pacific Ocean islands of the Belkofski and Dolgoi groups.

Low-level old cirques in the Kenai Mountains suggest that the climatic snowline was depressed more than 1,000 feet during the Naptowne glaciation. Charlesworth (1957, p. 652) estimates that snowlines were, in general, depressed between 1,000 and 2,000 feet in northern latitudes during the last Pleistocene ice age. The snowline on Kodiak Island and on the coastal margins of the Kenai and Aleutian Mountains now lies between 3,000 and 4,000 feet in elevation. The climatic snowline on the coastal islands west of Kodiak lies below an elevation of 3,000 feet. A drop of 1,000 to 2,000 feet during Naptowne time throughout the coastal region would therefore have depressed the snowline close to present sea level, causing expansion of present icecaps on the coastal ranges and creating local icecaps on Kodiak Island and on the Shumagin Island group. As reconstructed from the regional morainal evidence, these icecap areas in Naptowne time coincided closely with present areas of higher precipitation (pl. 2) and emphasize the dominant role played by the distribution of total precipitation on the location and size of present and past glaciers in the region.

The extent of Naptowne ice outward from the precipitation-favored side of the Kenai Mountains is not known, because deposits left by the ice are submerged beneath the Gulf of Alaska. However, it is believed that ice must have extended out an appreciable distance into the Gulf of Alaska and completely filled Prince William Sound. Tarr and Martin (1914, p. 469) consider that the fiordlike submarine topography of the Prince William Sound resulted from glacial ice excavation during Pleistocene time. From photointerpretation of parts of this region, the author believes that the distribution of fresh-appearing moraines and ice-scoured slopes indicates that the sound was last filled with ice, which completely surrounded Montague Island to elevations between 1,000 and 2,000 feet or higher, during late Pleistocene (Naptowne) time. Henry Coulter (oral communication, 1958), from geomorphic studies near Valdez, believes that ice during the last major glaciation nearly covered the bordering Chugach coastal ranges and was at least several thousand feet thick along the landward margin of the sound. Thus, on the basis of this coastal evidence, it seems that whereas during Naptowne time interior glaciers from the Kenai-Chugach Mountains icefields advanced distances of from 15 to 20 miles into the Cook Inlet from present ice fronts, coastal glaciers fed from the same icefields coalesced and must have formed a huge ice shelf that extended out into the Gulf of Alaska for an unknown but appreciably greater distance. If Capps (1937) was correct in his postulation that ice extended some 50 miles into the Pacific Ocean southeast of Kodiak Island, a seaward extension of much more than 50 miles is suggested for the coastal ice to the northeast as this would have been supplied from higher and larger nourishment centers. Capps (1935) believed that Middleton Island, which lies 70 miles seaward from the Kenai Mountain coastline, may have been covered by glacial ice during the last major glaciation. Miller (1953) believes that there is no evidence on the island for a postbedrock glaciation. The bedrock of the island is made up of a thick section of semiconsolidated fossiliferous marine tills associated with well-sorted and stratified marine sediments that he believes are of either Pliocene or Pleistocene age. The tilted bedrock sequence is truncated by a series of little-weathered or -eroded uplifted marine terraces that he believes are most probably late Pleistocene and Recent in age. The mollusk shells collected from the semiconsolidated bedrock deposits of the island are identical with those of living cold-water forms, most of which fall within their known recent geographic range. This evidence is not incompatible with the interpretation that at least some of the marine till beds of Middleton Island were deposited during late Pleistocene time and that the uplifted terraces represent uplift (either isostatic or tectonic) following retreat of late Pleistocene ice. Miller, however, on the basis of degree of compaction and lithologic similarity of these deposits with comparable deposits along the northeast coast of the Gulf of Alaska, favors a Tertiary age for the Middleton deposits.

The seaward position of Naptowne ice along the northeast coast of the Gulf of Alaska, as shown in plate 2, is generally consistent with the geomorphic evidence in the Prince William Sound area (Henry Coulter, oral communication, 1958) and in the region south of Cross Sound (Clyde Wahrhaftig, oral communication, 1958), which records ice thicknesses of from 2,000 to more than 3,000 feet along present coastlines during what seems to have been the last major glaciation in these regions. The higher mountains and generally high precipitation rates in the intervening coastal region between Cordova and Cross Sound suggest that the potential seaward extension of ice here should have been just as great, if not greater, than in the adjoining coastal sections. That this may not have been so is indicated by Miller (1958), who recognizes no high-level deposits of late Pleistocene age on the narrow coastal shelf, and who believes that the recorded glacial sequence in the area is anomalous in respect to the North American glacial record and thus may be related to tectonic activity. Uplifted marine terraces and historically recorded faulting and uplifts characteristic of the coastal region of Alaska south of Cordova have not been observed by the author nor reported from the coastal region north of Cordova. It is evident that late Cenozoic tectonic activity of major magnitude and restricted essentially to the fault-bounded crustal block south of Cordova introduces a complicating factor in the interpretation of the glacial sequence recorded here.

Judgment of tectonic control for glacial events depends on either establishing contemporaneity between tectonic and glacial movement or the absence of parallelism between glacial movement and the climatic history of the region. In this regard the writer deems it significant that the oldest recorded glacial advances of the coastal Malaspina glacier, between A.D. 600 and 1290 and A.D. 1700 and 1791 (as dated by Plafker and Miller, 1957, 1958), were essentially contemporaneous with culminations of the Tunnel I and II glacial advances, dated ca. A.D. 1000 and between A.D. 1500 and 1850, respectively, in the Cook Inlet region, and directly correlate with continental climatic events both from North America and northern Europe (Karlstrom, 1955b, 1956; pl. 7 this report). Likewise, Deevey and Flint (1957) correlate their radiocarbon-dated coastal glacial sequence from Glacier Bay and Cross Sound with the comparable climatic record (the recurrence surface sequence) of northern Europe. This regional and extraregional parallelism strongly suggests that at least some of the coastal glaciers between Cordova and Cross Sound responded directly to climatic rather than tectonic causes.

The relative intensities of glacial advance recorded for Cook Inlet glaciers and the Malaspina glacier are also consistent with a climatic interpretation. Radiocarbon-dated moraines of Tunnel I and II age lie respectively 500 and 300 feet in front of Tustumena glacier, which drains the interior margin of the Harding Icefield (fig. 9), and about 1 mile and ½ mile in front of Bartlett glacier, which drains the interior margin of an icefield near Prince William Sound (fig. 10). Contrasted with the position of the equivalent moraines as much as 10 to 20 miles in front of the coastal Malaspina glacier, the recorded intensity differences of glacial advance are consistent with the three glaciers' orographic position relative to the coast and to present precipitation supply. The Malaspina glacier moraines record the oldest coastal glacial advances and are the equivalent of the youngest moraines in the morainal sequence of Cook Inlet. On the basis of relative intensity, then, it is reasonable to conclude that Malaspina glacier, like the Cook Inlet glaciers, must have been much more extensive in pre-Tunnel time and, during Naptowne time, probably terminated some distance seaward of the present coastline. Miller (1958) concludes that coastal Bering glacier has not been any more extensive than at present since late Wisconsin time. As Bering glacier drains from the same general alpine icefield within the same area of high precipitation as does nearby Malaspina glacier, this geomorphic interpretation poses a problem now unresolvable in terms of both a simple climatic or a simple tectonic explanation.

KENAI LOWLAND

GEOGRAPHY

Kenai Lowland is bordered on the west by Cook Inlet, on the east by the coastal Kenai Mountains, and on the north by Turnagain Arm (fig. 1). The lowland is a broad low shelf 20 to 50 miles wide and 106 miles long that covers an area of about 3,600 square miles between lat 59° N. and 61° N. and long 150° W. and 152° W. It is mantled largely by glacial deposits. Most of the lowland is less than 400 feet above sea level; surfaces are flat to undulating; and local relief varies from a few feet to more than 200 feet. The Caribou Hills, a broad glaciated upland north of Homer, rise abruptly 1,000 to 2,000 feet above the general lowland surface. Remnants of this same upland surface occur as piedmont slopes adjacent to the Kenai Mountains between Skilak and Tustumena Lakes.

Drainage in the lowland is poorly integrated; and numerous lakes, marshes, and muskeg areas make up more than one-third of the total surface. Two major lakes, Tustumena and Skilak, occupy glacially scoured and moraine-dammed troughs and are drained respectively by the Kasilof and Kenai Rivers, which empty into Cook Inlet. The shoreline of Kenai Lowland is characterized by wave-cut cliffs that range in height from 800 feet in the Kachemak Bay area to less than 50 feet near the mouths of major drainage lines.

GEOMORPHOLOGY

Kenai Lowland is subdivided on the basis of topography and geology into seven areas herein named "Nikishka Lowland," "Bear Creek Upland," "Skilak Platform," "Ninilchik Lowland," "Caribou Hills," "Homer Bench," and "Fox River Lowland" (pls. 3, 4).

NIKISHKA LOWLAND

Nikishka Lowland lies north of the Kasilof River and the Caribou Hills Upland. It is characterized by a complex largely modified morainal topography, extensive areas of muskeg and swamp, a peculiar anastomosing pattern of broad-floored largely abandoned drainage lines, poorly integrated drainage, and numerous lakes. The eastern margin of the lowland is characterized by a series of old, modified lateral moraines of Eklutna and Caribou Hills age that flank the Kenai Mountain front in its northern part; in its southern part the front is flanked by a series of younger, less modified spatulate end moraines of Knik and Naptowne age that, in the form of well-preserved lateral moraines, are traceable on valley walls back into the Kenai Mountains toward the Harding Icefield. The westernmost part of the lowland near East Foreland and Boulder Point is underlain by remnants of end moraines of Knik and Naptowne age deposited by the Trading Bay ice lobe, which advanced southeastward across Cook Inlet from Alaska Range sources. South of East Foreland the moraines of Knik age have been destroyed; and the Naptowne moraines are fronted by a terraced, channeled, and lake-dotted sand and gravel plain that extends southward to Kenai and is coextensive with a broad coastal terrace lying between the Kenai and Kasilof Rivers. An interlobate moraine of Eklutna age forms a higher rib of ground in the central part of the lowland. It is bordered to the southeast by an extensive muskeg area and a channeled sand and gravel plain with numerous lakes and is drained by Moose Creek and the Chickaloon River. To the northwest the interlobate moraine is bordered by a dissected area drained by the Swanson River and Beaver Creek and is characterized by an anastomosing system of largely abandoned muskeg-filled drainage channels and a series of muskeg-covered terrace levels (fig. 3). The lobation of the interlobate moraine expresses in a striking manner the boundary of coalescence within the lowland between the Susitna River, Beluga Lake–Trading Bay, and Redoubt Bay ice lobes from Alaska and Aleutian Range sources; the Turnagain Arm ice lobe from Chugach–Kenai Mountain sources; and the compound Skilak Lake–Killey River–Tustumena Lake ice lobe from Harding Icefield sources. At its northern end the interlobate moraine is crossed at an angle by an arcuate belt of moraines that roughly parallels Chickaloon Bay between Point Possession and the Kenai Mountains and which marks a major readvance in Knik time of the Turnagain Arm ice lobe into the Nikishka Lowland. A comparable belt of moraines between Potter and Point Campbell, just across the arm, has been mapped in the Anchorage area (Gordon Gastil, written communication; Miller and Dobrovolny, 1959) and are believed by the author to mark the north Knik boundary of the Turnagain Arm ice lobe in the upper Cook Inlet area. Gastil maps these moraines as pre-Naptowne; Miller and Dobrovolny suggest that they are Naptowne in age. Reasons for this difference in interpretation are discussed later.

On the eastern margin of the Nikishka Lowland, in the type locality near Naptowne Lodge at Sterling, the Naptowne morainal record is of at least four major advances: the Moosehorn (outermost continuous morainal boundary), Killey, Skilak, and Tanya. A partly buried morainal knoll just outside the Naptowne boundary near Naptowne may represent either a recessional Knik phase or an advance of Naptowne age that just preceded the Moosehorn advance. The named Naptowne events are represented by broad morainal belts whose boundary relations (local transection of morainal trends, boundary drainage diversions, and melt-water channel relations) imply regrouping of ice tongues and readvances following retreats from earlier advanced positions. The names of these advances are derived from the Moosehorn Rapids, formed where the Kenai River cuts through the outermost morainal belt of Naptowne age near Sterling (formerly Naptowne); from the Killey River, which flows across the second morainal belt; and from Skilak Lake, which is surrounded by moraines making up the third belt of the Naptowne morainal complex. Although the fourth and youngest Naptowne advance is recorded by moraines and stratigraphic relations in the Skilak Lake area, it is named from Tanya Lake, which lies within a comparable, but topographically better expressed, belt of moraines deposited by the Tustumena Lake ice lobe of Naptowne age. Comparable belts are also noted for the morainal complexes of Naptowne age deposited by the Killey River, Tustumena Lake, and Kachemak Bay ice lobes. The major geomorphic break in these Naptowne complexes is marked by the morainal belt of the Skilak advance, which is equivalent to the Nicolai Creek moraines of Karlstrom (1953) and Krinsley (1953). This parallel sequence of moraines deposited by coalescent as well as separate ice lobes strongly implies that these Naptowne advances were events of regional rather than local climatic significance.

Moraines of the Moosehorn and Killey advances lie closer together in the Tustumena Lake area than they do to the northeast near Skilak Lake; to the southwest, near Anchor Point, moraines of Moosehorn age are missing, and moraines of Killey age mark the Naptowne maximum of the Kachemak Bay ice lobe. A buried till unit exposed in the sea bluffs southeast of Anchor Point is considered by Krinsley to record a distinctly separate Moosehorn advance that fell short of the succeeding Killey advance. Comparable geographic shifts in glacial intensity with time are known from other regions. In the Alps, the Mindel glaciation was the maximum in the east, and the younger Riss was the maximum in the west (Charlesworth, 1957, p. 933). In the midcontinent, the Wisconsin maximum was attained during Tazewell time in Illinois; and much later, during Mankato time, in Iowa and South Dakota.

The amount of retreat between the Moosehorn, Killey, Skilak, and Tanya advances is not known. However, from the similarities in topographic expression and weathering of the subordinate morainal belts, it is believed that the magnitudes of retreats are probably measurable in terms of several miles rather than several tens of miles and certainly do not represent complete deglaciation back into the mountains prior to the next advance. The younger morainal belts between the Tanya moraines and the present ice front of Tustumena glacier record two post-Naptowne glacial advances attributed to the Alaskan glaciation.

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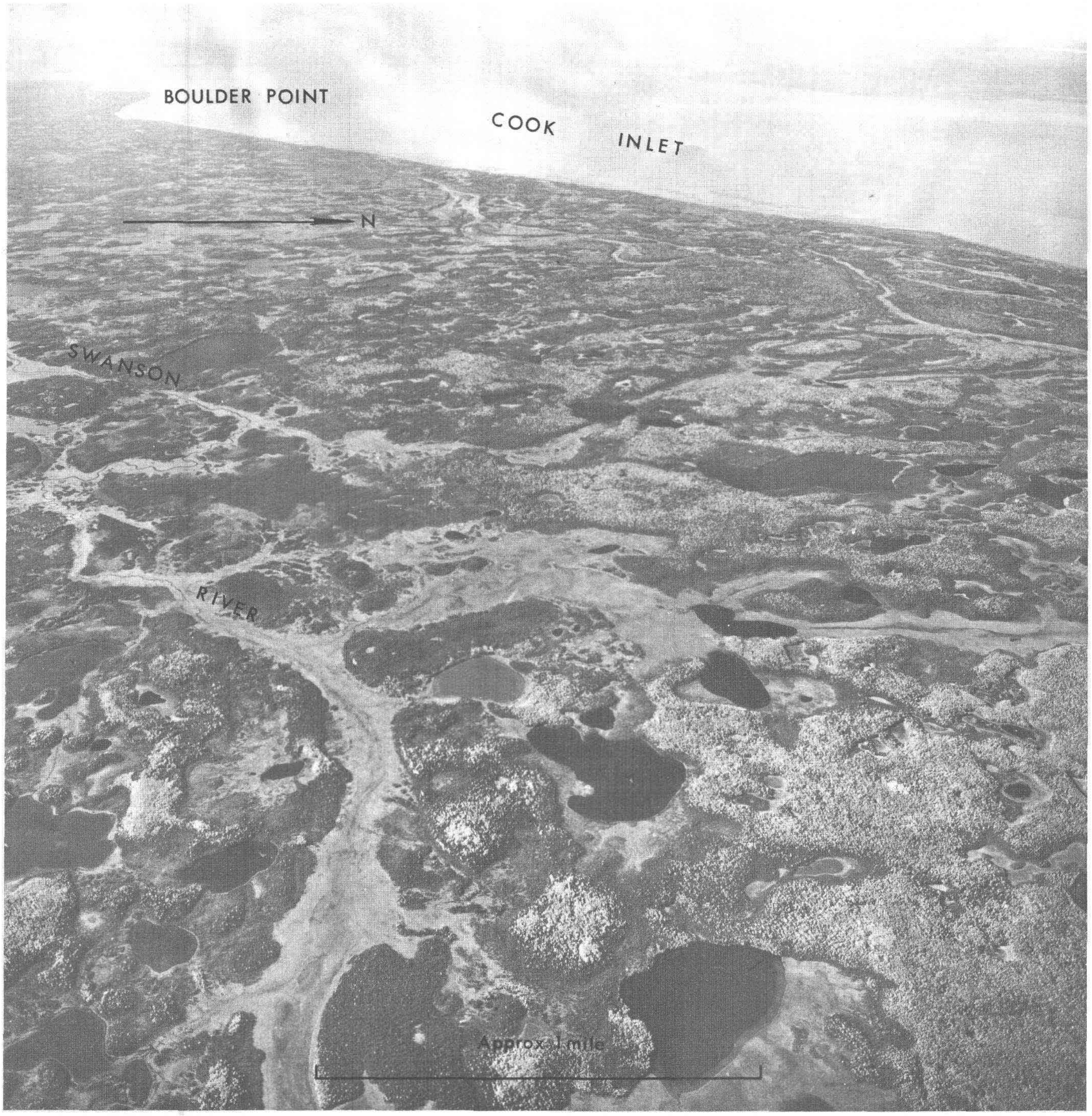


FIGURE 3.—Oblique photograph of northern part of Nikishka Lowland, between Point Possession and Boulder Point. Cook Inlet and Aleutian Range in background. Illustrates the peculiar anastomosing and reticulate largely abandoned drainage pattern developed on the emerged irregular floor of the proglacial lake and the character of the lakes that dot the lowland surface. Marsh-filled drainage lines and lakes in foreground drain into the upper reaches of Swanson River.

Below an elevation of about 750 feet, the pre-Skilak moraines throughout the Nikishka Lowland are conspicuously different in topographic character from those that rise above that elevation along the front of the Kenai Mountains. Morainal ridges at the lower elevation have slopes that are commonly step-terraced, and many have broad flat summit areas underlain by uncontorted laminated to finely stratified silt and sand laid down in quiescent waters. Prominent sets of essentially horizontal terrace remnants cut across the trends of morainal ridges and are concentrated near elevations of 750 and 500 feet along the eastern margin of the Nikishka Lowland. These terraces are best developed outside the Naptowne end-morainal boundaries along the lower slopes of the Bear Creek Upland near the Funney River and along the Kenai Mountain front north of Jean Lake. The terraces are cut into lateral moraines of Knik and Eklutna age and are traceable across a complexly terraced alluvial plain that is incised below a hummocky morainal surface where the Chickaloon River flows into the lowland from the Kenai Mountains. A series of abandoned melt-water channels emanating from Naptowne end moraines of the Tustumena Lake ice lobes terminate downslope at terrace levels between 500 and 750 feet in elevation. These geomorphic relations thus suggest development in a large lake that submerged most of the Nikishka Lowland during the maximum phases of the Naptowne glaciation. Another set of prominent terraces, cut at elevations between 250 and 300 feet throughout the lowland, are graded to abandoned channels that cut through end moraines of the Moosehorn and Killey advances and apparently terminate at the end moraines of the Skilak advance in both the Skilak and Tustumena Lake areas. These suggest a lower lake-level stand during the Skilak maximum. Terraces are also numerous below the 250-foot elevation. The most prominent occur at elevations between 100 and 150 feet (125-foot terrace) and at about 50 feet. Both of the lower terrace levels are restricted largely to the coast. The 125-foot terrace is most prominently developed in the Kenai-Kasilof area (Karlstrom, 1958), where it forms a coastal bench that is cut down below the level of the interlobate moraine of the Eklutna glaciation. The coastal bench is graded to a terrace level lying above the Kenai River and can be traced a short distance inland up the Kenai River valley. A much higher strandline, about 1,000 feet in elevation, is suggested by terrace remnants across the trends of lateral moraines of Caribou Hills and Eklutna age along the Kenai Mountain front north of Jean Lake. Uplifted tidal flats occur at elevations between 10 and 20 feet near the outlets of the Kasilof, Kenai, Swanson, and Chickaloon Rivers. These tidal flats postdate the drainage of proglacial-lake waters below the 50-foot strandline and are attributed to a sea-level stand during late Naptowne time that was higher than the present sea level in Cook Inlet.

The peculiar anastamosing and reticulate drainage pattern of the broad-floored, terraced, and largely abandoned drainage channels on lower ground northwest of the interlobate moraine (pl. 3) is atypical of normal drainage development under subaerial conditions and strongly suggests elements of scabland topography developed under torrential-flood conditions. In view of the fact that these channels are developed on the irregularly modified morainal floor of a proglacial lake with a complex hydrologic history, they are believed to be largely the product of sudden releases of proglacial-lake waters accompanying partial or complete drainage of the lake. The uniformly poor integration of drainage and unfilled lake depressions throughout the lowland suggest a youthful surface and support the conclusion derived from other geomorphic information that the lowland emerged for the last time as dry land in late Naptowne time. The numerous lakes of the lowland thus must occupy either original depressions in the emerged proglacial-lake floor or depressions that were subsequently formed or enlarged by such processes as differential compaction of the fine-grained bottom sediments, thawing of ground ice, wave and ice action along shorelines, and damming of abandoned channel segments by slope slumping, alluviation, and muskeg development.

BEAR CREEK UPLAND

Bear Creek Upland is a broad piedmontlike surface between 1,500 and 3,000 feet in elevation fronting the Kenai Mountains and projecting westward into the Nikishka Lowland between Tustumena Lake and the Killey River. (pl. 3). The upland surface is mantled by highly modified moraines and associated drift of Caribou Hills age, and its steeper flanks are plastered with lateral moraines of Eklutna, Knik, and Naptowne age deposited by the Killey River and Tustumena Lake ice lobes. Unlike their extensions within the Nikishka Lowlands, the moraines on the upland are mantled by proglacial-lake sediments, and the primary glacial and associated coarse granular glaciofluvial deposits crop out at the surface beneath either a thin loess mantle or a bare frost-stirred zone. Modification of the upland moraines is primarily a product of subaerial weathering and erosion and presumably also is a direct function of time. Distinct and progressive stages in the modification of primary morainal form are evident for the moraines from the Naptowne (least modified) to the Caribou Hills (most modified). These relative morphological differences hold for each morainal belt through vertical intervals of 1,000 to 2,000 feet; and they are not gradational with elevation but change abruptly at the major morainal boundaries, suggesting significant age differences between the moraines. Moraines of Eklutna age locally form reentrants up major canyons cut through the drift of Caribou Hills age, indicating appreciable retreat of the ice prior to its readvance into the lowland in Eklutna time. Similar but somewhat less pronounced reentrant relations are recorded for the lateral moraines of Knik and Naptowne age along the south side of the upland. Shifting of ice supplies between glaciations is suggested by angular relations in morainal trends along the major boundaries.

No systematic ground examination has been made of the pre-Naptowne deposits on the Bear Creek Upland, and the weathering and boulder characteristics of the various moraine deposits in this area are not known. However, a ground study of the same sequence of moraines was made nearby on a comparable upland surface fronting the Kenai Mountains just north of Bear Creek Upland and between the Killey River and Skilak Lake. This upland area was chosen for a reconnaissance ground study because of its somewhat easier access from the highway net and because photointerpretation suggested that a miniature record of much of the Cook Inlet glacial chronology might be provided by a complex of small lobate end moraines deposited on the upland surface by an escape glacier that fed from an icefield through a low col in the marginal high mountain ridge.

SKILAK PLATFORM

Skilak Platform is a glaciated small platformlike area lying between 2,000 and 2,500 feet in elevation between the Killey River and Skilak Lake (pl. 5). Along its southeastern side is a graywacke-argillite mountain ridge that rises to between 3,000 and 4,500 feet in elevation and which is part of a system of ridges that forms the arcuate rim of a large compound cirque drained by Benjamin Creek. A glacially rounded bedrock knoll of graywacke-argillite stands about 1,100 feet above the general level of the platform along its southern margin. To the south, west, and north the platform is bounded by steep moraine-covered slopes that descend into the valleys of Benjamin Creek and the Killey River and into the Skilak Lake trough. Highly modified lateral moraines of Caribou Hills age occur along slopes of the mountain ridge to the east up to an elevation of about 3,500 feet; at higher elevations on the graywacke-argillite bedrock slopes are granitic erratic boulders attributed to the Mount Susitna glaciation. Moraines of Eklutna, Knik, and Naptowne age rim, and lie below, the platform on the surrounding valley slopes. Thus the morainal record indicates that the platform was completely covered by ice during Caribou Hills and earlier time and that it stood above the general level of lowland ice during Eklutna and later time. On the platform surface lies a series of nested end moraines deposited by an escape glacier that spilled through a low col in the surmounting mountain ridge from a high-level icefield. This icefield occupied the compound cirquelike head of Benjamin Creek and during glacial maxima, was coextensive with the enlarged Harding Icefield. This morainal complex is made up of three distinct groups of moraines with differing topographic expression, suggesting three distinctly different ages of glacial advance. The outermost belt of moraines is made up of at least three subdued and rounded ridges that are dissected and segmented by broad channels filled with outwash graded to the moraines of the intermediate belt. Although also modified, the intermediate belt of moraines is less subdued and locally retains relatively steep-sloped ridges and a few shallow undrained depressions. In contrast, the innermost belt of moraines is essentially unmodified and is characterized by a complex of steep-sloped intersecting subparallel ridges with intervening relatively deep undrained depressions along the crests of subordinate morainal groups. Flat marshy, completely filled areas lie behind the outermost belt of moraines; two shallow lakes occupy a less completely filled area bounded by the intermediate belt of moraines; and a deeper lake, confined by steep morainal slopes, is bounded by major ridges of the innermost belt of moraines.

Major discontinuities in morainal trends are marked along the boundaries separating the three morainal belts; and in the bedrock trough leading down from the spillway col, lateral moraines of the innermost belt are overlain by at least two generations of rock-glacier deposits supplied by talus accumulations near the base of the steep valley walls. The relative differences in geomorphic expression of these moraines are of the same order of magnitude as those expressed by the moraines of Eklutna, Knik, and Naptowne age deposited elsewhere in the lowland by the major ice lobes of Cook Inlet. A high-level outwash terrace along King County Creek drainage originates along the outer boundary of the oldest continuous moraines deposited by the escape glacier and is graded to kame terraces at the upper contact of lateral moraines of Eklutna age that rim the platform surface. The outer boundary of the escape glacier's moraines crosses at sharp angles the trends of the Caribou Hills lateral moraines on the platform. These geomorphic relations emphasize a post-Caribou Hills age as well as the essential contemporaniety both of the maximum advance of the escape-glacier lobe onto the platform with the maximum extent of Eklutna ice and of the subsequent glacier advances with the maximum extents of Knik and Naptowne ice in the adjoining lowland. The rock glaciers near the upper end of the spillway trough are comparable in topographic position, sequence, and expression with rock glaciers and moraines of post-Naptowne age found in alpine valleys throughout the Kenai Mountains and are attributed to the Alaskan glaciation.

The end moraines of Eklutna, Knik, and Naptowne age and the recessional-morainal remnants of Caribou Hills age deposited by the escape glacier on the platform surface occupy an area less than 2 miles square. They were laid down in a comparable depositional environment within a restricted area and were derived from a common source area between Benjamin Creek and the Harding Icefield. They therefore provide an unusually favorable field laboratory for a comprehensive and controlled study of geomorphic features associated with the Cook Inlet morainal sequence and relating to the character and velocity of processes affecting surficial deposits in the region. Fog, rain, and high winds restricted the author's ground observations to less than 2 of the 5 days spent on the platform in 1954; so a projected statistical sampling of surface features could not be completed. However, time did permit field checking of the major morainal boundaries drawn from aerial photographs, and this resulted in some additional ground observations that lend geomorphic support to the impression of significant age differences between the major morainal groups in the region. The surface-boulder counts given in table 1 are but part of a larger plan to sample all moraines of the Skilak Lake and Killey River ice lobes as well as those of the escape glacier. Although preliminary, results are encouraging and suggest that surface-boulder counts made in selected sites, and emphasizing ratios of incompetent to competent rock types, may provide valid indices of relative age for purposes of correlation and quasi-quantitative estimates of the intervals represented between glaciations.

TABLE 1.—*Surface-boulder counts, Skilak Platform, Kenai Lowland*

Station	Glaciation	Gray-wacke-argillite	Granite	Graywacke-argillite/granite ratio	Age factor Naptowne ratio/ × ratio	Age, in calendar years, if Naptowne 20–25,000 years
1	Naptowne	117	9	13:1	1	20–25,000
2	Knik	16	3	5.3:1	×2.5	50–65,000
3	Eklutna	40	14	2.9:1		
4	do	39	13	3:1	×4.5	90–110,000
		79	27	2.9:1		
5	Caribou Hills.	95	48	2.0:1		
6	do	176	115	1.5:1	×7.7	155–190,000
		271	163	1.7:1		

The deposits in the subalpine tundra-covered escape-glacier moraines on Skilak Platform consist of coarse bouldery till with a sandy matrix containing pebbles, cobbles, and boulders made up exclusively of granite and graywacke-argillite rock types derived locally from the Harding Icefield area to the east. Dense homogeneous greenish-gray subgraywacke rock types present in small amounts in morainal deposits of the Skilak Lake and the Killey River ice lobes nearby were not found in the escape-glacier morainal deposits. Gray to dark-gray massive to finely bedded graywacke-argillite makes up the overwhelming proportion of the rock material in the escape-glacier deposits and, below the surface frost-stirred zone, seems to maintain a constant ratio to the granitic rock types in all the morainal belts. Numerous disintegrated frost-split graywacke-argillite surface boulders and a concentration of angular graywacke-argillite particles in the frost-stirred upper layer of the morainal deposits indicate that the graywacke-argillite boulders are much more susceptible to weathering in the subalpine climatic regime than the homogeneous dense granular granitic types that tend to weather by slow surface granulation and rounding of exposed surfaces. The striking and progressive increase in the proportion of granite surface boulders, from the youngest (Naptowne) to the oldest (Caribou Hills) moraines sampled, thus seems to be the direct product of differential destruction of the less resistant graywacke-argillite rock types and resultant concentration, with time, of the more resistant granitic types.

With the possible exception of the boulder sampling of the moraines of Knik age, the counts made at selected sites in roughly equivalent areas on the different moraines are believed to reasonably represent the total surface-boulder composition and concentration on the moraines. This conclusion is supported by comparable results obtained from two check counts made in separate areas on moraines of both Caribou Hills and Eklutna ages.

The major differences in the graywacke-argillite- to granite-boulder ratios on the moraines are given a quantitative expression in the boulder count. If a uniform rate of surface weathering is assumed for the time interval involved, the boulder ratios indicate that the Knik moraines may be from 2 to 3 times as old, the Eklutna moraines from 4 to 5 times as old, and the Caribou Hills moraines more than 7 times as old as the Naptowne moraines. If an age of about 20,000 to 25,000 years is assumed for the moraines of Naptowne age on the platform, as suggested by radiocarbon-dating of Naptowne end moraines of the Trading Bay ice lobe (see p. 57), the differences in the boulder ratios provide ages of ca. 50,000 to 65,000, 90,000 to 110,000, and 155,000 to 190,00 years, respectively, for moraines of the Knik, Eklutna, and Caribou Hills glaciations.

The numerical accuracy of the derived boulder ratios and their use as quantitative factors in the derivation of age in terms of calendar years may be questioned because of uncertainties connected with the representativeness of the present sampling, with the assumption of a uniform rate of weathering for the time intervals involved, and with the mean carbon-14 age of the Naptowne end moraines derived by correlation with the Trading Bay ice lobe moraines. However, the ratios do demonstrate significant age differences and roughly equal time intervals between the Naptowne, Knik, and Eklutna glaciations, and a somewhat longer interval between the Eklutna and the Caribou Hills glaciations. These relative differences conform with the geomorphic evidence found in topographic modification and boundary relations which also suggest that a longer interval of time intervened between the Caribou Hills and Eklutna than between the Eklutna, Knik, and Naptowne glaciations. Although crude, the relative age differences indicated by the boulder counts are probably of the right order of magnitude; and the derived ages, in calendar years, may be useful as a first approximation of the actual ages of the pre-Naptowne glaciations in Cook Inlet.

NINILCHIK LOWLAND

Ninilchik Lowland lies south of the Kasilof River and forms a narrow terraced coastal bench 10 to 15 miles wide and 60 to 70 miles long between Cook Inlet and the Caribou Hills. The Ninilchik Lowland is a southward extension of the Nikishka Lowland and is the product of the same glacial and glaciolacustrine history. It differs from the Nikishka Lowland by having somewhat higher average elevations, fewer lakes, and a thinner mantle of surficial deposits on Tertiary bedrock. It is characterized in its northern lowland by numerous broad muskeg-floored northeast-southwest-trending channelways that are in part occupied and in part crossed by drainage lines heading in the Caribou Hills to the east; in its southern part it is characterized by hummocky moraines of Naptowne age (fig. 4). Muskeg-covered benches locally underlain by finely stratified sand and gravel are cut into the flanks of the Caribou Hills; the most prominent benches occur at about 500- and 750-foot elevations and seem to be comparable to the proglacial-lake strandlines developed at the same elevations in the Nikishka Lowland to the north. A higher bench level lies at about the 1,000-foot contour. High-level terraces in the headwater valleys of Deep Creek are seemingly graded to this bench level and to dissected end moraines of Knik age that lie upvalley, suggesting that the bench marks a proglacial-lake-level stand during the Knik maximum.

CARIBOU HILLS

The Caribou Hills is a broad glaciated upland between Homer and Tustumena Lake that rises abruptly 1,000 to 2,000 feet above the Ninilchik and Nikishka Lowland surfaces to the west and north and 2,000 to 3,000 feet above Kachemak Bay and Fox River valley to the east and south (fig. 4). The upland includes the major part of the same dissected upland surface that is represented to the north by the Bear Creek Upland and the Skilak Platform and records in its nearly continuous mantle of morainal deposits the same glacial history. The highest levels of the dissected surface, at Ptarmigan Head (elevation 2,850 ft) and northeast of Ninilchik Dome (elevation 2,400 ft), are mantled by highly modified moraines and associated drift and are the type locality of the deposits of Caribou Hills age (Karlstrom, 1953; Krinsley, 1953). Lower upland surfaces and steep confining flanks of the Caribou Hills are plastered with lateral moraines of Eklutna, Knik, and Naptowne age deposited by the Tustumena Lake and Kachemak Bay ice lobes. During Knik and Naptowne time these lobes did not coalesce along the western flanks of the upland, but ice rose high enough in the Kachemak Bay trough to partly override the western flank of the upland in the form of ice tongues that penetrated westward into the headwater areas of the Deep Creek and Anchor River drainage lines. Downvalley from the end moraines of Knik age, in the upper reaches of the Deep Creek drainage lines, the creeks flow in deep terraced canyons; upvalley the creeks flow in shallow trenches cut below a broad muskeg-covered valley floor whose surface is graded to the end moraines of Naptowne age.

HOMER BENCH

Homer Bench is a narrow lowland surface lying between steep 500- to 800-foot-high bedrock bluffs and Kachemak Bay at the southern tip of the Kenai Lowland. Twenhofel (1952) speculates that the bench is an uplifted marine terrace. No marine fossils have been found in the alluvial sand and waterlaid blue-gray silt that underlie much of the bench surface (D. B. Krinsley, oral communication, 1958), and it is believed that the bench is of glacial origin, largely excavated during the Skilak advance of the Naptowne glaciation. The surface of the bench is largely covered by coalescent alluvial fans that descend from steep gullies in the surmounting bedrock bluff. These fans mantle deposits laid down during retreat of the same ice lobe that produced the lateral moraines near Fritz Creek, at the southwest edge of the bench, at an elevation between 400 and 500 feet.

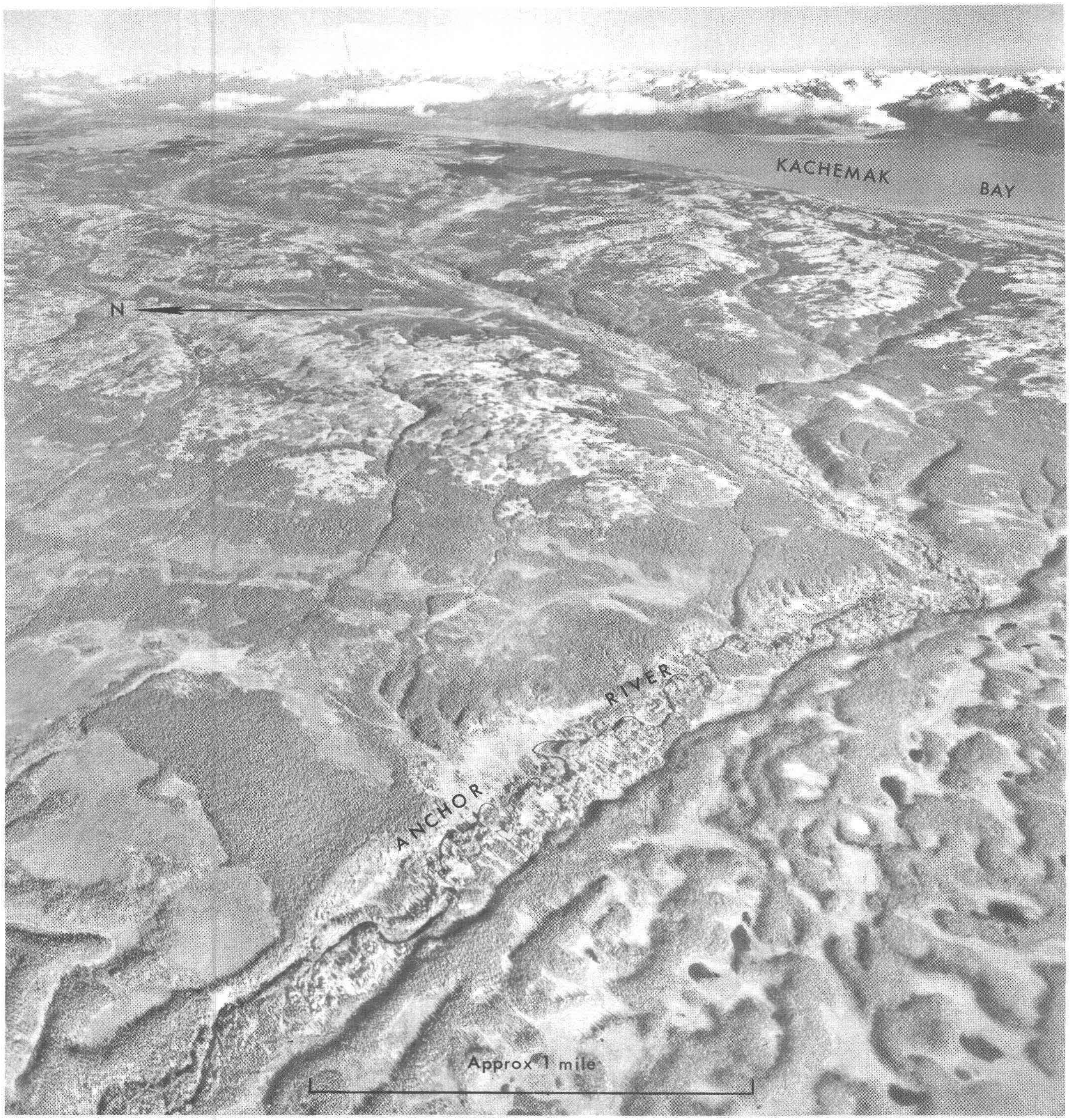


FIGURE 4.—Oblique photograph of southern part of Ninilchik Lowland near Anchor Point, Kenai Lowland, with Caribou Hills Upland in middle ground and Kachemak Bay and Kenai Mountains in the background. Anchor River marks the boundary between the hummocky surface, with muskeg- and marsh-filled depressions, of the moraines of Naptowne age in right foreground and the channeled and terraced marsh and muskeg-covered proglacial-lake floor in left foreground.

Homer Spit, one of the most conspicuous geomorphic features of the Kenai Lowland, extends out into Kachemak Bay for about 4 miles, or more than half way across the bay. The spit is made up of coarse beach and bar gravel and connects to the lowland along a sea bluff cut in till of Naptowne age. Large glacial boulders are present in the beach deposits exposed at low tide; and on its downbay side, the spit is fronted by a submerged shelf, the Archimandritof shoals. These features suggest that the spit represents a subaqueous endmorainal accumulation and that the Archimandritof shoals may be its subaqueous outwash counterpart. Bjørn Andersen examined the spit with the author in 1955 and considered it comparable in all major aspects to the numerous wave-worked convex-upvalley end moraines in Norwegian fiords. These Norwegian moraines were deposited in deep water, and during subsequent emergence they were covered by beach gravel resulting from wave sorting and reworking of the primary morainal deposits. The peculiar convex-upvalley ground plan of these fiord moraines is considered to reflect deposition and differential wave action along an ice front extending into deep water where more extensive calving takes place in the central floating part of the glacier than along its shallow-water margins where the ice is grounded. As the spit lies between end moraines attributed to the maximum extents of Skilak and Tanya ice in Kachemak Bay, it apparently marks a middle or late Skilak ice position that extended into relatively deep proglacial waters. As evidence in the Nikishka Lowland is of proglacial-lake levels below 275 feet in elevation in the period following the Skilak maximum, it is possible that Homer Spit was formed when proglacial-lake waters stood at the 50-foot, or more probably the 125-foot, strandline level.

FOX RIVER LOWLAND

The Fox River Lowland, a broad flood-plain area drained by the Fox and Bradley Rivers and by Sheep Creek, is at the head of Kachemak Bay between the Caribou Hills Upland and the Kenai Mountains. The lowland surface is everywhere below an elevation of 200 feet and locally is subject to periodic flooding by the melt-water streams that drain large glaciers in the adjoining Kenai Mountains. Near Kachemak Bay the lowland is extremely poorly drained and is underlain by tidal silt. Inland the lowland is better drained and is underlain by sand and gravel valley trains graded to recent moraines and the fronts of the mountain glaciers.

BEDROCK GEOLOGY

Kenai Lowland is in the Cook Inlet Lowland physiographic subprovince, which is a structural basin underlain by mildly deformed and undeformed semiconsolidated to unconsolidated deposits of Tertiary and Quaternary ages and bordered by alpine mountains composed of folded, faulted, and intruded consolidated rocks of Mesozoic age.

At the surface, or at shallow to moderate depths, the Kenai Lowland is underlain by the Kenai formation of Eocene age, which is composed of semiconsolidated silt, sand, and gravel and is locally coal-bearing (Martin and others, 1915; Cobb, 1951). In the southern part of the lowland the Kenai formation is probably more than 5,000 feet thick (Cobb, 1951, p. 9) and underlies a nearly continuous thin mantle of glacial drift, alluvium, and loess covering the glacially molded and stream-dissected Caribou Hills Upland. Tertiary bedrock, which is largely mantled by glacial and loess deposits throughout the Caribou Hills, is nearly continuously exposed in the sea bluffs from the head of Kachemak Bay to a point near Clam Gulch just south of the mouth of Kasilof River. The Kenai formation is mildly deformed and is locally cut by normal faults of small displacement. The regional strike roughly parallels Cook Inlet, and the regional dip is inland toward the Kenai Mountains.

North of Kasilof River the Tertiary bedrock is covered by a thicker mantle of glacial drift and alluvium and is nowhere exposed above beach level. The Richfield Oil Corp. Swanson River unit 1 well, drilled in the Nikishka Lowland and spudded on April 5, 1957, penetrated an unexpected thick section of Tertiary rock to depths greater than 11,215 feet (Kirschner, 1958).

In isolated outcrops, the non-coal-bearing zones of the Kenai formation are difficult to distinguish from similar deposits of Quaternary age that are locally made up largely of reworked Tertiary material. The most northerly exposure of bedrock of unquestionable Tertiary age is a coal-bearing section along the Kasilof River west of Sterling Highway. The presence of much clastic coal in glacial deposits exposed along the Killey River and in the sea bluffs of Turnagain Arm suggests that Tertiary bedrock may be at relatively shallow depths in these areas adjacent to the Kenai Mountain front.

Tertiary deposits have yet to be identified positively from the Bear Creek Upland area. However, it is believed that this drift-covered upland surface is underlain largely by Tertiary bedrock, as is the comparable surface of the nearby Caribou Hills. This is suggested by the similarity of topographic form and by the clastic coal in basal Pleistocene sediments locally exposed along the Killey River. Structural relations between the Tertiary formations underlying the lowland and the older formations of the nearby Kenai Mountains are not known, for the rocks are not exposed along the zone of contact. However, the geomorphology of the mountain front in relation to the known bedrock exposures closely delimits a contact whose trace strongly suggests a steep westward-dipping normal fault, with the younger Tertiary formations on the downthrow side, paralleling the mountain front. This in turn suggests that the Cook Inlet Lowland may occupy a grabenlike structure. If so, normal-fault relations should be expected along the western margin of the trough as well. Such faults have not been mapped in the region, and if present, they must be largely buried beneath Pleistocene sediments. The recent fault cutting Naptowne end moraines in the Susitna Valley, however, falls in line with the northwestern margin of the trough, as marked by the Talkeetna Mountain and Mount Susitna fronts, and records normal-fault displacement with the trough-side block down relative to the bordering mountain blocks. According to Gordon Gastil (oral communication, 1955), who ground checked the fault for the author, topographic displacement along the fault suggests a dip slip of less than 10 feet. This fault is in line with a major shear and reverse-fault zone (the Castle Mountain fault) mapped along the southern flanks of the Talkeetna Mountains and thus appears to represent recurrent recent movements along a preexisting master fault zone that at least in part borders Cook Inlet along its northwestern margin. The position of this recent tensional fault across the axis of the Susitna Valley indicates that the Susitna Lowland belongs to a crustal block tectonically separate from the Cook Inlet and Matanuska Valley block and that a thinner section of Tertiary rocks may lie beneath the Susitna Lowland than beneath the lowland areas south of and on the downthrown side of the fault.

Highly deformed, fractured, faulted, and intruded graywacke and argillite are the predominant rock types in the Kenai Mountains. They constitute a stratigraphic and structural complex containing rocks of differing ages and diverse lithologic character, mainly of poorly sorted sandstone and shale but including small amounts of chert, limestone, conglomerate, and volcanic dikes and sills. As most recently mapped (Dutro and Payne, 1957), the graywacke-argillite formations of the northern three-fourths of the Kenai Mountains are of middle and Late Cretaceous age, whereas graywacke-argillite formations in the southern one-fourth include rocks of Jurassic and Early Cretaceous age. Other rock types in the Kenai Mountains include (1) intrusive granitic masses of both Mesozoic and Tertiary age that are most abundant on the southern and eastern coasts but which are also believed to occupy a large area underlying Harding Icefield; (2) marine limestone of Jurassic age with associated chert, argillite, and volcanic rocks in the Port Graham area near Kachemak Bay; and (3) volcanic rocks interstratified with graywacke and argillite along the western front of the Kenai Mountains between Skilak Lake and Turnagain Arm. The zone of volcanic rocks interstratified with graywacke and argillite exposed north of Skilak Lake may represent the gradational contact zone between the Mesozoic volcanic rocks of probable Jurassic and Triassic age and the graywacke-argillite formations of middle and Late Cretaceous age mapped (Dutro and Payne, 1957) in the Turnagain Arm region. If so, the contact shown on plate 3 provides a previously unmapped extension of the probable Jurassic-Cretaceous boundary along the eastern margin of the Cook Inlet region and indicates a major structural transection of the volcanic and graywacke beds by the mountain-front fault. The unmapped area of granitic rock in the Harding Icefield region was early recognized (Martin and others, 1915) on the basis of abundant granitic erratic material in glacial deposits of the Benjamin Creek area. Ground observations in 1953 revealed the intrusive contact between medium- to coarse-grained granite and country rock of graywacke and argillite on a nunatak along the northern border of the icefield. The dimensions and shape of this intrusive mass are not known, but the distribution of granitic erratics derived from the icefield area strongly suggests that it is of batholithic proportions and that it underlies an appreciable part of the area covered by the icefield.

PLEISTOCENE STRATIGRAPHY

The Cook Inlet sea bluffs expose thick and nearly continuous sections of Pleistocene sediments and provide an unusually favorable opportunity for detailed study of their stratigraphic record. The sea-bluff stratigraphy of the Nikishka Lowland, along with other critical stratigraphic sections exposed elsewhere in Cook Inlet, is shown in plate 6. The bluff stratigraphy in the area between Kenai and Kasilof was described by Karlstrom (1958). Stratigraphic relations exposed in the Nikishka Lowland sea bluffs are, in general, representative of the Pleistocene deposits throughout Cook Inlet and are described briefly below.

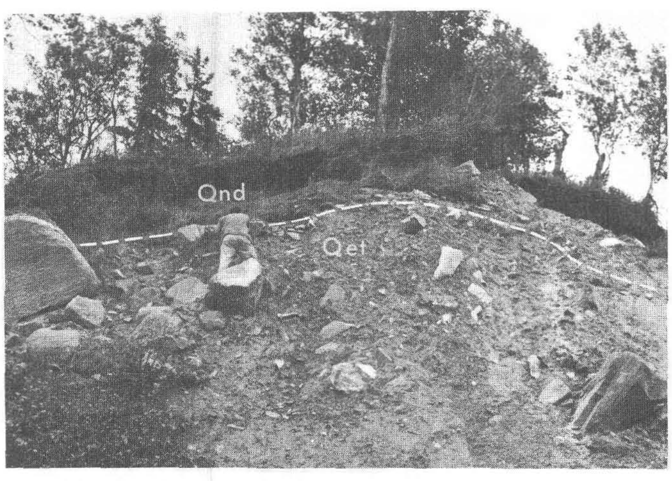
NIKISHKA LOWLAND SEA-BLUFF STRATIGRAPHY

North of Kenai the sea bluffs expose primary glacial deposits of Naptowne, Knik, and Eklutna age. These deposits are everywhere overlain by proglacial-lake sediments that in turn are overlain by bog deposits occupying poorly drained surface depressions or flats, by a thin loess mantle covering the better drained areas of the lowland, or locally—for example, near Point Possession—by thick windblown-sand deposits.

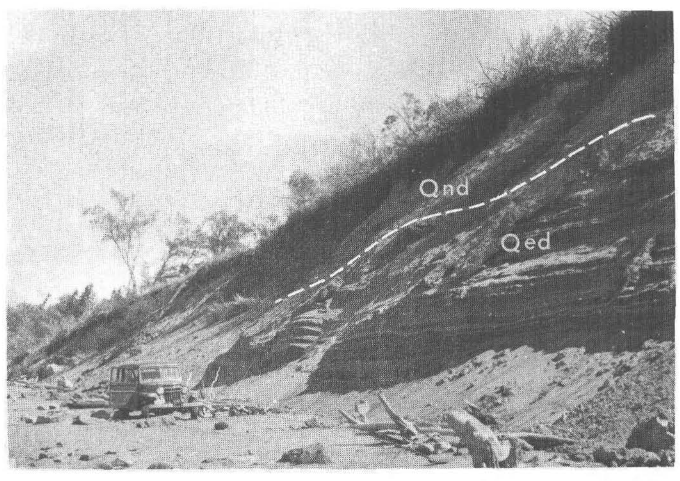
Between Boulder Point and the Swanson River (pl. 6, profile II; fig. 5 A–D), blue-gray silty boulder till and associated drift in the end moraines of Naptowne age unconformably overlie buff to gray till and associated drift in end moraines of Knik age. The till of Knik age in turn unconformably overlies deeply and uniformly stained buff to brown silt, sand, gravel, and till of Eklutna age. In front of the end moraines of Knik and Naptowne age, the older deposits are not overlain by outwash graded to the moraines; instead, they are overlain by a complex of generally fine-grained sediments underlying a dissected and terraced terrain made up of laminated silt, stratified sand and silt, and rudely stratified stony silt with scattered boulders, cobbles, and pebbles. These deposits represent two major cycles of proglacial-lake deposition accompanying the glacial advances and separated by a major period of drainage, erosion, and subaerial weathering. The uppermost unit is essentially unweathered, and the surface soil profile is commonly restricted to overlying loess of dune deposits. Locally, however, where overlying windblown sediments are thin, oxidation extends down into the proglacial-lake sediments.

Because the surficial proglacial-lake deposits unconformably overlie sediments of Eklutna and Knik age as well as till of Naptowne age and are traceable beneath the till of Naptowne age, they record nearly continuous sedimentation in a proglacial lake that existed before, during, and following the advance of Naptowne ice into the Nikishka Lowland area. The underlying unit of proglacial-lake sediments locally shows weathering profiles between 10 and 20 feet thick and records an earlier cycle of glaciolacustrine and glaciofluvial sedimentation during and following the Knik advance. Deposits attributed to the Eklutna glaciation include the deeply weathered bouldery till made up largely of completely to partially disintegrated quartz diorite boulders exposed near Swanson River (fig. 5*A*) and the stratigraphically higher deeply and uniformly limonite-stained recessional deposits of laminated silt and sand exposed near Bishop Creek that contain much clastic coal and wood but which lack boulders and cobbles (fig. 5*B*). The absence of ice-rafted boulders suggests that these sediments were deposited when Eklutna ice had largely or completely disappeared from the Cook Inlet trough and that they may be, at least in part, interglacial in age. Wood collected near Bishop Creek from near the base of the recessional deposits of Eklutna age (carbon-14 *loc.* 3)[3] gave a minimum carbon-14 date of pre-23,000 B.C. The deposits here, as elsewhere between Kenai and Point Possession, contain a rich suite of rock types including gabbro, diorite, granite, basalt, rhyolite, conglomerate, sandstone, shale, quartzite, schist, gneiss, some limestone, and graywacke-argillite. Most of these rock types are foreign to the northern part of the Kenai Mountains and are found only in the glacial deposits of the lowland west of a line marked by the interlobate moraine of Eklutna age. This indicates derivation from Talkeetna, Alaska, and Aleutian Range sources and deposition by the Susitna River, Beluga Lake, and Trading Bay ice lobes. The position of the till of Eklutna age near the Swanson River in relation to the reconstruction of ice lobation in the lowland suggests that it marks an interlobate accumulation between the Susitna River, Beluga Lake, and Trading Bay ice lobes. Large predominantly angular boulders in the deposits

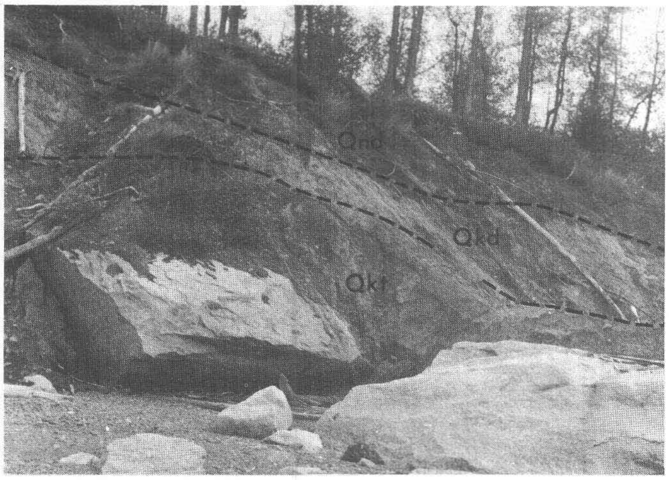
[3] All carbon-14 results discussed in this paper are listed in table 3; the locations of all carbon-14 samples are indicated on plates 1 and 4.



A. At Swanson River mouth, Nikishka Lowland.

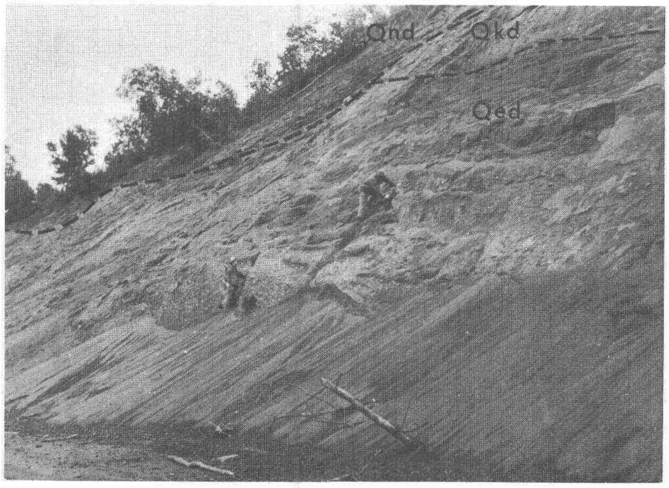


B. A quarter of a mile west of Bishop Creek, Nikishka Lowland.

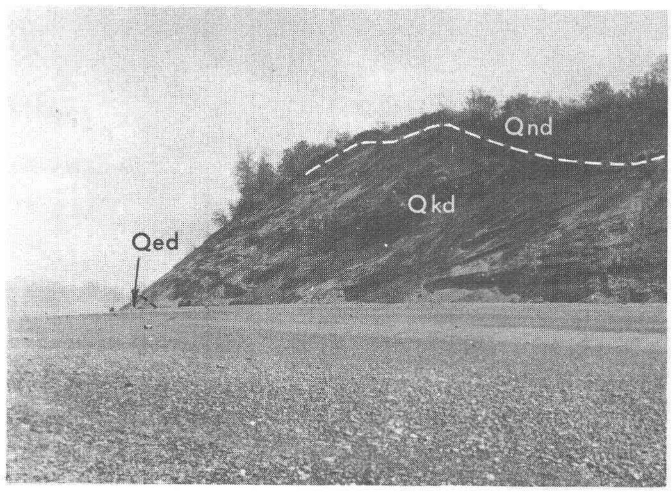


C. 2⅔ miles west of Bishop Creek, Nikishka Lowland.

D. 3¼ miles west of Bishop Creek, Nikishka Lowland.



E. Half a mile east of Point Woronzof near Anchorage.



F. At Point Woronzof near Anchorage.

FIGURE 5.—Photographs of sea-bluff exposures in upper Cook Inlet illustrating character and stratigraphic relations of glacial drift units. Qnd, unweathered gray to blue-gray stratified drift, predominantly proglacial-lake sediments of Naptowne age; Qkd, partly weathered buff to gray stratified drift, predominantly proglacial-lake sediments of Knik age; Qkt, boulder till of Knik age; Qed, deeply weathered buff to brown stratified drift of Eklutna age; Qet, boulder till of Eklutna age.

(fig. 5*A*) represent surface accumulations derived in large part from the quartz diorite pluton of Mount Susitna that stood as a nunatak above the ice surface in the lower Susitna Valley during Eklutna time.

South of the end moraine of Naptowne age at East Foreland (pl. 6, profile I) the end moraines of Knik age have been eroded, and the end moraines of the Naptowne age border a terraced and channeled sand and gravel plain that extends southward along the coast to and beyond the Kenai River.

Exposed in the sea bluffs are three main stratigraphic units. The lowest unit, attributed to the Knik glaciation, is a partly exposed section of iron-stained and contorted sand and gravel locally interbedded with blue-gray silt beds and uncomformably overlain by till of Naptowne age at East Foreland. A lignitized transported log collected from the basal 12 inches of a surface bog, and presumably derived from the underlying gravels of Knik age, dates pre-38,000 B.C. (carbon-14 loc. 4). The second unit is an intermediate section of laminated silt and finely stratified sand and gravel. It grades northward into coarser sand and gravel and is traceable to, and in part beneath, till of Naptowne age at East Foreland. The basal contact of this unit generally lies above an elevation of 100 feet, and between Nikishka No. 1 and Salamato Creek, it is characterized by a thick basal section of finely laminated blue-gray silt and fine sand that rests unconformably upon the contorted gravel unit beneath and grades upward into a predominantly fine- to coarse-grained gray sand unit with channel and scour structure. Iron staining and mottling of this upper sand unit are largely restricted to lenses and beds of gravel and seem to be largely the product of hematitic precipitation from meteoric waters. Relations with the till at East Foreland indicate that this second unit was largely deposited during the initial phases of the Naptowne ice advance across Cook Inlet to its maximum position at East Foreland. A transported log collected from the upper part of this unit dates 37,000 B.C. ± 3,000 (carbon-14 loc. 5). Another sample collected near Kenai from a somewhat comparable stratigraphic position, but somewhat closer to beach level, dates pre-22,000 B.C. (carbon–14 loc. 7). The third and uppermost unit is a thin essentially unweathered blue-gray sand and gravel unit that mantles the plain and fills channels cut into the underlying sand and gravel unit. As in the underlying unit, the mean grain size of the surface gravel and sand unit increases northward. Near Kenai it is made up predominantly of fine- to coarse-grained sand; near East Foreland it is mainly a coarse cobbly gravel underlying terraccs cut on the flanks of the end moraine of Naptowne age. This upper unit therefore appears to be largely a product of partial dissection and reworking of the underlying deposits by proglacial-lake waters during progressive lowering or oscillation of water levels following the retreat of Naptowne ice from its maximum position.

Till of Knik age is not exposed in the sea bluff south of East Foreland; it has been either completely eroded or lies below the exposed portion of the bluff section. Projection of the trends of the preserved remnants of the end moraines of Knik age south of Boulder Point toward the Salamato beach bluffs suggests that Knik ice may have reached within a mile of Salamato Creek. In the lower sand and gravel unit in this sector of the sea bluffs is a major southward-inclined overturned fold that conceivably could have been formed by the Knik advance. If so, the fold may closely mark the maximum extent of Knik ice in this locality.

Thick bog deposits occupy channels cut in the surface of the gravel and sand plain. These channels mark irregular terraced and abandoned drainage lines now occupied by a series of lakes and muskeg-filled swamps and depressions. The stratigraphy of these bog deposits exposed in the sea bluffs suggests a complex history for the channels. The thickest deposits occupy channels that are cut down through the surface sand and gravel units into the lowermost highly deformed and oxidized gravel and silt unit. Bog deposits at the north of Nikishka No. 1 are floored by contorted thin gray sand and silt layers interbedded with two peat and organic silt layers overlain by undeformed organic silt and peat sections. Deformation of the basal organic layers is more intense in the bogs near East Foreland than in correlative beds in bogs farther to the south. The lowermost contorted peat layer, as represented in the Nikishka No. 1 bog, dates 10,500 B.C. (carbon–14 loc. F–1). Bogs near Salamato Creek floor at a somewhat higher elevation and contain in their basal parts two highly contorted silt and sand beds separated by a distinct unconformity. These basal beds are unconformably underlain by more highly contorted sand and gravel and unconformably overlain by undisturbed organic lake silt and peat which, on the basis of stratigraphic position, are correlated with the contorted organic layer in bogs F–1 and F–2. Two ash layers occur in the contorted basal silt and sand bed. Wood collected from along the unconformity between the two basal beds dates pre-35,000 B.C. (carbon–14 loc. 6).

The fold pattern in the basal part of the Nikishka and Salamato bogs is not symmetrically disposed in relation to the basin contours but, in general, reflects development under differential stress directed roughly southward. This seems to exclude formation under local basin-environmental conditions such as those owing to melting out of ice blocks (glacial ice or permafrost), to centripetal slump toward the axes of the basins as a consequence of differential compaction, or to frost action, and strongly suggests deformation by ice shove or ploughing of marginal sediments during repeated glacial advances of the Trading Bay ice lobe. If this is so, the Salamato bog channels were largely developed and deformed within a proglacial-lake environment during the maximum Knik advances, and the Nikishka No. 1 bogs, during the Naptowne advances. As recorded at both Boulder Point and East Foreland, the deposits of the Naptowne end moraines are also deformed, suggesting that post-Naptowne maximum readvances are involved in the deformation of the marginal sediments. The undisturbed organic sediments in the upper parts of all the bogs near East Foreland and Boulder Point thus should postdate the retreat of Naptowne ice well across the inlet from Boulder Point and East Foreland and the drainage of proglacial-lake waters below the general level of the sand and gravel plain.

From the Swanson River north nearly to Point Possession (pl. 6, profiles II, III, IV, and V) the sea bluffs transect a series of coastal terraces, generally less than 125 feet in elevation, underlain by a series of proglacial-lake-bottom sediments. These sediments are made up largely of rudely stratified blue-gray stony silts interstratified and interfingered with finely laminated sand beds and, locally, with crossbedded gravel beds. The stratigraphy along this coastal section, like that west of the Swanson River, records two major cycles of proglacial-lake sedimentation separated by a major unconformity and, locally, by a weathered profile. The buried profile records a significant interval of subaerial weathering and has been largely removed by erosion that preceded or accompanied deposition of the overlying proglacial-lake sediments.

The deposits of Naptowne age are mainly unweathered and are largely made up of blue-gray stony silts that show initial dip relations to the irregular erosional surface cut into the underlying proglacial sediments of Knik age. During early mapping in the area these stony silts were mistaken for till. More detailed inspection of the sea-bluff stratigraphy indicated that much of the apparent unsorted aspect of the sediments was the product of fine slump veneers that accumulate quickly on the bluff faces and tend to obscure the fine and continuous stratification relations and initial dip that exist in the unmantled sediment. Both horizontally and vertically, the massive to crudely stratified stony silt beds grade into, and interfinger with, well-stratified sand, silt, and gravel facies. Locally, the interrelated sand beds and lenses contain armored clay balls that definitely indicate a subaqueous origin. Deformational features in the sediments are rare, of small scale, and generally are most readily explained as the product of differential compaction or of subaqueous slump or iceberg drag (penecontemporaneous deformational features). Lag concentrations of sand, sand and gravel, or boulders commonly form a surface veneer beneath terrace surfaces and in channels cut into the lowland surface and record reworking of the finer grained lake-bottom sediments by wave and stream action accompanying and following drainage of the proglacial lake. Scattered boulders occur in the stratified sand and silt beds as well as in the generally more poorly sorted stony silt beds and represent either ice-rafted material dropped into the proglacial lake from icebergs or lake-ice or slump material that slid into the lake from nearby higher ground.

The underlying proglacial-lake sediments of Knik age are comparable in most details with the sediments of Naptowne age. Locally, however, they retain buried weathered profiles as much as 20 feet in thickness and in general, contain a larger percentage of stratified sand and gravel. The proglacial-lake sediments of Knik age are predominantly of stratified sand and gravel near the end moraines of Knik age. At an appreciable distance from the end moraines—for example, near Gray Cliff—the sediments are finer grained stony silts. This lateral change toward coarser, better sorted facies of the sediments adjacent to end moraines thus seems to reflect proximity to melt-water supplies and deposition by stronger transporting currents adjacent to the ice fronts. Near Point Possession these sediments are traceable beneath till of Knik age where locally they unconformably overlie older sediments attributed to the Eklutna glaciation.

Southeast of Point Possession (pl. 6, profile V) the Turnagain Arm sea bluffs expose a thick section of drift underlying an irregular terraced surface that lies generally between elevations of 125 to 150 feet. Till and associated drift attributed to the Knik glaciation constitute the dominant stratigraphic unit in the bluff, and they are divided into three main subunits. The lowest subunit is stratified blue-gray to gray sand and gravel that thickens northwestward and, near Point Possession, includes stony silt and laminated blue-gray silt beds. The intermediate subunit is bouldery sandy silt till that is traceable nearly continuously from beach level near Chickaloon Bay to the top of the bluff near Point Possession. The top subunit is stratified sand and gravel, predominantly fine to coarse sand, that overlies the till in part conformably and in part unconformably. These deposits of Knik age are deformed into broad flexures locally cut by high-angle faults. A profile of weathering, suggested by buff staining of the deposits, is largely restricted to the upper part of the top subunit of stratified sand but penetrates the underlying till where it occurs near the top of the bluff near Point Possession. Stratigraphic relations along the base of the till suggest no major depositional hiatus, and the underlying stratified deposits are considered to represent glaciolacustrine and glaciofluvial deposits laid down during the advance of the Turnagain ice lobe of Knik age into the northern part of the Nikishka Lowland. The overlying sediments are mainly finely stratified and show coarser grained marginal facies and initial dip relationships to the irregular partly eroded upper contact of the till unit. They are considered to represent sedimentation in the proglacial lake that existed during retreatal phases of the Knik glaciation.

The sediments of Knik age unconformably overlie deeply ironstained deposits attributed to the Eklutna glaciation near Point Possession and are unconformably overlain by blue-gray stoney silt beds that occupy depressions cut into the weathered sediments of Knik age. These basin accumulations of stratified stony silts are comparable to the surface sediments exposed elsewhere in the lowland that were deposited in the proglacial lake of Naptowne age. Their presence here along the coast, combined with the absence of recognizable end moraines or till of Naptowne age in the Turnagain Arm section of the Nikishka Lowland, indicates that during its maximum extent the Turnagain ice lobe of Naptowne age must have fronted somewhere northwest of the present coastline. Whether the deformation of the Knik and older deposits in the sea bluffs represents ice-shove by the near approach of Naptowne ice, or by an earlier advance during the general retreat of Knik ice from the lowland, is not known. Development by regional tectonic forces is considered unlikely because the deformation of the Pleistocene sediments is restricted to the area of the end moraines of Knik age and is not evident in sediments of comparable age exposed in the sea bluffs to the southwest.

Bog deposits buried beneath thick dune deposits at the top of the bluffs record organic accumulations in depressions on the proglacial floor after final drainage of lake waters below an elevation of about 125 to 150 feet. In contrast to the rich suite of rock types in the glacial deposits southwest of Point Possession and derived chiefly from Talkeetna Mountain and Alaska Range sources, the deposits southeast of Point Possession are predominantly made up of graywacke-argillite, granite, and greenstone rock types derived from local sources in the Kenai and Chugach Mountains to the east. Much clastic coal in these sediments suggests the presence of Tertiary bedrock at relatively shallow depth in the lowland between Point Possession and the Kenai Mountain front.

DISTRIBUTION AND CHARACTER OF THE SURFICIAL DEPOSITS IN THE NIKISHKA LOWLAND

Inland from the coast, observations on the surficial deposits are restricted to natural exposures along drainage lines and to artificial exposures in roadcuts and in numerous trenches dug through the loess mantle at selected stations throughout the lowland. In general, the deposits in these relatively shallow exposures belong to three main stratigraphic units. They are (1) the thin, nearly continuous surficial mantle of loess and, locally, thicker deposits of windblown sand; (2) the proglacial-lake sediments of Naptowne age made up of a variable thickness of essentially unweathered blue-gray to gray stratified gravel and sand, laminated silt and sand, and massive to rudely stratified stony silt that nearly everywhere underlies the loess mantle of the lowland; and (3) a complex of older sediments including buff to gray till and ice-contact glaciolacustrine and glaciofluvial deposits that unconformably underlie either loess or proglacial-lake sediments, or both.

LOESS MANTLE

The loess mantle throughout the lowland ranges in thickness from a film to more than 6 feet but is generally from 2 to 4 feet thick. It is composed of well-sorted windblown material predominantly of silt size. A well-developed but generally shallow podzolic soil profile developed in the loess characteristically has a thin gray leached A horizon and a red-brown, red, yellow, or buff iron-stained B horizon that grades downward into unoxidized olive-drab to gray sediment. Throughout the lowland the deposits are devoid of detectable amounts of calcium carbonate, and the depth of oxidation provides the main field criterion for determination of depth and intensity of soil development. Throughout the lowland the depth of podzolic soil development below the vegetation mat varies somewhat from place to place, depending on vegetal cover, topographic position, character of the underlying materials, and depositional history; but nearly everywhere it is between 2 and 5 feet deep and most commonly terminates above the base of the loess mantle. In contrast, soil development in the thinner loess deposits overlying moraines of post-Naptowne age in the lowland and in valleys of the adjoining Kenai Mountains is much shallower; in fact, everywhere observed it is less than 1 foot deep.

At many places the loess is highly frost churned, and extreme contortions are outlined by the podzolic and other soil horizons as well as such basal reference beds as the volcanic ash. Examples of deformation by frost action are shown in figures 6 and 7. Near bluff margins the loess deposits tend to thicken and locally they contain several buried soil profiles separated by windblown sand or silt, recording a multiple cycle of wind deposition. Wood collected from a culture layer buried beneath 6 inches of loess in the Kenai-Kasilof area (carbon-14 loc. H) dates A.D. 1500±200 years.[4]

PROGLACIAL-LAKE SEDIMENTS OF NAPTOWNE AGE

The most significant generalizations that can be made concerning the distribution and character of the proglacial-lake sediments underlying the loess are as follows:

1. They disconformably underlie the loess mantle over much of the lowland, and where the loess is thicker than the depth of soil development, they are unweathered. This suggests that loess deposition essentially began immediately after cessation of proglacial-lake deposition as a product of wind action on the newly emerged and unvegetated bottom surfaces. Locally, lag deposits of wind-polished pebbles occur along the basal contact of the loess, indicating deflation prior to wind deposition.

[4] Skepticism expressed by the author as to the validity of the carbon-14 results from this sample in the description published by Broecker and others (1956) relates to an earlier unpublished result of less than 350 years and not to the age of 450 ±200 years B.P. (Before Present) as finally published. The published date seems fully consistent with the tree-ring, botanical, and geologic data relating to the archaeological site.

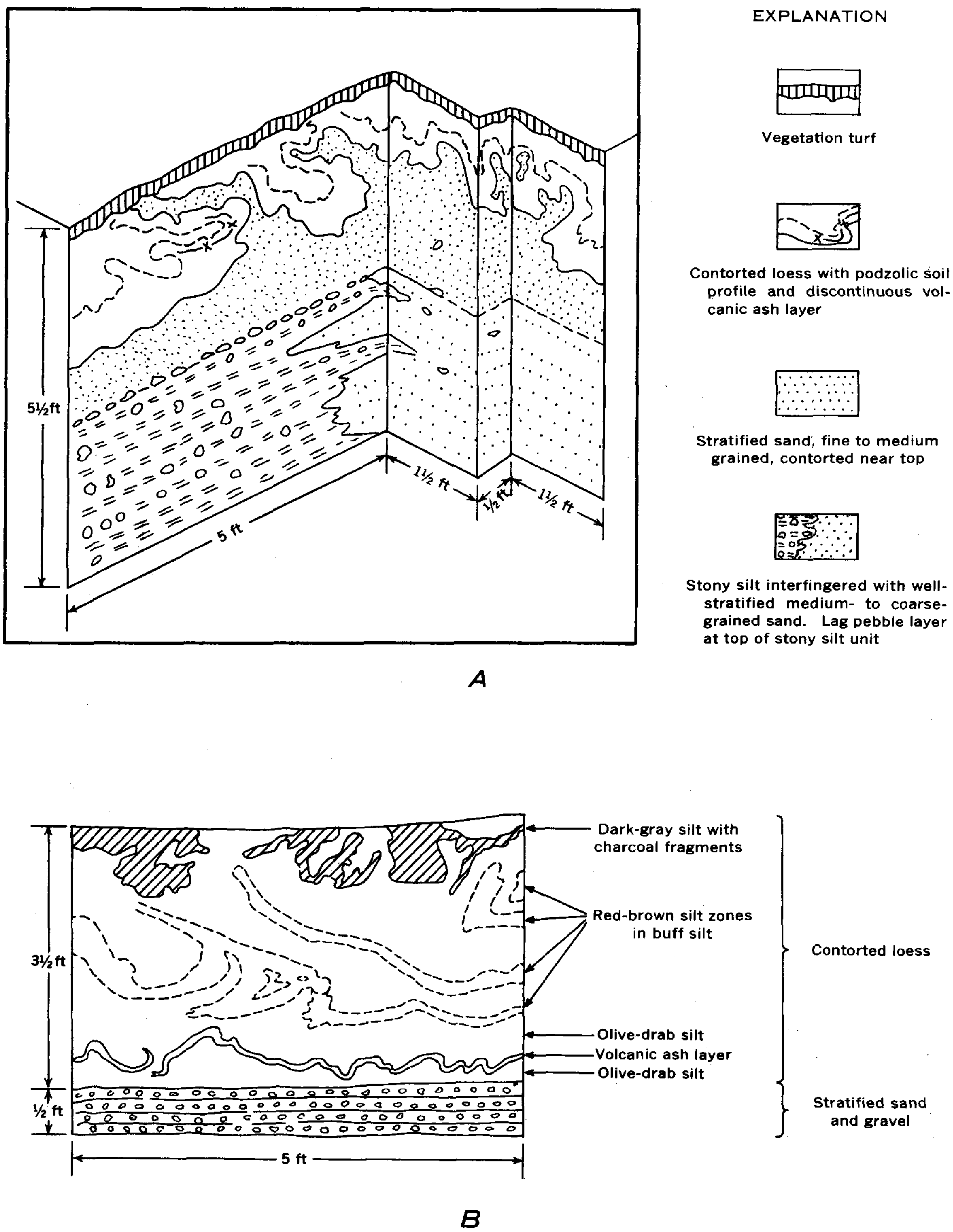
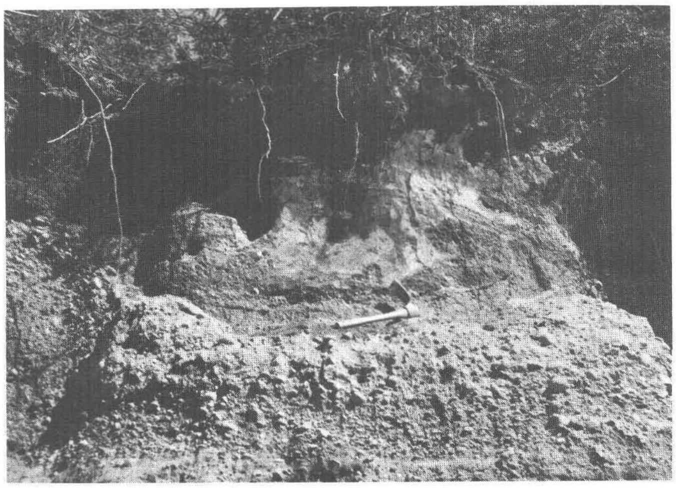


FIGURE 6.—Field sketches of frost-contorted loess overlying proglacial-lake sediments of Naptowne age as exposed in hand-dug trenches. *A*, 3⅜ miles north-northwest of confluence of west fork of Moose River with Moose River, 4½ miles northeast of Moose River bridge, Sterling Highway; *B*, near Naptowne Lodge on Sterling Highway.



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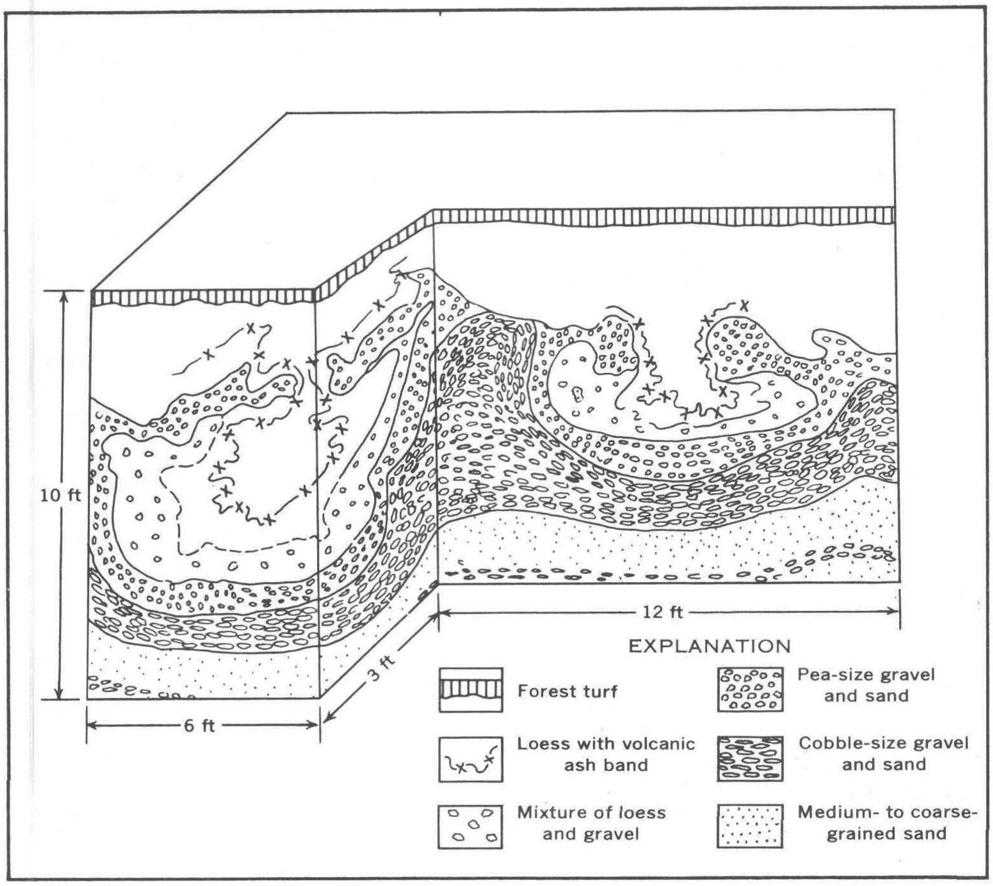
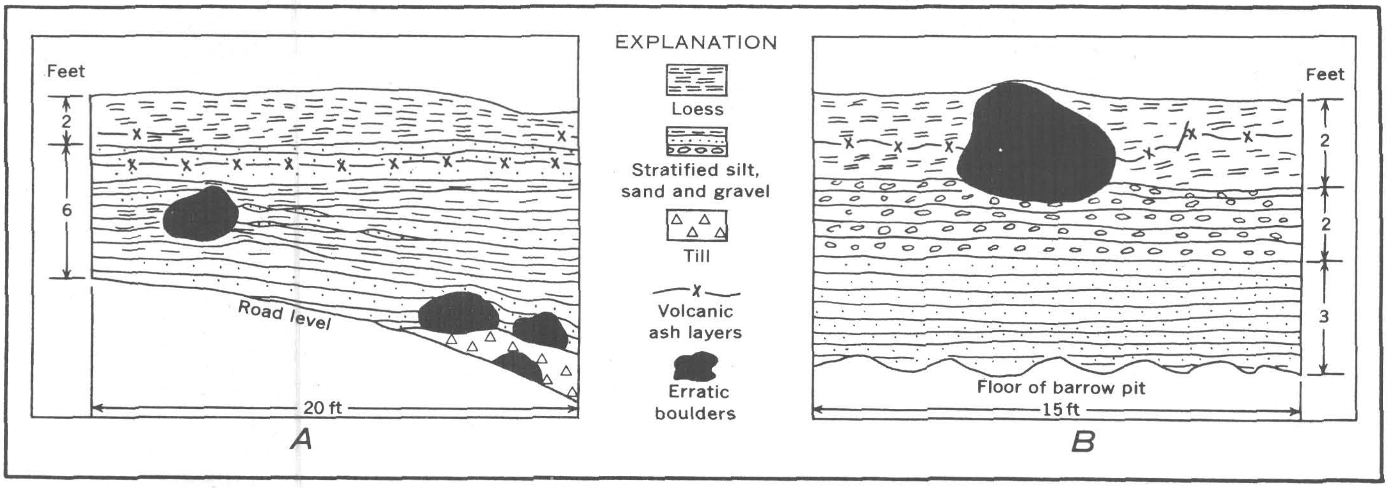


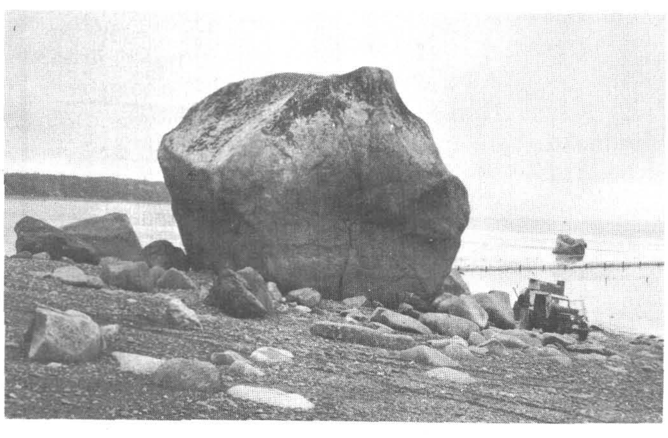
B

FIGURE 7.—Frost-contorted loess in sea bluffs 3 to 3½ miles north of Salamato Creek, Nikishka Lowland, Alaska. *A*, Detailed view of loess body intruded downward into stratified sand and gravel; *B*, three-dimensional field sketch of downward intruded loess bodies, including the one shown in *A*.

2. The deposits are extremely variable in mechanical composition, ranging from coarse poorly to well-sorted sand and gravel beneath strandlines to finely laminated silt and sand deposits commonly interstratified with stony silt beds. The silt and sand deposits are thickest in the low areas between the major morainal belts in the lowland but are also present in the form of finely laminated (varved?) silt and sand on the flat summit areas of the morainial ridges as high as 400 to 500 feet in elevation. In local exposures, the deposits can be traced continuously over the tops of buried morainal ridges, indicating that the water body in which they were deposited stood higher than the elevation of these ridges.
3. In general, the deposits are coarser grained near end moraines of Naptowne age (melt-water sources) and are progressively finer grained in outlying areas of the lowland.
4. They show initial dip relations to underlying contacts, are thickest in depressions, and thin laterally through coarser grained and interbedded facies where underlying deposits rise high in the exposure.
5. Large boulders and cobbles are commonly concentrated along the unconformity cut into underlying deposits, particularly where these deposits are of till or stony silt, and are either completely or partly buried by the proglacial-lake sediments (fig. 8*A*). Other boulders and cobbles are completely en-



A, *B*, Field sketches of exposures in Nikishka Lowland illustrating stratigraphic position of erratic boulders in relation to proglacial-lake sediments. *A*, Roadcut on moraines of Knik age approximately 1¾ miles due south of Boulder Point. Elevation between 250 and 300 feet. *B*, Borrow pit on south side of Sterling Highway about half a mile northeast of Soldotna. Elevation between 150 and 200 feet.



C, Granitic boulders on beach near Boulder Point, Nikishka Lowland. Boulders either represent material washed out of till of Naptowne age exposed in nearby sea bluffs or ice-rafted material dropped during retreat of Naptowne ice from Boulder Point.

FIGURE 8.—Field sketches and photograph illustrating stratigraphic position of erratic boulders in deposits of Nikishka Lowland.

closed in the water-laid sediments and indicate penecontemporaneous deposition either because of short gravity transport downslope from nearby higher ground or because of ice rafting (fig. 8).

6. In numerous exposures a distinctive discontinuous ash layer, commonly associated with a brownish organic layer that lies slightly higher stratigraphically, occurs in the upper part of the water-laid deposits (figs. 6, 7, 8). This ash and the associated brown layer have been found only in exposures underlying surfaces above 200 to 300 feet in elevation. Deposits containing these distinctive reference beds are exposed in roadcuts along the Sterling Highway at elevations between 300 and 350 feet, overlying till of Moosehorn and Killey age; at elevations between 250 and 450 feet, in the deposits mantling the morainal belts of Knik and Eklutna age between the settlement of Sterling and the Kasilof River and north to the Swanson River along the oil-well access road; in hand-cut trenches above an elevation of 250 feet in deposits mantling moraines of Naptowne and Knik age just south of Boulder Point; and above an elevation of 300 feet in deposits mantling moraines of Eklutna and Knik age in the northern part of the lowland. From the distribution and elevation of these reference beds in water-laid deposits, it is evident that a volcanic-ash fall occurred in the region during a time when proglacial-lake levels were higher than 400 feet in elevation but prior to retreat of Naptowne ice from the end moraines of Skilak age, as these moraines lie at lower elevations and are not covered by proglacial-lake sediments. Ash underlying stratified sand and gravel has been reported from the surficial deposits of the end moraines of Naptowne (Killey) age near Anchor Point at an elevation of 250 to 300 feet but has not been found on the younger Naptowne deposits in the Homer area (D. B. Krinsley, oral communication, 1958). The ash and associated brown band were observed by the author in proglacial-lake sediments between elevations of 200 and 250 feet in a roadcut south of the Nikishka Lowland near Clam Gulch and in stratified sand and gravel that unconformably overlie kame deposits in the Anchorage area at an elevation of 200 to 250 feet in a gravel pit on the Seward Highway near O'Malley Road. The author believes that these ash-bearing water-laid sediments in the Ninilchik Lowland and in the Anchorage area, as they occur in comparable stratigraphic sequences, record the same post-Moosehorn, pre-Skilak ash fall that is recorded in the Nikishka Lowland and provide a further demonstration of the regional extent of the proglacial lake.

7. The deposits include numerous diastems, disconformities, unconformities, pavement layers of wind-polished pebbles and cobbles, and locally one or more organic layers which mark depositional hiatuses and record short-term oscillations of lake levels.

8. Where observed throughout the lowland, the deposits are not significantly deformed, indicating development and preservation within a relatively stable depositional and postdepositional environment. Local minor deformational features appear to have resulted from such processes as differential compaction, subaqueous slump, congeliturbation, or iceberg dragging. Major deformational patterns suggesting deposition under, alongside of, or over large melting glacier-ice blocks have not been found in the deposits.

9. The deposits mantle the flanks and summits of morainal belts of the Eklutna, Knik, and the older Naptowne advances in the lowland. They occupy interridge depressions and locally bury till ridges in Naptowne moraines of Moosehorn and Killey age but are absent on the moraines of Skilak and younger age, which are capped only by loess.

The distribution and character of these water-laid deposits throughout the Nikishka Lowland are consistent with the geomorphic evidence of a proglacial lake environment throughout the upper part of Cook Inlet region during the Naptowne glaciation and provide additional information concerning the history of this lake. The complex history of lake-level fluctuations suggested by the multiple terrace levels in the lowland is, in general, confirmed by the numerous diastems in the proglacial-lake sediments that record significant but short-term hiatuses in the depositional sequence. The detailed correlation of individual diastems exposed with particular terrace levels has not been done and must await more detailed mapping in the area. Nonetheless, the general distribution of the sediments overlying all the pre-Skilak moraines of the lowland to elevations of over 400 feet and their absence on moraines of Skilak and later ages agree with the fragmentary strandline evidence of higher lake stands at 750 and 500 feet during Moosehorn and Killey time and lake stands at about 275 feet and lower during and following the Skilak maximum. The apparent absence below an elevation of about 50 feet of ash commonly present at higher elevations in the basal part of the overlying loess in turn indicates that a volcanic eruption and ash fall occurred prior to final recession of proglacial-lake waters from about the 50-foot strandline level.

OTHER GLACIAL AND RELATED DEPOSITS

Deposits exposed locally beneath loess or proglacial-lake sediments of Naptowne age on the Nikishka Lowland inland from the coast include till and ice-contact glaciolacustrine and glaciofluvial deposits of Naptowne to Eklutna age.

Till of Naptowne age is exposed in roadcuts along Sterling Highway between Naptowne Lodge at Sterling and the Kenai Mountain front. As exposed in these roadcuts, morainal till of the Moosehorn advances is an olive-drab to grayish sediment with a sandy silt matrix and an overwhelming predominance of discoidal to tabular pebbles and cobbles of graywacke and argillite, some graywacke-argillite boulders, and a few pebbles and cobbles of subgraywacke and granite. Morainal tills of the Killey, Skilak, and Tanya advances are coarser grained, grayer in color, and contain a small but somewhat higher percentage of granitic-rock particles than the till of Moosehorn age. The predominance of well-rounded discoidal and tabular pebbles and cobbles of graywacke in the moraines of Moosehorn age, similar in size and shape to the material in the Skilak Lake modern beach deposits, suggests that the Naptowne ice overrode comparable beach deposits in its advance to its maximum position. Weathering on these four belts of moraines is comparable, and a podzolic soil profile from 2 to 5 feet thick is generally restricted to the loess and proglacial-lake sediments overlying the till. Surface boulders of both graywacke-argillite and granite types show little or no evidence of weathering or disintegration. Deep cuts made through the pre-Skilak interlobate moraine by the new cutoff road through Jean Lake valley at an elevation of about 500 to 550 feet expose contorted laminated buff lake silt underlying unweathered basal till of Naptowne age. The degree of weathering in these lake silts suggests that they are of late Knik rather than early Naptowne age. If so, this means that a high-level lake stand persisted in the region relatively late in Knik time and that the proglacial lake generated by the Naptowne glaciation did not rise higher than 500-foot elevation until after the Jean Lake and Skilak Lake ice lobes coalesced outside the boundaries of the Kenai Mountains and began building the interlobate moraine which crests between 600 and 650 feet in elevation.

Along the new road alinement of Sterling Highway east of Jean Lake, thick sections are exposed in roadcuts through moraines of the Tanya advance. Till beneath these moraines is extremely coarse and gravelly, and in the basal zone it contains transported blocks of extremely contorted lake silt. The till stands in near vertical contacts with highly contorted lake sediments, recording readvances of Naptowne ice during Tanya time in a small marginal lake that was dammed between the ice front and the valley-floor divide (550–600 ft. in elevation) during the late Naptowne deglaciation of Jean Lake valley. The marginal glacial lake in Jean Valley was but part of a much larger ice-dammed lake system that occupied the upper Kenai River valley system in late Naptowne time.

River bluffs along the Killey River locally expose thick sections of glacial drift underlying moraines of Naptowne age. The Naptowne moraines of the Killey River ice lobes were deposited generally above the level of proglacial-lake waters and are veneered by a 1- to 6-foot-thick loess mantle that directly overlies bouldery unweathered till. The till is typically olive drab to gray in color, has a sandy silt matrix, and contains pebbles, cobbles, and boulders of graywacke, argillite, subgraywacke, and granite rock types. A well-defined podzolic soil is developed in the overlying loess; and where the loess is thin, the soil extends a short distance into the underlying till. Soils developed on the moraines of the Skilak advance are from 2 to 4 feet deep, or similar to those developed in the surficial deposits throughout the Nikishka Lowland. Partly exposed river-bluff sections observed along the Killey River record at least one, and probably two, older drift units made up of till and associated fluvial and lacustrine deposits. These deposits are locally deeply iron stained and weathered and are separated by major erosional unconformities. In the absence of more complete sections, the age and number of pre-Naptowne glaciations recorded in the sediments remain uncertain, but it is likely that the lowermost drift exposed in the bluffs is at least as old as Eklutna age. Locally, the lowermost deposits exposed along the Killey River contain much clastic coal, suggesting the presence of Tertiary bedrock at relatively shallow depth within the valley.

A thick section of glacial drift underlying morainal deposits of Naptowne age is exposed in Indian Creek valley at the head of Tustumena Lake. Here, the till of Naptowne age is an extremely coarse gravelly bluish-gray to gray sediment made up predominantly of cobbles and boulders of graywacke-argillite, subgraywacke, and granite rock types. The till is generally overlain by 1 to 3 feet of loess. A podzolic soil profile, generally 2 to 4 feet thick, is developed on the surficial deposits in the area. As exposed locally in the river bluffs, the unweathered till of Naptowne age unconformably overlies more than 100 feet of coarse gravelly till or channel gravel that is yellow buff to brown in the upper 50 feet and olive drab and bluish gray in the lower 50 feet. Limonitic staining of matrix and weathered particles in the upper part of the section grades through a mottled yellow and grayish zone into the underlying unweathered and unstained zone. In character and depth of weathering, these buried deposits are similar to those of Eklutna age exposed elsewhere in the region, so they are provisionally considered to be of Eklutna age. If this assignment is correct, as Knik as well as Naptowne ice unquestionably overrode this area, erosion must have removed deposits of Knik age as well as a part of the upper zone of the deposits of Eklutna age prior to deposition of the overlying till of Naptowne age.

Compacted slightly deformed and iron-stained silt and sand containing fragments of twigs and clastic coal are exposed at beach level in a wave-cut bluff at the north corner of Tustumena Lake (carbon–14 loc. 8). These sediments, presumed to be of Knik age, are overlain by blue-gray and gray laminated silt and stratified sand and gravel comparable to sediments associated with till of Naptowne age exposed nearby. Twigs and wood fragments collected from the basal sediments gave a date of pre-30,000 B.C. (W–76).

Till attributed to the Knik glaciation, and underlying 5 to 15 feet of proglacial laminated sand and silt, is exposed in a roadcut just west of Moose Creek. The till is composed of olive-drab to gray sandy and gravelly sediment with numerous rounded pebbles, cobbles, and boulders of graywacke, argillite, subgraywacke, and granitic rock types derived from the Kenai Mountains. It is in contact on the west with a buried section of deformed and faulted interbedded silt, sand, and gravel that indicates stress from the east. The overlying undeformed proglacial-lake sediments are slightly cemented with silica and are overlain by about 2 feet of loess with a podzolic soil profile and, locally, an ash layer near its base. The till is considered to be of Knik age because it underlies the outer boundary of the end-morainal complex of Knik age as defined geomorphologically, because the associated outwash suggests deformation in front of a westward-advancing ice front, and because the till contains Kenai Mountain lithologies whereas the deposits immediately to the west and associated with the Eklutna interlobate moraine are characterized by a mixture of rock types derived from eastern as well as western sources.

Deep roadcuts in the interlobate moraine of Eklutna age, where crossed by Sterling Highway and the oil-well access road, locally expose till, highly deformed ice-contact deposits, stony silt, undeformed stratified silt, sand, and gravel unconformably below a mantle of loess and the undeformed proglacial-lake sediments of Naptowne age. This older complex of sediments in general occurs at shallower depth along the flanks and near the tops of the modified morainal ridges and lies at greater depth in the broad flat poorly drained areas between the terraced ridges. Large erratic boulders are commonly concentrated along the upper contact of the stony silt and till facies and are either completely or partly buried by the overlying sediments. These boulder concentrations at or just beneath the surface are thus most commonly seen in construction operations on steep ridge slopes, near the top of ridges, and on the faces of terrace scarps where the overlying deposits are thinnest. The primary glacial deposits exposed in the interlobate moraine are considered to be of Eklutna age because they lie beyond the boundaries of the subsequent glaciation and thus must have been deposited prior to the Knik glaciation. The overlying and associated proglacial-lake sediments probably include deposits of both Eklutna and Knik age. With the possible exception of a buff-colored unsorted bouldery sediment (stony silt or till?) exposed in a pit at the well site near the Swanson River, none of the older sediments observed elsewhere within the Eklutna moraines show the deep-weathering characteristics that are seen in sediments of Knik and Eklutna age exposed locally along the sea bluffs. This is probably attributable in part to the shallow depth and paucity of available exposures and in part to the fact that, where exposed, erosion as marked by the overlying unconformity has largely or completely removed the weathered upper zone of the older sediments.

CORRELATION WITH THE TYPE-SECTION DEPOSITS OF THE EKLUTNA AND KNIK GLACIATIONS

Stratigraphic evidence for two pre-Naptowne glaciations was first recognized by the author in river-bluff exposures along the Eklutna River north of Anchorage and in sea-bluff exposures along the northwestern shore of Knik Arm. At both localities, two drift units, including till and associated glaciolacustrine and glaciofluvial deposits, underlie surficial till of Naptowne age; and at both, the lowermost drift unit is a deeply and uniformly limonite-stained, yellow-buff to buff unit 50 to 100 feet thick unconformably overlain by a moderately oxidized unit, which in turn is overlain unconformably by the surface drift with a relatively shallower weathering profile. On the basis of stratigraphic position and relations to regional morainal boundaries, the lowermost drift is correlated with the third oldest set of moraines of the Eklutna glaciation, named from the exposure in the Eklutna Valley. The intermediate drift unit of the Knik glaciation, as defined from the exposures along Knik Arm, is post-Eklutna and pre-Naptowne in age.

TYPE SECTION OF DRIFT OF THE EKLUTNA GLACIATION

The type-section drift of the Eklutna glaciation is exposed in an approximately 150-foot-high bluff along the Eklutna River 1½ miles west of the Eklutna Lake outlet (pl. 6, profile VIII).
The section is as follows:

Post-Naptowne and Naptowne glaciations
- 2–4 ft loess; podzolic soil development; buff to brown near top, grading down into olive-drab silt. Depth of oxidation 3–4 ft.

Naptowne glaciation
- 2–15 ft stratified gray sand and gravel; recessional outwash and terrace gravel.
- 0–25 ft olive-drab till with sandy silt matrix, sand pebbles, cobbles, and boulders of graywacke-argillite, granitic, and greenstone rock types.
- 10–30 ft gray stratified sand and gravel ranging from cobble to pebble size and locally containing well-stratified beds of coarse- to fine-grained sand; advance outwash or proglacial-lake sediments.

Unconformity

Knik glaciation
- 30 to 50-ft section, in large part mantled. Buff weathered bouldery till exposed locally near top. As much as 30 ft of blue-gray to gray laminated sand and silt exposed near bottom. Middle part mantled. Nature of the contact between till and underlying lake sediments not known.

Unconformity

Eklutna glaciation
- 40–60 ft of yellow-buff crudely to well-stratified cobbly gravel and sand; weathered recessional outwash.

The measured section lies between the 760- and 900-foot contours. Upstream, local bluff exposures show the lower section of drift of the Eklutna glaciation and the upper section of till and associated drift of Naptowne age. The middle section in these exposures, however, is made up of a series of blue-gray laminated silt and sand beds with locally some layers of brownish buff sand and gravel; the till of Knik age is missing. Thus, it seems that the till of Knik age was locally removed from the Eklutna Valley prior to deposition of the sediments of Naptowne age.

EXPOSURES OF DEPOSITS OF EKLUTNA AGE IN THE ANCHORAGE AREA

Observations on the character of the deposits underlying the lateral moraines along the flanks of the Chugach Mountains south of Eklutna River have been made by the author along Ski Bowl Road near Ship Creek and along roadcuts near Rabbit Creek. Another critical exposure has been mapped in the upper canyon of Campbell Creek by Miller and Dobrovolny (1959, p. 21).

A deep roadcut through a lateral-morainal ridge of Eklutna age is present along Ski Bowl road at an elevation of about 650 feet. The exposed section is interpreted as follows:

Post-Naptowne and Naptowne glaciations
- 2–3 ft loess, with podzolic soil profile extending locally below base into underlying sediments.

Naptowne glaciation
- 1–2 ft gray stratified pebbly and cobbly gravel with a slight iron staining locally at top.
- 2–6 in. of blue-gray finely laminated silt; proglacial-lake sediments.

Eklutna glaciation
- 15 ft of buff to brownish buff coarse bouldery till with pebbles, cobbles, and boulders of graywacke, argillite, greenstone, and granitic rock types predominantly, but with a few poorly consolidated sandstone cobbles of Tertiary age. A lag concentration of larger size particles at top of till suggests erosion and removal of finer grained materials prior to deposition of overlying laminated-silt unit.

Disconformity
- 15+ ft of ~~buff~~ to brownish buff fractured and jointed laminated silt; fracture planes coated with brown iron-oxide films; proglacial-lake sediments.

The lateral moraines which flank the front of the Chugach Mountains are terraced and generally mantled with thin deposits of loess and, locally, with water-laid gravel, sand, and finely laminated silt. In contrast to the deep and uniform brown coloration and iron staining of the underlying coarse till and fine-grained lake silt, the overlying coarse-grained sediments contain a weathering profile that is less than 3 feet thick. These pedologic differences suggest an appreciable difference in the ages of the till and of the overlying water-laid deposits and essentially eliminate the possibility that the surface deposits represent deposition by marginal melt-water streams contemporaneous with retreat of the Eklutna ice from the region. Insofar as the Ski Bowl road exposure lies below the highest level (about 750 ft in elevation) of the proglacial lake of Naptowne age as recognized on the adjoining Nikishka Lowland, the author believes that the little-weathered surficial layer of gravel and silt mantling the moraines of Eklutna age provides direct stratigraphic evidence of this lake in the Anchorage area.

No marked weathering hiatus appears to be present between the till and underlying deposit of lake silt, and it is probable that the lake silt represents proglacial-lake deposition contemporaneous with the advance of Eklutna ice into the area. Whether this lake was restricted to the Ship Creek valley as a consequence of damming of the tributary valley mouth by ice of the Matanuska–Knik River ice lobe, or whether it was part of a larger lake system which temporarily occupied the Cook Inlet trough prior to its complete filling by Eklutna ice, is not certain.

New road construction in 1957 near Rabbit Creek exposed a thick section of deposits within the morainal belt of Eklutna age between elevations of 800 and 900 feet. The deposits exposed in the roadcut lie beneath a terracelike surface cut along the flanks of the Chugach Mountains. They are interpreted as follows:

Post-Naptowne and Naptowne glaciations
0–1 ft of thin discontinuous red-brown to buff loess.
Unconformity
Knik glaciation
20–30 ft of laminated buff to gray silt and sand with a few scattered pebbles and cobbles. Upper 5 ft of exposed section is massive semiplastic silt, buff with subtle mottling, and with a suggestion of primary lamination and contortion (frost action). Leaf and twig impressions are locally present; the organic material is completely decomposed. Near the base of section buff to olive-drab silt is interbedded with well-stratified gray medium- to coarse-grained sand. The middle part of section is mantled.
Unconformity
Eklutna glaciation
10+ ft of buff coarse bouldery, gravelly till. Boulders are graywacke-argillite, greenstone, and granitic rock types; they show little sign of weathering and are generally sound. Locally, at top of till, lag concentrations of boulders and cobbles suggest some erosion of till prior to deposition of the overlying stratified sand and silt unit.

The fine-grained and laminated character of the silt deposits and their position beneath a topographic bench along the mountain front adjacent to the mouth of a mountain valley suggest that they were deposited in a large lake whose surface stood appreciably above an elevation of 900 feet and whose shoreline was some distance away. The general paucity of boulders and other coarser grained clastic components suggests deposition away from melt water as well as tributary sources. The general mottled buff coloration in the upper zone of the silt unit and its position above the highest recognized level (about 750-ft) of the proglacial lake of Naptowne age, but below the 1,000-foot strandline level attributed to a proglacial lake of Knik age on the Kenai Lowland, suggest that the high-level silt deposit in the Rabbit Creek drainage area may represent proglacial-lake deposits of Knik age.

Miller and Dobrovolny (1959) describe a section exposed nearby in Campbell Creek Canyon between elevations of 750 and 1,000 feet. Here, 85 feet of bouldery till rests on about 150 feet of bedrock and is overlain by more than 15 feet of stratified sand and gravel with a coarse cobbly lag bed at its base. In view of the stratigraphic relations in the lower section exposed at Rabbit Creek, it is possible that the surface sand and gravel at Campbell Creek may, at least in part, represent a coarser strandline facies deposited essentially contemporaneously with the deeper water silt deposits exposed near Rabbit Creek. The sections described above are schematically shown on plate 6, profile VIII, in relationship to the morainal boundaries and to probable high-level stands of the proglacial lakes of Naptowne and Knik age in Cook Inlet.

TYPE SECTION OF DEPOSITS OF THE KNIK GLACIATION

A most instructive stratigraphic section recording the relation of till of Knik age to older drift of Eklutna age and to younger drift of Naptowne age is exposed in the sea bluffs on the northwest shore of Knik Arm south of Goose Bay (pl. 6, profile X). At Goose Bay the bluff section is of an upper and lower till separated by a section of stratified silt, sand, and gravel with weathered horizons, two organic zones and associated profiles, and a thin shelly zone of laminated blue-gray silt. Both the lower and upper till units are traceable discontinuously in the sea bluffs south to the end moraine of Naptowne age near Point MacKenzie, where the upper till unit terminates and is replaced by stratified sand and gravel in the upper part of the bluff section. The lower till of Knik age is locally exposed near beach level through the bluff mantle to a point 3 to 4 miles west of the end moraines of Naptowne age. There, it is higher in the bluff and occurs in a near-vertical to steeply inclined contact with a highly contorted finely laminated buff to yellow-buff silt and sand containing disseminated particles and lenses of clastic coal. These contact sediments are similar in their uniform limonitic staining and in their stratigraphic position to deposits of Eklutna age underlying the end moraines of Knik age near Boulder Point on the Nikishka Lowland. Major recumbent folding (some folds of the magnitude of 25–30 ft from crests to troughs) and minor overturned folding and overthrust faulting to the south are recorded in these contact sediments and suggest ice shove from the north by the advancing Knik ice front. Both the undeformed till and deformed contact sediments are overlain unconformably by stratified sand and gravel deposits that underlie terrace surfaces which border, and locally cut into, the flanks of the end moraines of Naptowne age.

East of the contact between deposits of Knik and Eklutna age the till of Knik age is overlain by a thick section of laminated blue-gray silt that locally contains a marine shell zone lying about 30 to 50 feet above sea level. The shells are of the same species as those collected by the author from their original positions in the middle section of the Bootlegger Cove clay (of Knik age as used by Miller and Dobrovolny, 1959) exposed across Knik Arm near Point Woronzof. Earlier collections by Miller and Cooley (Miller and Dobrovolny, 1959, p. 45) and Frank C. Trainer (oral communication, 1956) from this type section of the Bootlegger Cove contained the following mollusks:

Baccinum cf. B. physematum Dall
Odostomia (Evalea) sp.
Nuculana fossa Baird
Cardium ciliatum Fabricius
Macoma cf. M. *Sabulosa* Gmelin
Saxicava pholadis Linné
Mya truncata Linné

At present these forms live in moderately shallow waters in the intertidal zone. Shells of these species have not been seen by the author on the beaches along the Cook Inlet coast north of Kenai except in Knik Arm where the Bootlegger Cove clay crops out in the sea bluffs. Miller collected from slump material, and he believes that the shells probably represent wave-tossed modern shells. Trainer considers that the shells were derived from the Bootlegger Cove clay. Shells collected by Trainer from the Bootlegger Cove clay and modern mollusk shells collected from Cook Inlet by the author were transmitted by the author to Dr. Herbert S. Potratz, Washington University, St. Louis, Mo., for chemical analyses of radioactive contents. The analyses indicate a major difference in the ionium and uranium disequilibrium ratios (Herbert S. Potratz, written communication, 1958; Sackett, 1958 [6]). The shells from the Bootlegger Cove clay contain 0.26 (±0.03) ppm (parts per million) uranium and have an ionium-uranium ratio of 0.34. The modern-shell material contains 0.32 ±0.03) ppm uranium and has an ionium-uranium ratio of 0.01. From a theoretical consideration of the radioactivity of these samples, Sackett suggests that the shells in the marine zone of the Bootlegger Cove clay probably are between 33,000 and 48,000 years old.

The only other known exposure of marine deposits in the coastal stratigraphy of Cook Inlet is reported from the southwest coast of Kodiak Island (Maddren, 1919; Capps, 1937). Here the marine deposits are overlain and underlain by till and occur about 20 feet above the present limit of high tide. According to Capps, these deposits indicate a relative elevation of Kodiak Island of between 30 and 50 feet at this place since deposition. Fossils collected by A. G. Maddren, identified by W. H. Dall, and reviewed by F. S. MacNeil (written communications, 1958) include the following forms:

Chlamys islandicus Muller
Monia macroschisma Deshayes
Tellina lutea Gray
Macoma middendorffii Dall
Cardita (Cyclocordia) Crebicostata Krause
Cardita (Cyclocardia) paucisostata Krause
Mya japonica Jay (Mya intermedia Dall)
Katisipho halli Dall
Tachyrhynchus polaris Beck
Astarte borealis Schumacher
Saxodomus giganteus Deshyates
Chrysodomus sp.
Cardita (Cyclocardia) cassidens Borderip and Sowerby
Boreotrophan sp.
Balnus sp.

[6] Sackett, W. M., 1958, Ionium-uranium ratios in marine-deposited calcium carbonates and related materials: Washington Univ., St. Louis, Mo., Ph. D. thesis.

According to MacNeil, all of the identifiable forms in this collection, like those collected from the Bootlegger Cove clay, are within their present geographic range.

The unweathered till overlying this marine zone on Kodiak Island was considered by Capps (1937) to most probably represent the Wisconsin glacial stage. As previously discussed, the last major glaciation of Kodiak Island is considered to be the equivalent of the Naptowne glaciation of Cook Inlet. This correlation, which is based on comparable stratigraphic position, weathering, and a consideration of ice extents in the region, is further supported by the local presence in both areas of a marine deposit that underlies surface till and which occurs between 20 and 50 feet above present sea level. These relations point to a higher sea-level stand in the Pacific Ocean and Cook Inlet preceding the last major glaciation of central Alaska. Just how much the present elevation of the marine zone is due to eustatic sea-level shifts or to postdepositional emergence resulting from isostatic or tectonic adjustments is not known. However, its position within an interglacial interval and the fact that it lies at approximately the same elevation in two widely separate localities suggest a significant eustatic marine transgression to levels above present datum in the region following retreat of Knik ice from the Cook Inlet trough but prior to the Naptowne glaciation. No comparable marine deposits have yet been found along the Kenai Lowland coastline. This suggests the possibility that the pre-Naptowne marine reentrant lay somewhere west of the present eastern shore of Cook Inlet. Detailed study of the startigraphy exposed in the sea bluffs along the west shore of Cook Inlet should permit more precise location of the western margin of this interglacial seaway.

The stratigraphy near Goose Bay provides a detailed record of the interval between the retreat of Knik ice and the advance of Naptowne ice in Cook Inlet and is interpreted as follows:

Post-Naptowne and Naptowne glaciation

12. 1–3 ft. loess with podziloc soil zone from 3–4 ft. thick; volcanic ash layer locally near base of loess. Locally dune sand as much as 30 ft. thick.

Disconformity

Naptowne glaciation

11. 0–20 ft. of predominantly olive-drab to gray laminated silt and sand, locally stratified gravel. Proglacial-lake sediments, commonly buff colored near top, postdate the Naptowne maximum.

Disconformity, locally unconformity

10. 10–30 ft. of blue grayish silty till with pebbles, cobbles, and boulders of metamorphic, igneous, sandstone, shale, graywacke-argillite, quartzite, and

chert rock types. The till locally contains striated and truncated boulder pavement surfaces, which record glacial readvances, and near base shows rude stratification with lenses and pockets of gravel. Locally near top the till grades into coarser bouldery facies that show some deep hematitic iron staining.

Gradational contact

9. 20–40 ft of well-stratified gray sand and gravel, locally crossbedded; contains some transported wood fragments near base. Crossbedding and imbricate structure indicates depositional currents from the northeast. Unit unstained and unweathered except for patches of iron staining locally present along basal contact. Advance outwash deposits.

Disconformity, locally unconformity

Pro-Naptowne glaciation

8. 0–6 ft of contorted stratified silt, sand, and gravel. At place where measured in detail, unit is made up of 2–3 ft of iron-stained gravel, ½ ft of iron-stained sand grading downward into ½–1 ft of unstained sand and laminated blue-gray silt.

Disconformity

Knik glaciation

7. 0–6 ft of deformed organic silt and peat deposits. Unit can be traced nearly continuously about 10 ft above beach level from Goose Bay 3 miles northeast along the coast, at which point it is truncated and overlain directly by till of Naptowne age. At Goose Bay the unit contains (from top to bottom): 1–2 ft of stratified gray and dark-gray organic silt, with two discontinuous ash layers, and some iron staining near top; 1–4 in. of woody moss peat; 2–2½ ft of dark brown to red-brown dense mossy peat; silt film; 1–2 in. of mossy woody peat; 4–5 in. of red-brown moss-sedge peat; 2 in. of dark brown dense moss-sedge peat; 2–3 in. of banded red-brown to dark-brown dense moss-sedge peat; silt film; 2 in. of dark-brown dense moss peat; 1–3 in. of laminated organic silt; and ½–1 ft of stratified slightly iron-mottled gray sand and blue-gray silt with scattered pebbles.

Disconformity

6. 20–30 ft of iron-stained and locally iron-cemented coarse cobbly stratified gravel with imbricate structures indicating deposition by currents flowing from northeast. Iron-staining is concentrated near top, but varies appreciably both in intensity and in distribution throughout the unit. The basal part is, in general, less iron stained than the upper part.

Disconformity

5. 0–1 ft of buff to brownish buff silt with numerous pebbles and cobbles. The unit apparently represents a mixture along the contact of the overlying gravel with the underlying silt. Although it is possible that the buff coloration may represent an interval of subaerial weathering prior to gravel deposition, it is more likely that it represents meteoric water staining concentrated along the base of the overlying more porous and permeable gravel unit.

Gradational contact

4. 0–6 ft of finely laminated blue-gray silt containing a middle zone rich in finely comminuted calcium carbonate shell fragments and a basal organic silt zone with numerous twigs and fragments of wood. The basal organic layer represents a buried bog and is assocated with a soil profile that penetrates into the underlying gravel and silt.

3. 0–3 ft of buff pebbly silt, marking a mixture of overlying silt with underlying stained gravel.

2. 5–15 ft of coarse cobbly sand and gravel, deeply iron stained and cemented.

Disconformity

1. More than 10 ft of blue-gray silty till, with pebbles, cobbles, and boulders of metamorphic, igneous, sandstone, shale, graywacke, argillite, quartzite, conglomerate, and chert rock types. Near the top of the unit the till is rudely stratified and contains lenses and pockets of washed gravel.

Wood from a transported log collected from near the base of the advance outwash (unit 9) dates pre-38,000 B.C. (W–644). If this transported log represents vegetation growing at the time of deposition rather than reworked older material, its age closely dates either the advance of Naptowne ice to the end-moraine position near Point MacKenzie and Cairn Point or the initial phase of Glacial Lake Cook. Wood collected from near the top and bottom of the underlying buried bog (unit 8) gives dates respectively of pre-36,000 B.C. (W–174) and pre-32,000 B.C. (W–77). Samples from the advance outwash (unit 9) and the upper (unit 8) and lower (unit 4) bog horizons are pending carbon–14 analyses at Lamont Laboratory with instruments that extend the carbon–14 dating range to 40,000 to 60,000 years or more. The results of these analyses should clarify whether the advance outwash sample is younger than the material in the underlying bog, as it should be if it represents vegetation growing before or at the time of maximum extension of Naptowne ice. The carbon–14 results may also provide finite dates for significant climatic events of the last interglacial period in Cook Inlet. Carbonate material from the shell zone in unit 4 is pending analyses by the Potratz ionium-uranium dating method that should clarify the present correlation of this zone with the marine shell zone found elsewhere in the Knik Arm area.

The significance of the Goose Bay section lies in its rather clearcut record of a series of important depositional events following retreat of Knik ice from, and prior to the advance of Naptowne ice to, its maximum position in the lowland. The presence of two buried organic soils and an intermediate marine zone suggests significant climatic and hydrologic changes within the Cook Inlet region during this time interval. The Goose Bay section combined with the stratigraphic relations exposed elsewhere along the sea bluff suggest the following sequence of events:

1. Advance of Knik ice to its maximum position west of Point MacKenzie where it overrode and deformed weathered sediments of Eklutna age.
2. Retreat of Knik ice in a proglacial-lake environment, recorded by laminated silt, sand, and gravel directly overlying till of Knik age.
3. Continued glacial retreat and drainage of the proglacial lake followed by subaerial erosion and vegetation expansion on the emerged land surface, recorded near Goose Bay by the basal organic layer of unit 4.

4. Submergence beneath marine waters that rose more than 50 feet above present datum, recorded by the marine shell beds near Point MacKenzie and presumably also by the shell zone in unit 4 near Goose Bay.
5. Re-emergence accompanied or followed by deposition of stratified sand and gravel at Goose Bay (unit 6), with subsequent subaerial weathering and bog accumulation in depressions on the emerged land surface (unit 7).
6. Inundation of the bog surface by rising proglacial waters (unit 8) accompanying the initial advance of Naptowne ice into the lowland and followed by continued advance to the maximum position near Point MacKenzie in a proglacial environment, recorded by the advance outwash and till near Goose Bay and by the laminated lake silt overlying the marine zone in front of the end moraines of Naptowne age. A brief interruption in the pro-Naptowne lake history is suggested by the unconformity and weathering profile(?) at the top of unit 8. This may therefore mark a brief drainage interval of an earlier lake phase accompanying a phase of glacial retreat just prior to the final readvance of Naptowne ice to its maximum position.
7. Fluctuating and falling lake levels accompanying retreat of Naptowne ice from its maximum position, recorded by terraces cut into the flanks of end moraines and the lowland surface.
8. Wind, deposition of loess and sand dunes subsequent to final drainage of the proglacial lake and retreat of Naptowne ice out of the Mantanuska Lowland.

CORRELATION WITH THE STRATIGRAPHIC RECORD IN THE ANCHORAGE AREA

In their engineering geology study of the surficial deposits of the Anchorage area, Miller and Dobrovolny (1957a, b; 1959) describe deposits which they assign to the Eklutna, Knik, and Naptowne glaciations. An isolated till-like lens of stony silt that lies along the contact between Bootlegger Cove clay and the overlying advance outwash deposits of Naptowne age near Cairn Point is attributed to a glacial advance which just preceded the maximum advance of Naptowne ice to the Elmendorf moraine at Cairn Point. On the basis of a radiocarbon date of pre-36,000 B.C. obtained from a sample collected from a bog buried beneath till and advance outwash deposits of Naptowne age near the Eagle River (pl. 6, profile IX), Miller and Dobrovolny concur with the author in the assignment of the Naptowne glaciation to all, not just part, of Wisconsin time, and of the Knik and Eklutna glaciations to pre-Wisconsin events. A brief field conference held jointly in the Anchorage area in 1956 with Robert Miller, Ernest Dobrovolny, and Wallace Hansen was most helpful in resolving differences of interpretation between the author's regional reconstruction of the glacial history and field interpretations placed on the Pleistocene deposits in the Anchorage area bearing directly on the regional glacial history. Some interpretative differences remain, however, and will be discussed below. The stratigraphy exposed in the sea bluffs along the southeast side of Knik Arm is shown in plate 6, profile IX. The localities of sections observed and measured by the author with hand level or by visual estimate are shown on the profile. The section between Eagle River Flats and a point 2¼ miles north has not been examined by the author and is shown as measured and interpreted by Miller and Dobrovolny (1959, pl. 3). However, the Eagle Bay section occurs at the same elevation as the Goose Bay section, and is comparable in stratigraphic detail. This suggests the alternate interpretation that the basal till near the Eagle River, mapped as Eklutna in age, may be instead the correlative of the basal till of Knik age exposed at Goose Bay. If so, then the discontinuous stony silt unit between advance outwash gravel and the overlying Bootlegger Cove clay, mapped as till of Knik age at Eagle Bay, may be but a contact-zone mixture of gravel and silt equivalent to the stony silt unit (unit 3) at the same stratigraphic position in the Goose Bay section.

Miller and Dobrovolny (1959) do not recognize either the middle marine shell zone in the Bootlegger Cove clay or the threefold subdivision in the associated glaciolacustrine deposits near Point Woronzof (fig. 5*E*). They favor the interpretation that the yellow-buff to gray deposits near Point Woronzof were deposited contemporaneously with the blue-gray Bootlegger Cove clay within a proglacial lake that developed during Knik retreat; that a thin zone of iron staining locally present along the upper contact of the Bootlegger Cove clay marks a period of interglacial weathering prior to the Naptowne advance; and that overlying finely stratified silt, sand, and interbedded gravel which flank, and in general mantle, the moraines of Knik age outside of the Naptowne boundary are primary glaciofluvial ice-contact and pitted outwash deposits of Knik age. On lower surfaces, such as near Point Woronzof, finely stratified deposits that comparably overlie the Bootlegger Cove clay and date ca. 9,500 B.C. are considered to be outwash deposits at Naptowne age. On the other hand, on the basis of strikingly similar stratigraphic sequences both above and below the distinctive marine shell zone exposed in the sea bluffs on both sides of Knik Arm, the author believes that:

1. The Bootlegger Cove clay records proglacial-lake sedimention accompanying both the Knik and Naptowne glaciations with an intervening interval of marine deposition.
2. The yellow-buff to buff to brown finely laminated silt and sand deposits that unconformably underlie the Bootlegger Cove clay and the shell zone near Point Woronzof are not a ground-water-stained facies of the Bootlegger Cove clay, as favored by Miller and Dobrovolny, but are equivalent to comparably deeply limonite-stained sediments of Eklutna age unconformably underlying till of Knik age near Point MacKenzie, Boulder Point on the Kenai Lowland, and in the Eklutna Valley.
3. The bulk of the buff-to-gray stratified silt, sand, and gravel with scattered large ice-rafted boulders also underlying the Bootlegger Cove clay near Point Woronzof are, as interpreted by Miller and Dobrovolny, glaciolacustrine deposits laid down during the Knik glaciation.
4. The overlying mantle of laminated blue-gray silt, gray laminated silt and sand, and stratified sand and gravel deposits here, as elsewhere in the Cook Inlet Lowland, predominantly record deposition in the proglacial lake of Naptowne age.

Modification of morainal forms by proglacial-lake erosion and deposition provides a direct explanation, the author believes, for the complexly terraced and channeled lowland surface; for the stratigraphic sequences exposed; and for the similarity of textures and soil development (Miller and Dobrovolny, 1959, p. 22, report an average depth of surface weathering of from 4 to 7 feet) of the water-laid surficial deposits mantling the morainal belts of Eklutna, Knik, and Naptowne age throughout the lowland around Anchorage. As in the Nikishka Lowland, the soils on the moraines of Eklutna, Knik, and Naptowne age near Anchorage are not developed on primary glacial deposits but on proglacial-lake and windblown sediments. Thus they reflect the time interval since final lake drainage in late Naptowne time and not the much longer intervals since retreat of Eklutna, Knik, and Naptowne ice from the region, as these events are locally recorded by drift units separated by weathering profiles in the coastal-bluff stratigraphy.

Miller and Dobrovolny classify the surficial water-laid deposits solely on the basis of topography and geomorphic position relative to the morainal belts in the area. Thus water-laid deposits flanking and overlying the moraines outside of the end morainal boundary of Naptowne glaciation are considered to be of glaciofluvial origin (pitted outwash, outwash, ice-contact) deposited during recession of Knik ice in a down-wasting ice-block environment. Comparable sand and gravel deposits at the same or higher elevations underlying terraces that flank the southeast margin of the dissected deltaic ridge of predominantly fine sand and silt between Point Woronzof and Point Campbell are considered to be prodelta deposits formed contemporaneously with delta development and along the delta's distal margin within the proglacial lake of Knik age. The deltaic deposits underlie surfaces that are above 300-foot elevations, indicating that proglacial waters must have been at least this high throughout the region. This means that Miller and Dobrovolny's pitted outwash, outwash, and ice-contact deposits which lie below 300 feet in elevation either were deposited in proglacial-lake water (and therefore are not glaciofluvial in origin) or represent deposition some time after drainage of the proglacial lake but prior to complete melting of Knik ice from the lowland. All existing lakes—including muskeg lakes and undrained depressions in the Anchorage lowland—are considered by Miller and Dobrovolny to be kettle lakes formed by melting of glacial ice blocks, even though many are formed in deposits overlying the Bootlegger Cove clay. All steep slopes on unconsolidated deposits are considered to be ice-contact slopes resulting from deposition along the steep sides of large down-wasting glacial ice blocks. This interpretation is difficult to reconcile with their evidence that the Bootlegger Cove clay fills the deepest depressions underlying the lowest areas in the lowland; is essentially continuous; shows normal stratigraphic relations to overlying and underlying sediments; and, as exposed in the sea bluffs away from the margin of moraines of the Naptowne glaciation, is essentially undeformed. Combined with the evidence of a marine transgression into the lowland following Knik retreat, these features indicate that deposition of the Bootlegger Cove clay must postdate, rather than predate, the complete disappearance of Knik ice from the lowlands. The overlying deposits, therefore, must be still younger and unrelated to deposition along the margins of glacial-ice blocks.

According to the author's interpretation, most of these mantling deposits record deposition or reworking of primary deposits in a proglacial lake of Naptowne age, with the finer grained sediments (the upper zone of the Bootlegger Cove clay) laid down in the deeper parts of the lake and the coarser grained facies deposited along the margins and beneath strandline terraces. Most steeper slopes do not represent ice-contact deposition but are beach scarps cut into the flanks of higher ground during static intervals of fluctuating lake levels. The existing lakes and undrained depressions for the most part represent either original depressions on the emerged lake bottoms or depressions that formed or were modified after emergence due to differential compaction, melting of ground ice, or other post-depositional processes. Excavations in the Spenard area in 1956 exposed a large lens of ground ice several tens of feet long and more than 10 feet deep in the Bootlegger Cove clay (Roger Waller, oral communications, 1956). This emphasizes the probability that many of the undrained depressions in the lowland resulted from or were modified by the melting of ground ice that must have been formed in the lake-bottom sediments only after emergence from beneath proglacial waters in late Naptowne time.

As in the Nikishka Lowland, many of the lakes in the Anchorage Lowland occur on terrace levels or in abandoned channels that appear to represent overflow channels across shoals or islands in the lake. The lakes and undrained depressions on the upper surface of the terraced and channeled deltaic deposits between Point Woronzof and Point Campbell probably have an origin comparable to that of the numerous lakes that dot the surface of the present large delta at the mouth of the Susitna River, and whose development are totally unrelated to melting of glacial-ice blocks.

Miller and Dobrovolny's (1959) classification of the surficial carbon-14-dated silt and sand deposits near Point Woronzof as outwash deposits of Naptowne age implies that the Knik-Matanuska River ice lobe lingered near its end position of Naptowne time as late as ca. 9000 B.C. This is incompatible with the regional evidence of the proglacial lake that submerged the lowland long after Naptowne ice had retreated from the end moraine position and with the radiocarbon evidence near the Matanuska glacier at the head of Matanuska valley (carbon-14 loc. V, Williams and Ferrians, 1958) which indicates that the Matanuska lobe of the Naptowne ice tongue had already retreated prior to 6000 B.C. well into the upper reaches of the valley near present ice sources. The carbon-14-dated deposits near Point Woronzof underlie a surface that is not graded to, but which lies below, terrace levels cut well below the sand and gravel plain that abuts the end moraine of Naptowne age in the Anchorage area. This sand and gravel plain is not radially graded to the arcuate end moraine but to a marginal source area near the Eagle River. Surface deposits show a marked and progressive change from finer grained material near Cairn Point to coarse bouldery gravel near the Eagle River. Local exposures in the marginal gravel apron indicate that it abuts against till along a steep erosional contact. All these features strongly suggest that the upper as well as lower terrace surfaces in the Anchorage area postdate retreat of the Naptowne ice from its end moraine position. As discussed below, the carbon-14-dated finely laminated deposits near Point Woronzof seem to record two of the latest high-level lake stands in the proglacial lake of late Naptowne age.

A major difference in interpretation lies in Miller and Dobrovolny's correlation of the deposits of Knik age as exposed in the sea bluffs with the lateral moraines on the Chugach Mountain front that the author originally defined as of the Swan Lake glaciation (Karlstrom, 1953) and then redefined as of Eklutna age (Karlstrom, 1955b, 1957a). Miller and Dobrovolny (1959) support their correlation by noting within the Anchorage area the absence of a well-defined morainal boundary between the high lateral moraines of Eklutna age and the end moraines of Naptowne age on the lowland and the lack of major weathering and textural differences in the lowland surficial deposits. As previously discussed, the author believes that this absence of well-defined morainal boundaries and of major weathering differences between the morainal belts in the lowland is the logical consequence of partial reworking and burial within the proglacial lake of Naptowne age.

According to the Miller and Dobrovolny reconstruction, Knik ice advanced completely beyond the boundary of the Anchorage area, and the Naptowne advance was the only piedmont glaciation in the area. However, stratigraphic and morainal evidence in the Nikishka Lowland, Kustatan Lowland, and near Anchorage (across Knik Arm) clearly indicate two separate piedmont glacier advances, the older of which was slightly more extensive than the Naptowne but much less extensive than the glaciation marked by the lateral moraines along the Chugach Mountain front. The presence of the till of the Knik glaciation 3 to 4 miles in front of the moraines of Naptowne age near Point MacKenzie clearly requires that the Knik ice front must have also stood in the nearby Anchorage area. The absence of till of Knik age in the sea bluffs west of Anchorage is therefore attributed by the author either to erosion, prior to deposition of the Bootlegger Cove clay, to below the base of the present exposures or to the Knik ice not advancing as far on the Anchorage side of Knik Arm as on the Point MacKenzie side. As shown in plate 6, profile IX, the author favors the interpretation that till of Knik age lies at depth below present sea level east of Point Woronzof. The arc of eroded remnants of morainal ridges that lies 3 to 4 miles south of the end moraine of Naptowne age in the Anchorage lowland area falls approximately in line with the outermost contact of buried till of Knik age exposed near Point MacKenzie and therefore presumably marks the outer boundary of the Knik-Matanuska ice-lobe advance during Knik time into the Anchorage area.

Gastil (written communication, 1955) mapped a pre-Naptowne arc of subdued and partly eroded morainal ridges bordering Turnagain Arm between Potter and Port Campbell. This morainal belt lies at a lower elevation than the lateral moraines of Eklutna age and outside the end moraines of Naptowne age in the Anchorage area. Miller and Dobrovolny (1959) describe these moraines and also consider that they might represent a separate glaciation. Because they erroneously assign a Knik age to the older lateral moraines nearby that, by definition, are of Eklutna age, they suggest that this younger belt of moraines may be Naptowne in age. These moraines in the Anchorage area fall directly in line with the arc of moraines deposited by the Turnagain ice lobe in the northern part of the Nikishka Lowland and are thus considered by the author to represent the Knik advance at least to, and perhaps slightly beyond, Fire Island, Point Campbell, and Point Possession.

According to this interpretation, the till that is discontinuously exposed in the middle section of the high sea bluffs east of Point Campbell (as mapped by Miller and Dobrovolny, 1959) thus reasonably represents deposition near the maximum margin of the Turnagain Arm ice lobe during Knik time. This is consistent with Miller and Dobrovolny's interpretation of the associated water-laid sediments as deltaic deposits laid down in a lake of Knik age but differs from their interpretation in that they consider that this lake formed along the front of an ice lobe which had its source either in the Susitna Valley or the Alaska Range to the northwest and west. Damming of the lake by ice from Susitna Valley or the Alaska Range is supported by the following arguments. 1. Because no clastic coal was observed in deposits near Potter, the abundant clastic coal in the deltaic deposits could not have been derived from the Turnagain Arm area but must have been transported by ice advancing southward or southeastward into the area from the Susitna Valley or the Alaska Range source areas of Tertiary rock. 2. The greater amount of gravel exposed near Point Woronzof than eastward around the Knik Arm sea bluffs indicates that the delta must have been supplied from northern or northwestern melt-water sources. However, there is abundant clastic coal in the sediments deposited by the Turnagain Arm ice lobe of Knik age east of Point Possession, indicating that either Tertiary bedrock or older glacial sediments containing clastic coal were overridden by the ice lobe during its westward advance across the lowland margin from the Chugach-Kenai Mountains to Point Campbell, Point Possession, and Fire Island. The absence of clastic coal in the deposits near Potter may mean that the Tertiary-Mesozoic bedrock contact lies somewhere at depth beneath the lowland surface just west of Potter. Clastic coal has been observed by the author in deposits exposed in roadcuts as far east as Little Rabbit Creek.

It is true that more gravel is exposed in the sea bluffs near Point Woronzof than to the east (pl. 6, profile IX); however, the gravel here largely represents deposition in a restricted channel cut into underlying buff to yellow-buff laminated silt, sand, and gravel of Eklutna age (fig. 5*F*). The sea bluffs transect these channel-fill deposits roughly at right angles to the buried channel axis and the concave gravel beds dip 10° to 20° out from the bluff, recording deposition from the southwest or from water flowing out of Turnagain Arm. Further, Miller and Dobrovolny describe coarse granular deposits, which flank the delta deposits along the southwest margin and locally overlie the Bootlegger Cove clay, as prodelta sediments deposited contemporaneously with delta formation. The development of these extremely coarse flanking deposits as bottom-set sediments along what would be, according to their interpretation, the distal side of the delta is difficult to reconcile not only with normal delta development but also with their concept that the delta was supplied from Alaska Range or Susitna Valley sources. No erratic material has been observed by the author near Point Woronzof that appears suggestive of exclusive Alaska Range sources, such as is found immediately to the south along the Nikishka Lowland coast and on the summit area of Mount Susitna. Perhaps of more significance, however, is the regional morainal evidence which indicates that ice from the more distant Susitna Valley and Alaska Range sources did not approach nearly as close to Point Woronzof during Naptowne and Knik time, nor remain as long in the area during Eklutna retreat, as did the ice from the nearby Chugach Mountain sources. The presence of till near Point Campbell and its absence in the Point Woronzof section to the northeast thus seem fully consistent with the morainal evidence of proglacial-lake deposition in the Point Woronzof area during Knik time when the Turnagain Arm ice lobe fronted near Point Campbell and the Knik-Matanuska ice lobe fronted near Point MacKenzie.

MORAINES AND GLACIAL STRATIGRAPHY OF POST-NAPTOWNE OR ALASKAN AGE

Post-Naptowne glacial advances are represented by a sequence of fresh-looking moraines that lie between more modified moraines of Naptowne age and the fronts of existing glaciers, such as Tustumena glacier in the

Kenai Lowland, and in numerous alpine mountain valleys throughout the Kenai Mountains. Comparable recent moraines and related talus and rock-glacier deposits are found in the alpine areas throughout the state (Péwé and others, 1953; Andersen, (written communication, 1955; Karlstrom, 1955b, 1957; Wahrhaftig, 1958) and are readily accessible from the Alaska Railroad where it crosses the Kenai Mountains and the Alaska Range. To this most recent series in the Cook Inlet glacial chronology the name Alaskan glaciation is applied.

It is possible from photointerpretation of recent morainal sequences in the Kenai Mountains to distinguish two distinctly separate series of glacial advances of Alaskan age. This twofold subdivision is supported by detailed ground mapping of the recent moraines on the Kenai Lowland in front of Tustumena glacier, in the upper Placer Creek valley near the section house of the Alaska Railroad at Tunnel, and in Palmer Creek valley. Vegetation on the older moraines is, in general, more continuous and more mature than that growing on the younger moraines; but the character of the vegetation cover varies appreciably from valley to valley, depending on the elevation of the moraines and their proximity to the coastal side of the mountains. In most of the alpine valleys, lateral boundaries of the older set of recent moraines are partly overlapped or obliterated by valley-wall talus, alluvial cones, and gully erosion, whereas the lateral moraines of the younger set of moraines are generally undissected. Where observed on the ground, the older morainal complex of the Alaskan glaciation is characterized by shallow but distinct podzolic soil development (weathering profiles 4–12 in. deep). The younger moraines show but incipient soil development. This is in contrast to soil-profile depths of greater than 2 feet developed in loess mantling moraines of Naptowne age. This pedologic difference thus suggests a significant retreatal interval between the late Naptowne and Alaskan glaciations.

From type sections near the head of Tustumena Lake in the Nikishka Lowland (fig. 9) and near the section house at Tunnel near Bartlett glacier (fig. 10), the glacial advances represented by the older moraines are named the "Tustumena advances," and those represented by the younger moraines are named the "Tunnel advances." The morainal record, where best preserved, comprises at least 3 major Tustumena advances and 2 major and several minor Tunnel advances.

TUSTUMENA ADVANCES

At the type locality near the head of Tustumena Lake, moraines of the Tustumena advances occur less than a mile downvalley from the moraines of the Tunnel advances, which margin the present Tustumena glacier front (fig. 9). The latest Tustumena advance is represented by a nearly continuous forest-covered end moraine that borders the lake head and is partly buried by outwash graded upvalley to the younger sparsely vegetated to bare moraines of the Tunnel advances. At least two older and more extensive Tustumena advances reached beyond the present margins of Tustumena Lake, and these are represented only by forested lateral moraines preserved locally along the base of the bedrock valley wall southeast of the mouth of Indian Creek. The youngest moraine of the Tustumena advance is mantled by a 1½- to 2-foot-thick loess unit containing 2 weakly developed buried soils and recording 2 separate intervals of accelerated loess and sand deposition that may have resulted from increased alluviation and wind action upvalley accompanying the advance of Tustumena glacier to the positions of moraines of the Tunnel 1 and 2 advances. In contrast to soil-profile depths of from 2 to 4 feet developed downvalley in loess overlying the moraines of Tanya age, the combined depth of soil development associated with the surface soil and the two buried soils in the loess covering the moraines of the Tustumena advances is less than 8 inches.

Moraines of Tustumena age are particularly well developed and preserved near the head of Palmer Creek valley in the Kenai Mountains. These morainal deposits are covered by a continuous mantle of alpine tundra; soil development is from 3 to 8 inches deep. They lie upvalley from forested and more deeply weathered morainal deposits of Naptowne age and downvalley from less weathered and essentially unvegetated moraines of Tunnel age that margin cirque glaciers at the valley head.

Forested moraines of Tustumena age ocur just above the margins of shrub-covered moraines of Tunnel age in Placer Creek valley. Soil profiles in these deposits are developed to depths of 5 to 12 inches. During the maximum of the Tustumena glaciation in the Placer River valley, ice from Bartlett glacier coalesced with Spencer glacier and pushed to an end position somewhere in lower Placer Creek valley. The end moraines have been either totally washed away or else buried by outwash deposits that completely fill lower Placer Creek valley, and the lateral position of maximum Tustumena ice on the steep valley walls of the area has yet to be established by detailed mapping.

TUNNEL ADVANCES

Minor differences in vegetal cover, soil development, and geomorphic and stratigraphic relations among the moraines of the Tunnel advances in front of Bartlett

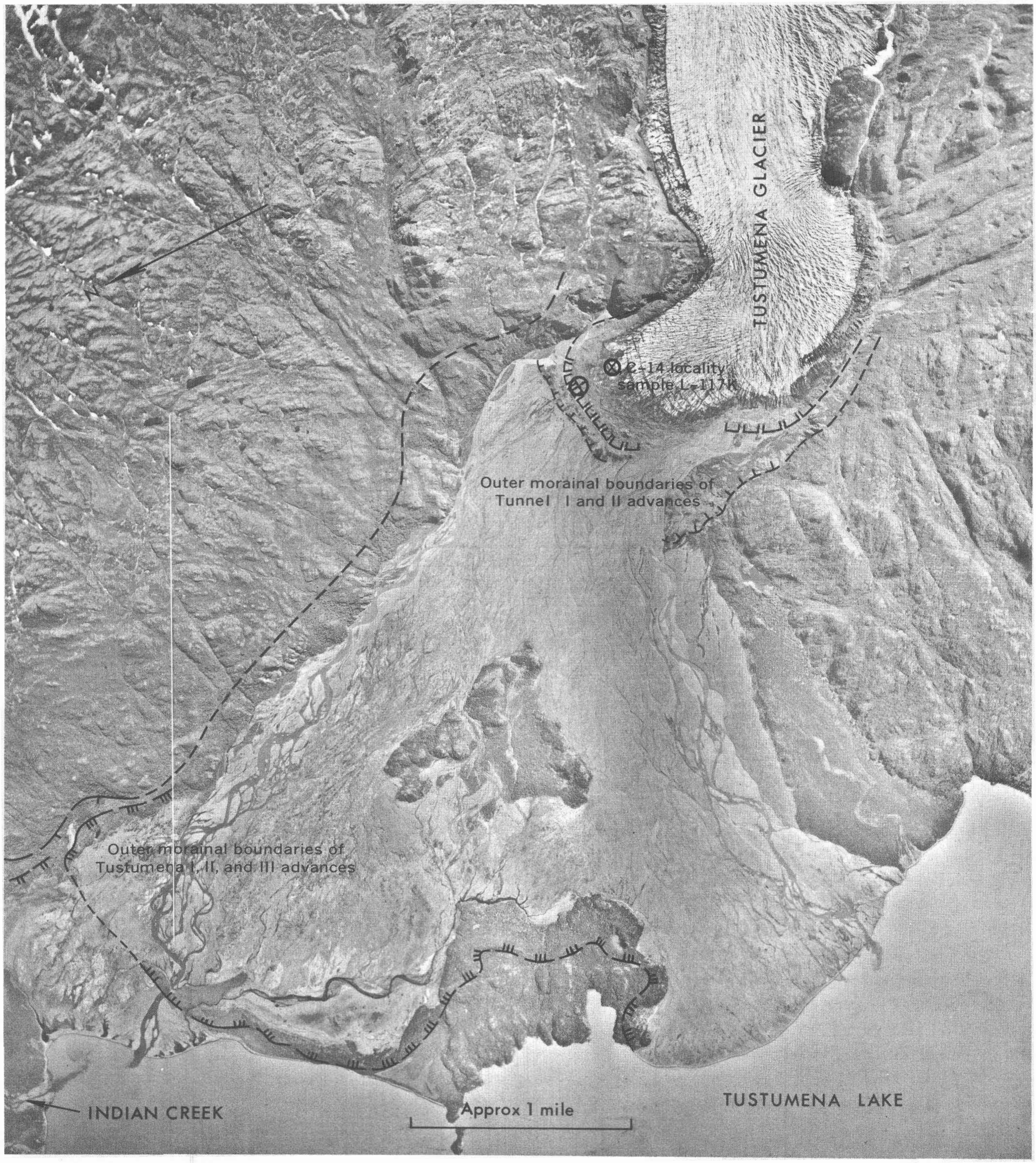


FIGURE 9.—Vertical photograph of moraines and outwash apron between front of Tustumena glacier and head of Tustumena Lake, Nikishka Lowland.

FIGURE 10.—Oblique photograph of Bartlett and Spencer glaciers flowing northwestward from coastal icefield in the Kenai Mountains near Prince William Sound.

and Tustumena glaciers are consistent in recording two main glacial advances separated by an interval in which the glaciers apparently retreated upvalley from present ice-front positions. Uprooted and ice-transported trunks of mature spruce, birch, and alder trees are incorporated in the till of the innermost belt of moraines (Tunnel II advance) within 300 feet of the present stagnating ice front of Tustumena glacier (fig. 9). This fossil forest is exposed in an area now devoid of forest and apparently represents an overridden forest that grew upvalley prior to the Tunnel II advance. Moraines of the Tunnel I advance lie just outside of moraines of the Tunnel II advance but within 500 feet of the present Tustumena glacier ice front; they are covered with willow thickets, whereas moraines of the Tunnel II advance are bare of vegetation. End moraines of Tunnel II age locally overlap and transect the trends of the Tunnel I moraines. Wood from the uprooted forest buried in till of Tunnel II age dates A.D. 1550 ± 150 years (L–117K), suggesting that the Tunnel II advance began somewhere upvalley from the present glacial front some time between A.D. 1400 and 1700, or ca. A.D. 1500.

Moraines of the Tunnel I and Tunnel II advances in Placer River valley lie respectively 1 mile and ½ mile downvalley from the present front of Bartlett glacier (fig. 10). The maximum extent of the Tunnel I advance is marked by a distinctive trimline separating a mature forest of mountain hemlock and aspen growing on deposits of the Tustumena advances from alder thickets which largely cover the moraines of Tunnel I age (fig. 11). In contrast, the moraines of Tunnel II age are covered by scattered thickets of mature alder within the outmost morainal belt, more scattered thickets of immature alder within an intermediate belt, and are essentially vegetation-free in a broad inner zone bordering Bartlett glacier. As examined along the lateral morainal boundary south of Bartlett glacier, soil development—if evident at all—is no more than a film of oxidation beneath scattered patches of moss on moraines of Tunnel II age; whereas, beneath the nearly complete moss-grass cover on moraines of Tunnel I age, iron staining extends as much as an inch into the underlying deposits. Surface boulders on Tunnel II moraines are largely free of lichen and show little evidence of surface alteration; those on Tunnel I moraines have a dull-gray weathered appearance and have an appreciably greater portion of their surfaces covered by lichens.

The stratigraphic section exposed in a railroad cut near the section house at Tunnel is as follows:

FIGURE 11.—Lateral moraines of Tunnel I age marginal to Bartlett glacier, upper Placer Creek Valley, Kenai Mountains. Photograph illustrates character of trimline between the mature forest of mountain hemlock covering moraines of Tustumena age and the alder- and grass-cover of the younger Tunnel moraines. Bartlett glacier lies just beyond the right edge of the picture, which shows the east-facing valley wall of Placer Creek in the background. Type locality of the Tunnel advances, youngest glaciation recognized in Cook Inlet.

3. 4½–6 ft. of olive-drab to blue-gray sandy boulder till of Tunnel I age; incipient soil development beneath 2–4 in. of organic turf.
2. Buried soil marked by local pockets of peat, uprooted trees (including mature hemlock, spruce, and alder), and buff oxidation that penetrates from 2–5 in. into underlying deposits. carbon–14 sample W–318 was collected from tree stump in place.
1. 10–15 ft. of olive-drab to blue-gray sandy boulder till of Tustumena III age overlying graywicke-argillite bedrock locally exposed above railroad grade level. carbon–14 sample W–78 taken from transported log collected from basal part of exposed till.

Wood from the forest zone overridden by Tunnel I ice and collected from this railroad cut dates A.D. 550 ±220 years (W–318; carbon–14 loc. R). The forest zone marks the termination of the Tustumena III retreatal interval prior to the advance of Tunnel I ice to its maximum position in the area. Its age, combined with that derived from the forest overridden by Tunnel II ice in the Tustumena glacier area, indicates that Tunnel I glacial maximum was between ca. A.D. 500 and 1500. Underlying the buried forest zone in the railroad cut is an older till with a buried soil typical of the deposits of Tustumena age as mapped elsewhere in the region. Wood from the ice-transported and -scoured log incorporated in the basal part of the buried till dates 420 B.C. ± 100 years (W–78; carbon–14 loc. R). The greater age of this sample is consistent with its lower stratigraphic position relative to the buried forest in the exposure and suggests that the Tustumena III advance, as best marked by end moraines near Tustumena glacier and in Palmer Creek, attained its maximum some time between ca. 500 B.C. and ca A.D. 500. If this interpretation is correct, the moraines of the Tustumena I and II advances must have been deposited prior to ca. 500 B.C.

End moraines of the Alaskan glaciation in front of Spencer glacier have been largely destroyed and (or) buried by the extensive outwash apron and valley train that fills lower Placer Creek valley. Spencer glacier is just north of, and downvalley from, Bartlett glacier. A log collected from till associated with a remnant of an end moraine about 1 mile downvalley from the front of Spencer glacier dates post-A.D. 1650 (L–163G; carbon–14 loc. S), which suggests Tunnel II age for the moraine. Historical records indicate readvances of Spencer glacier in the late 1890's and about 1916 (Wentworth and Ray, 1936). Field mapping of the glacier front by the author in 1953 and comparison with maps and photographs dated 1931, 1947, and 1951 indicate that the glacier expanded slightly to develop push moraines in the outwash apron between 1931 and 1947, and again between 1947 and 1951. When observed in 1953, the glacier had retreated 200 to 400 feet from its 1951 position (fig. 12).

FIGURE 12.—Position of Spencer glacier ice front in 1953 relative to its 1951 position and to remnants of push moraines that record ice advances ca. A.D. 1950 (not shown, but just in front of 1951 position) and ca. A.D. 1940. Trimline at upper margin of alder-covered Tunnel moraines shown on bedrock spur in middleground of photograph. Behind spur lies Bartlett glacier.

RADIOCARBON-DATED UPLAND TYPE BOGS

Numerous bogs occur in depressions on valley floors and higher slopes and surfaces throughout the Kenai Mountains and on the upland surfaces of the adjoining Kenai Lowland. Several have been measured and sampled for radiocarbon dating with the expectation that they would shed additional light on the climatic and glacial history of the region. The selected bogs lie at high elevations, occupy closed depressions, and presumably in their stratigraphic sequences record hydrologic changes that were directly responsive to changing precipitation rates such as those determined for the ombrogene or raised bog type (Granlund, 1932). If true, this means that recorded intervals of lower water-table levels should coincide with low precipitation periods favoring glacial retreat. Radiocarbon results have been obtained from basal organic samples collected by the author from 2 upland bogs in the Kenai Mountains (carbon–14 loc. P and Q), and by William S. Benninghoff from 1 bog (carbon–14 loc. N) on an upland surface in the Caribou Hills near Homer. In addition, radiocarbon results are available for basal samples, collected by Bjørn C. Andersen in the company of the author, from two upland bogs in the Talkeetna Mountains. Analyses of additional samples collected from these and other upland bogs can be expected to provide significant information bearing on local depositional controls in alpine and subalpine areas and will permit more precise correlations with climatic and geologic events recorded elsewhere in the region.

KENAI PENINSULA

A 4- to 6-foot-thick bog is exposed at an elevation between 500 and 600 feet in a roadcut along the Seward-Anchorage highway approximately 2 miles southeast of the Hope road junction in Sixmile Creek valley. The bog deposits directly overlie varved silt and clay that were laid down in a glacial lake during Naptowne time when the Turnagain Arm glacier created an ice dam within the lower part of Sixmile Creek valley. This lake was drained during late retreat of Naptowne ice out of Turnagain Arm, and bog deposition commenced in depressions on the emerged lake floor. Wood collected from the base of the bog immediately above the varved marginal lake sediments dates 4850 B.C. ±500 years (L–237F), and thus provides a close minimum date for drainage of the lake and late (Tanya?) retreat of Naptowne ice from the area. Since drainage of the lake, Sixmile Creek has cut a 50-foot-deep canyon in the bedrock underlying the lake sediments. The measured section is as follows:

9. 5–8 in. of dark brown silty woody peat.
8. 10–14 in. of red-brown silty moss-peat containing volcanic ash or silt layer ⅛–1/16 in. thick, 1½ in. down from top of unit.
7. 3–6 in. of greenish buff to gray silt.
6. 2–4 in. of woody moss peat.
5. 14–16 in. of red-brown peaty organic silt.
4. 2–10 in. of greenish buff to gray silt.
3. 6–10 in. of dense platy woody peat. Sample L–237F, wood fragments collected from base of unit.
2. 6–8 ft. of varved blue-gray silt stained greenish buff in upper 1–3 in. Laminae average 1/16–⅛ in. in thickness. Lake sediments of Naptowne age.
1. Graywacke-argillite bedrock exposed to creek level.

As the dated woody peat layer is overlain by organic silt indicating a return to wetter depositional conditions, it records an interval of bog drying which, on the basis of its radiocarbon age, was essentially contemporaneous with the recurrence boundary dated ca. 4600 B.C. in Sweden and with a comparable bog drying period radiocarbon-dated 4430 B.C. ±350 years near Cochrane, Canada (Karlstrom, 1956).

In nearby Ingram–Granite Creek valley, a small kettlelike bog deposit underlain in part by bedrock and in part by till of late Naptowne age is exposed in a roadcut along the Seward-Anchorage highway between elevations of 1,000 and 1,100 feet about 2 miles northeast of Tin Can–Lyon Creek bridge (carbon-14 loc. Q). The bog is in a depression on a moraine-covered bedrock ridge that lies well above the drainage levels of the divide area between the headwaters of Ingram and Granite Creeks. The bog contains (from top to bottom) 3 to 5 feet of interbedded moss-sedge woody peat and organic silt; 8 to 12 inches of wind-blown silt with a thin discontinuous ash layer near its base and a well-developed soil profile extending 3 to 5 inches down from the top contact; and from zero to 5 feet of till and associated drift of Naptowne age overlying graywacke-argillite bedrock. The record is of a dry interval of loess deposition and soil development following retreat of Naptowne ice from the valley and prior to a return to wetter depositional conditions and peat accumulation in closed depressions that can be equated with the expansion of alpine ice during Tustumena and later time as recorded by moraines in nearby tributary valley heads. The date of 2550 B.C. ± 450 years (L–237), obtained from moss peat collected from the lower 6 inches of the peat section, falls between the 4850 B.C. date obtained for late Naptowne retreat in the Sixmile Creek bog and the pre-500 B.C. age inferred from the railroad-cut section near Tunnel for the Tustumena I and II advances. The combined radiocarbon evidence from the Kenai Mountains thus suggests that the moraines of the Tustumena I and II advances were deposited some time between 2550 and 500 B.C.

William S. Benninghoff (oral communication, 1954) sampled an upland bog that occurs at an elevation of 1,300 feet on the southeast side of Lookout Mountain, approximately 5 miles north of Homer (carbon-14 loc. N). The radiocarbon sample (L–137T; 3850 B.C. ± 500 years) was a composite of sedge peat and wood fragments obtained by drilling with a Hiller Sampler at five places into the bog. Although some contamination of the sample with peat from upper layers may have occurred, Benninghoff feels that the date is probably valid. The sampled zone was a woody peat layer 15 to 17 feet below the surface of the bog and 2 to 2½ feet above the base of the peat section resting on sorted silt and sand. Stratigraphic relations between the sampled bog and the underlying drift of Eklutna age are not known. As dated, the woody zone—which seems to represent a significant dryer period in the history of bog development—is essentially contemporaneous with the buried soil in Bog Q, with the recurrence surface (interval of bog drying) dated in northern Europe ca. 3500 B.C., with a radiocarbon-dated period of bog drying (3350 B.C. ± 300 years) recorded in a bog near Cochrane, Canada (Karlstrom, 1956), and with the altithermal soil of western United States associated with charcoal dated 3500 B.C. ± 160 and 3830 B.C. ± 160 (Scott, 1956, p. 426).

SOUTHWESTERN TALKEETNA MOUNTAINS

Two bogs in the Willow Creek area, southwestern Talkeetna Mountains, have been sampled by Bjørn C. Andersen and the author. Basal organic silt was sampled by peat borer at a depth of 15 feet in a bog in the lateral moraine complex 2.5 miles west-southwest of the steel bridge at the mouth of Willow Creek valley (carbon-14 loc. T). The lateral moraines are of Eklutna age; and the bogs and lakes, present on the upland surface between elevations of 1,500 to 1,600 feet, occupy broad depressions between morainal ridges. Great care was exercised in sampling the basal layer by peat borer, and it is believed that the sample is probably uncontaminated and that the radiocarbon result of 9980 B.C. ± 250 years (W–360) is a valid date. However, the stratigraphic relations between the sampled bog and the underlying drift of Eklutna age are not known.

The second bog sampled occupies a closed depression within the large main morainal complex in Willow Creek valley attributed to the Naptowne glaciation (carbon-14 loc. U). The bog was excavated by shovel to a depth of 7 to 8 feet, and twigs and wood fragments collected had a base date of 7920 ± 250 years (W–336). The stratigraphic relations between the sampled layer and the underlying drift are not known.

RADIOCARBON-DATED SEDIMENTS OF TUSTUMENA AGE IN THE HOMER AREA

The Homer area was covered by ice of Naptowne age that during retreat fronted in a proglacial lake. As recorded in the coastal lowland bog at carbon-14 locality L, retreat of the ice uncovered the Homer spit area, and proglacial water receded below an elevation of 20 to 25 feet prior to 7000 B.C. Subsequent deposition in the form of coalescent alluvial fans and slump deposits mantled the till and proglacial-lake sediments in the area. Radiocarbon analyses of organic material buried beneath these surficial deposits indicate recent impulses of sedimentation in the Homer area essentially contemporaneous with glacial advances of Tustumena age dated in the northern part of the Kenai Peninsula.

According to D. B. Krinsley (oral communication, 1952), wood apparently representing a forest destroyed by a sudden impulse of colluvial deposition on a steep slope was collected from a zone underlying 6 feet of stabilized slope wash and landslide debris and overlying 8 feet of stratified silt and sand resting on till of Naptowne age. The sample dates 300 B.C. ± 300 years (L-137K; carbon-14 loc. K), or essentially contemporaneous with the forest remains dated 420 B.C. ± 100 years (W-78) incorporated in the basal till zone of Tustumena III age in the Placer Creek valley near Tunnel.

William S. Benninghoff (oral communication, 1953) collected a spruce root from a depth of 4½ feet—about 18½ feet above mean high tide—in an alluvial-fan section exposed along the sea bluffs 50 yards west of Miller's Landing near Homer. According to Benninghoff, the spruce root was buried in a late interval of deposition during the development of the numerous extensive alluvial fans which spread over Homer Bench from source gullies at the base of the Tertiary sandstone and siltstone bluffs that confine Homer Bench to the northwest. The spruce root dates 1250 B.C. ±150 years (L-117B; carbon-14 loc. M), or within the time interval between 2550 and 500 B.C. derived for the Tustumena I and II glacial advances from the radiocarbon-dated glacial stratigraphy in the northern Kenai Mountains. Past periods of accelerated alluviation in the Homer area can be reasonably equated climatically with increased precipitation rates, and thus with conditions favoring glacial advances in the high alpine valleys of the adjoining Kenai Mountains. On this basis, the intermediate age of the dated alluvial impulse in the Homer area strongly suggests that it is more likely correlative with the intermediate Tustumena II advance than with the earlier Tustumena I. If so, an age of ca. 1000 B.C. is obtained for the Tustumena II moraines. The buried spruce root presumably represents a period of alluvial-fan stabilization and forest growth in the Homer area. This inferred drier-period is then contemporaneous with the dry period marked by the recurrence surface IV of the Scandinavian bog chronology, dated ca. 1200 B.C.

COASTAL-BOG STRATIGRAPHY AND FAUNA

COOK INLET

More than one-third of the Cook Inlet Lowland is covered by poorly drained ground underlain by a few feet to more than 20 feet of organic silt and peat. Blanket deposits of peat and organic silt cover large areas of flat terrace and bottom-land surfaces. Thicker bog deposits of organic silt and peat occupy basinlike depressions and channels in the irregular topography of the lowland. Thick basin, or topogene, type bog deposits are locally exposed in the sea bluffs and are readily accessible for detailed study of the bog stratigraphy. These deposits provide essentially continuous and sensitive depositional records relating to the climatic and hydrologic history of the region, and a number of them have been measured and sampled for radiocarbon dating. In addition, two tidal marshes in the region—one near Goose Bay, the other near Girdwood—have been stratigraphically measured and sampled. The radiocarbon-dated bogs and other measured bogs are shown in plate 6, which portrays their intercorrelations and relationship to underlying glacial drift.

The bog deposits examined in the region range from finely laminated organic silt deposited in lake or pond environments to woody moss peat deposited above surface-water levels. The organic deposits have been subdivided on the basis of composition and megascopic plant remains into the following broad ecological and environmental categories:

1. Woody peat. Predominantly fibrous mossy peat containing abundant tree remains including twigs, branches, trunks, and locally stumps in place of birch, spruce, alder, aspen, and cottonwood. Represents terrestrial peat and forest accumulations above surface- and ground-water levels.
2. Heath peat. Predominantly fibrous mossy peat locally containing some sedge-grass remains, and with abundant twigs and roots of heath-type plants including dwarf birch, crowberry, Labrador-tea, cranberry, speracea, and blueberry. Represents terrestrial peat accumulation at or above groundwater levels.
3. Sedge peat. Predominantly dark-gray to black sedge-grass peat with a pronounced platy structure. The sedge peat locally contains some mossy peat and remains of various reed-type aquatic plants. Represents terrestrial peat accumulation at and just below surface-water levels.
4. Pond deposits. Predominantly alternate layers of organic silt and detrital peat containing remains of reedlike aquatic plants, seeds, spruce cones and needles, fragments of birch bark, and locally, beaver-gnawed wood. Represents deposition in shallow water ponds.
5. Lake deposits. Predominantly finely laminated organic silt commonly containing diatoms, scat-

tered seeds and plant fragments, spruce cones and needles, and locally, pelecypods and gastropods. The mollusks and diatoms identified from these lake silts (table 2) include a rich suite of fresh-water forms. Represents deposition in deeper quiescent water of closed lake basins.

These categories and the environmental interpretations are essentially those used by Dachnowski-Stokes (1941) in his stratigraphic studies of Alaskan bogs. The subdivision emphasizes the broad stratigraphic units in the bogs. More detailed study of pollen, spore, and microfossil stratigraphy should permit more refined subdivision and contribute additional information on the biologic sequence in the region. Samples for pollen analyses have been collected at close intervals from many of the bogs, but analyses are still pending. A pollen profile, still unpublished, has been completed for the bog near Homer (carbon-14 loc. L) (Benninghoff and Brush, 1957). Heusser (1958) summarizes the pollen data available from this and other sites in Alaska. Owing to small scale of presentation, only the broad subdivision of terrestrial peat deposits and of pond and lake organic deposits can be shown in plate 6. The more detailed stratigraphy of representative bogs is shown in plate 7.

Depending on local environmental factors such as depth of basin, threshold conditions, underlying materials, and relation to ground-water levels, the character of the bog deposits varies somewhat from locality to locality. In general, however, the bogs which floor at the higher levels in the sea bluffs are thicker and represent a longer stratigraphic history than those that floor at lower levels. Most are similar in that their stratigraphic sequences do not record progressive filling of the depositional basins with time but, instead, show a series of depositional interruptions and repeated returns to wetter environmental conditions following intervals of dryer conditions. The parallelism expressed by the stratigraphy of the widely separate bogs is strong evidence for some sort of regional hydrologic control. Development of bogs in depressions on an old proglacial-lake floor indicates that they should provide an essentially complete depositional record from the present back to late proglacial-lake events:

For convenience of description, the bogs are subdivided into bog groups on the basis of locality and stratigraphic similarities.

Bog group A includes two tidal bogs of comparable stratigraphy (pl. 6, profile X) whose surfaces are just above mean sea level near Girdwood (Bog A–1) along Turnagain Arm and at Goose Bay along Knik Arm (Bog A–2). The tidal-bog record at both localities is of a lower peat unit, exposed only at low tide, interbedded with thin tidal-silt beds; an intermediate thick tidal-silt section; and an upper peat unit comprising alternate forest- and sedge-peat layers and thin tidal-silt layers. The peat beds record intervals in the past when sea level was generally lower than at present; the tidal-silt beds record intervals when sea level was generally higher than at present. Observations at Girdwood in 1950, 1951, 1953, 1955, 1957, and 1958 indicate that storm tides, which did not flood the tidal-bog surface prior to 1953, began depositing a thin surface silt layer that has become progressively thicker each year since 1953, suggesting the recent sea-level transgression that has been recorded elsewhere in the world (Charlesworth, 1957, p. 1365). Wood collected from the lower and upper peat beds at Girdwood dated respectively 850 B.C. and A.D. 1250 and indicates significant sea-level fluctuations in the region between and around these dates. The detailed stratigraphy and the radiocarbon-dated boundaries of Girdwood tidal bog are shown in plate 7. A photograph of the bog is shown in figure 13.

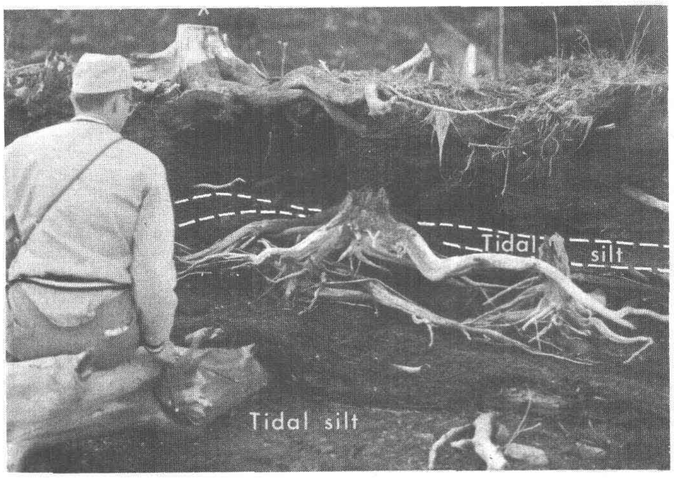


FIGURE 13.—Stratigraphy of upper peat unit, Girdwood tidal bog A–1, Upper Cook Inlet. The fallen log on which the man is sitting marks the lowest of the three forest zones separated by beds of sedge peat and underlain and overlain by tidal silt. "Y" marks in-place location of stump from which carbon-14 sample W–175 was collected; "X" marks tree-ring dated stump.

Bog group B comprises three surface bogs of comparable gross stratigraphy. These bogs are on surfaces at elevations between 50 and 125 feet that lie in front of and behind the end moraine of the Naptowne glaciation in the Anchorage area (pl. 6, profile IX). All three bogs contain a lower and an upper peat unit that are separated by an unconformity and a laminated sand and silt unit in Bog B–1, a laminated silt and sand unit with two thin peat beds in Bog B–2, and two inorganic silt layers and an intermediate organic silt layer in Bog B–3. The lower peat bed in all three bogs rests on water-laid sand and silt and thus represents an interval of subaerial peat accumulation separating two intervals of water deposition. In Bog B–1, a sample collected from the lower peat by Robert Miller (Miller and Dobrovolny, 1959, p. 68) dates 9650 B.C. (W–540), or apparently contemporaneous with the interval of subaerial weathering recorded by buried soil beneath the organic silt bed that dates 8420 B.C. in Bog D–1 near Point Possession.

Bog group C comprises two radiocarbon localities on Fire Island that were examined and sampled by Robert Miller, Ernest Dobrovolny, and W. R. Hansen (Miller and Dobrovolny, 1959, pp. 32, 89) (pl. 6, F–2). As described by the collectors, the bluff section at radiocarbon locality C–2, 1 mile east of Fire Island light, contains the following sequence (from top to bottom):

6. 3 to 20 ft. dune sand.
5. 5 ft. of platy silty peat, W–556, collected along contact with underlying unit.
4. About 1 or 2 ft. of silt with peat fragments.
3. About 1 or 2 ft. of tight clay.
2. 20 ± ft. of blue-gray silty till.
1. 25 ± ft. of tan silt.

Because of vertical bluffs, units 2 to 6 were not measured or examined in detail. The section is similar to that overlying weathered till of Knik age near Point Possession; and the author believes that unit 5, interpreted as unweathered till of Knik age, represents unweathered proglacial-lake stony silt sediments of Naptowne age. The overlying sand-dune-buried bog on Fire Island dates 7350 B.C., or essentially contemporaneous with the comparable buried peat beds dated near Point Possession.

At radiocarbon locality C–1, the bluff sequence exposed 0.6 mile northeast from Fire Island triangulation station is described as follows (from top to bottom):

5. About 20 ft. of dune sand containing layers of buried logs and stumps, carbon-14 sample W–541 collected from stump, with roots penetrating underlying unit, in lower foot of dune sand.
4. 3 ft. of brown-stained sand (buried soil).
3. Thin white ashy sand (podzolic layer?).
2. 2 ft. of brown silt.
1. Gravel, thickness not measured.

The buried compound soil apparently formed contemporaneously with bog deposition at locality C–2. Sample W–541 provides a date of after ca. A.D. 1330 for accelerated cliff-head dune formation and burial of the land surface along the coastal margin of Fire Island in the vicinity of Bog C–1.

Bog group D includes three measured bogs near Point Possession that are exposed in the sea bluffs between elevations of 100 to 150 feet and are buried by a variable thickness of windblown sand underlying cliff-head dunes (pl. 6, profile V). Each of the three bogs contains two basal beds of organic lake silt separated from each other and from underlying proglacial-lake stony silt by soil profiles or thin peat layers indicating short intervals of subaerial weathering; an intermediate thick peat bed of predominantly woody or heath moss; and an overlying section of stratified predominantly dune sand. Wood from the middle of the lowermost organic-silt bed dates 8420 B.C. in Bog D–1. Wood and organic silt from the overlying organic-silt bed dates, respectively, 7550 B.C. in Bog D–3, and 7250 B.C. in Bog D–2. Wood from the base of the stratigraphically higher peat bed dates 6580 B.C. in Bog D–1. The five samples analyzed from these bogs give ages that are internally consistent, within the limits of dating error, with each other and with their stratigraphic position. Samples W–602, W–603, and W–474, analyzed by the more accurate gas-counting method, confirm the general accuracy of samples L–137D and L–163D, which were analyzed earlier by the solid-carbon method. As radiocarbon-dated, the beginning of main peat accumulation near Point Possession was contemporaneous with deposition of the lower peat bed exposed near Boulder Point in Bog E–1. The detailed stratigraphy of Bog D–1 is shown in plate 7.

Bog group E is made up of four measured bogs whose surfaces are below an elevation between 50 and 60 feet along the sea bluffs between the Swanson River and Boulder Point (pl. 6, profile II). Bogs E–1 and E–4 contain a lower peaty bed that is either missing or covered with slump in Bogs E–2 and E–3. Two samples, L–1170 and L–163B, collected from near the base of the lower peat bed in Bog E–1, provide an average date of 6475 B.C. for the beginning of peat accumulation. All four bogs contain near their top a zone marked by three closely spaced thin sand and silt layers immediately above a boundary that marks an abrupt change from wetter to drier depositional conditions. Radiocarbon dating of this reference zone in Bog E–4 gives an average date of 1800 B.C. (L–163E, L–163F), and in Bog E–1, an average date of 1800 B.C. (L–117N, L–434). The reference zone immediately overlies a boundary marking a change from deeper lake to beaver-pond deposition in Bog E–4, from beaver-pond to woody- and heath-peat deposition in Bogs E–3 and E–1, and from lake-silt to moss-peat deposition in Bog E–2. The differences in the type of deposits involved reflect differences in elevation of the depositional basins, threshold conditions, and relation to regional groundwater levels. The detailed stratigraphy of Bog E–1 is shown in plate 7.

Bog group F includes two measured bogs immediately south of East Foreland that lie below an elevation of 100 feet (pl. 6, profile I). The deposits in both bogs contain a deformed basal section made up of two thin peat and organic-silt layers interbedded with stratified silt, sand, and gravel; an undeformed middle section of laminated organic silt rich in fresh-water diatoms and mollusks; and an upper surface layer of moss-sedge peat. The lowermost contorted peat layer in Bog F–2 dates 10,900 B.C. ±300 years (W–416). The detailed stratigraphy of the stratigraphically similar but more highly deformed Bog F–1 is shown in plate 7.

Bog group G comprises two measured bogs near Salamato Creek that lie below an elevation of 150 feet. Both bogs contain a basal layer made up of 1 or 2 thin beds of contorted silt and sand separated from each other and from underlying contorted iron-stained gravel by angular unconformities; a thin zone of 2 or 3 layers of peat and organic silt interbedded with stratified sand and silt; a thick section of organic lake silt rich in fresh-water diatoms and pelecypods; and a surface layer of moss-sedge peat. Wood collected from between the two contorted silt and sand layers at the base of Bog G–2 dates pre-35,000 B.C. The lowermost contorted silt unit, apparently present only in Bog G–2, contains two ash layers which may have been deposited at the same time as the two ash layers that occur in the bog buried beneath till of Naptowne age near Goose Bay. The two ash layers at both localities underlie radiocarbon-dated zones that date beyond the range of the dating method and overlie deposits of Knik age. The second uncontorted basal organic layers in Bogs G–2 and G–1 were correlated, on the basis of stratigraphic sequence, with the contorted basal beds in Bogs F–1 and F–2. Recent analysis of a sample collected from the first basal uncontorted organic bed in Bog G–2 provides a date of 11,550 B.C. ± 400 years (W–748), which is consistent with this correlation.

The radiocarbon-dated bog near Homer (carbon-14 loc. L, pl. 6, profile VI) is exposed in the sea bluffs one-quarter mile west of the base of Homer Spit and occupies a kettle depression in till of Naptowne age. The bog occurs on a surface that lies between 20 and 25 feet above mean sea level. According to the collector (William S. Benninghoff, oral communication, 1954), the carbon-14 sample was made up of transported wood fragments (probably willow and balsam poplar) incorporated in a water-reworked zone immediately overlying unweathered till and directly underlying 8 to 9 feet of limnetic peat. The character of the gross stratigraphy of the peat deposits is not known. The fossil-pollen record of the overlying peat shows a long period before appearance of spruce and birch trees in the Homer area (Benninghoff and Brush, 1957). Carbon-14 sample L–137W dates 7050 B.C. ± 750 years. The Homer coastal bog is significant in that it provides a minimum age for the underlying till of the Skilak advance, indicates that sea or proglacial-lake levels have not risen above the 20- to 25-foot level in the past 9,000 years, and is consistent with the records of bogs E–1, D–1, and C–2 in showing an important regional hydrologic change from higher to lower water levels at about 7000 B.C.

The coastal bog near Ninilchik (carbon-14 loc. I) was examined and sampled by D. B. Krinsley. A date of 7650 B.C. ±700 (L–137L) was obtained for wood collected from the base of a 10-foot-thick peat section in a broad-floored abandoned drainage line overlying 20 feet of stratified sand and gravel resting on gray till. No description of the bog stratigraphy is available, and the elevation of the bog is not reported.

The coastal bog near the Anchor River (carbon-14 loc. J) was examined and sampled by William S. Benninghoff. A tentative date of 5350 B.C. ±600 years (L–137U) was obtained from alder twigs and fragments of coniferous wood collected from silty limnetic peat at a depth of around 10 feet. According to Benninghoff (oral communication, 1954), the stratum of limnetic peat is the basal member of the peat deposit and overlies 15 inches of fine mineral soil mottled light brown and gray that is interpreted as a former forest soil. Sample L–137U was dated by the early solid-carbon method at Lamont Laboratory. It was given only one run, rather than the two or more runs used in deriving most of their early solid-carbon results, and has been set aside by the laboratory for recounting. The bog was sampled for pollen analyses, but no description of the bog stratigraphy or drift sequence beneath it is available.

The coastal-lowland type bogs briefly described above and shown graphically in plate 6 record synchronous depositional changes in isolated basins that are separated by as much as 150 miles. The integration of this regional hydrologic record with the sea-level record of the tidal bogs and with the glacial and glaciolacustrine record of Cook Inlet, as graphically shown in plate 7, will be discussed in the section, Pleistocene history.

GULF OF ALASKA

Pertinent radiocarbon dates from coastal bogs on the Kodiak Island group at the mouth of Cook Inlet and on Perry Island in Prince William Sound have been published recently (Heusser, 1959). Basal organic beds from bogs whose surfaces lie about 20 feet above present sea level near Afognak Village (carbon-14 loc. Y) and on the southern coast of Perry Island date respectively 7400 B.C. ±320 years (K–AGS–3) and 7490 B.C. ±350 years (I–AGS–4). Samples from basal organic beds of surface bogs whose surfaces lie about 100 feet above present sea level at Karluk (carbon-14 loc. W) and at Kodiak (carbon-14 loc. X) date 1520 B.C. ±180 years (I–AGS–1) and 6920 B.C. ±300 years (I–AGS–3), respectively. Pollen profiles from these and other bogs sampled along the coast between Kodiak Island and California constitute the basis for Heusser's reconstruction of late-glacial and postglacial climatic events. The carbon-14 dated zones represent the lowermost levels probed in sampling by peat borer, and the nature of the unpenetrated underlying deposits and their stratigraphic relations are not known.

The Kodiak Island and Perry Island sites were covered by glacial ice during Naptowne time; the dated basal organic layers thus provide minimum dates for deglaciation of these coastal sites. However, in the absence of critical geologic information on the nature and sequence of the underlying sediments, it is uncertain whether the dated zones represent organic accumulation closely following deglaciation or, as equally likely, later postglacial deposition related only indirectly to the regional chronology of glacial retreat.

The sampled Afognak and Perry Island bogs are comparable in topographic setting and age to the coastal Bog L near Homer and provide the same inference of essental crustal stability relative to sea level over at least the past 9,000 years. This is regionally compatible with the absence of recognized elevated marine strand lines in Cook Inlet and in the coastal areas north of the Chugach-St. Elias boundary fault and indicates that the divergent younger ages of the dated bogs at higher elevations near Kodiak and Karluk cannot be reasonably related to differential postglacial sea-level shifts but must be related to other more restricted environmental factors affecting local accumulation and preservation of organic material. This is seemingly recognized by Heusser, who derives precise and diverse rates of postglacial uplift from comparably dated coastal bogs at different elevations in the Yakataga Lowland south of Cordova, but who makes no comparable calculations from the dated Kodiak and Perry Island bogs.

The basic assumption used by Heusser, that the basal layers in the Yakataga Lowland coastal bogs record organic accumulation that began immediately after emergence from beneath the sea, is provided with some geologic support by the coastal evidence of uplifted marine terraces which postdate the Naptowne maximum, and by the presented carbon-14 data which suggest that the sampled bogs at higher elevations began to accumulate prior to those at lower elevations. Nonetheless, the assumption that the lowest organic beds sampled by peat borer must necessarily closely date the time of marine emergence of the sampled sites is subject to major qualifications that can be directly satisfied only by a more detailed study of the individual bog environments, and particularly of the geologic sequence recorded by the underlying and unpenetrated sediments. That the southeastern coast of Alaska has been subject to a complex history of late Quaternary uplifts, not experienced by the crustal block north of the Chugach–St. Elias boundary fault seems certain. The postulated amounts and carbon-14-based rates of differential uplift along the coast south of the boundary fault, however, are less certain.

FAUNA

The fauna identified from coastal-bog samples are listed and discussed below.

Fresh-water mollusks.—Fresh-water mollusks collected from the coastal-bog sediments were identified by J. P. E. Morrison of the U.S. National Museum. Bogs G–1 and G–2 yielded the following forms: *Anodonta* cf. *A. beringiana* Middendorff, collected from the upper 10 feet of the organic-silt unit; and *Pisidium* cf. *P. idahoense* Roper, collected from the basal part of the organic-silt unit. Bog E–3 yielded *Valvata lewisi mergella* Westerlund, *Lymnaea stagnalis* Linné *Stagnicola palustris* Müller, *Gyraulus parvus* Say, *Armiger crista* Linné *Pisidium liljeborgi Clessin*, *Pisidium vesiculare* Sterki, and *Pisidium subtruncatum* Malm, collected from the 10-foot-thick silt unit. (See pl. 6 for location of collecting sites.)

According to F. Stearns MacNeil (written communication, 1951), all the identified mollusks are living species, but several have not been reported previously from Alaska; all are strictly fresh-water forms and not estuarine in origin as had been considered probable by the author in 1951.

Fresh-water diatoms.—Eighty-five species and varieties of fresh-water diatoms were identified from silt samples collected from Bogs G–1 and G–2 (table 2). Sample 3427 was collected from Bog G–1 from the top of the upper organic-silt and sand section lying below a 5-foot-thick peat bed. Samples 3428, 3429, and 3420 were collected from Bog G–2 from, respectively, near the base of the upper organic-silt unit, the middle of an underlying 10-foot-thick section of finely laminated gray organic silt, and a compact blue-gray inorganic silt layer about 13 feet below sample 3429. No diatoms were found in the compact blue-gray inorganic basal silt layer (sample 3420).

According to K. E. Lohman (written communication, 1956) the diatoms in these assemblages are similar to those now living in the littoral zones of large cool to cold fresh-water lakes and in the fresh-water zones of many estuaries. No marine species were found, and only seven of the listed species and varieties prefer slightly saline to brackish water. The diatoms identified are still represented in living assemblages in many parts of the world, and the age of the sampled Alaskan bogs can hardly be older than late Pleistocene. This diatom-age determination is supported by radiocarbon dating and the regional geology which indicates that the collected lake sediments were deposited in late and post-Naptowne (Wisconsin) time and postdate 11,000 B.C.

TABLE 2.—*Fresh-water diatoms from coastal-bog sediments, Nikishka Lowland*

[Identification by K. E. Lohman. Relative abundance is indicated by D, dominant; A, abundant; C, common; F, frequent; and R, rare. See plate 6 for location of collecting sites]

Species	Locality		
	3427	3428	3429
Amphora ovalis Kützing	F	R	R
cf. *A. proteus* Gregory	F	R	F
Caloneis bacillum (Grunow) Mereschowsky	------	------	R
schumanniana (Grunow) Cleve	------	R	------
schumanniana var. *biconstricta* Grunow	------	R	------
silicula (Ehrenberg) Cleve	F	------	------
silicula var. *truncatula* Grunow	F	------	F
silicula var. *tumida* Hustedt	------	F	F
Campylodiscus noricus Ehrenberg	------	------	F
noricus var. *hibernica* (Ehrenberg) Grunow	C	F	------
Cocconeis placentula Ehrenberg	R	------	------
placentula var. *lineata* (Ehrenberg) Cleve	F	F	------
Cymatopleura elliptica (Brebisson) Wm. Smith	F	F	C
elliptica var. *nobilis* (Hantzsch) Hustedt	------	R	------
solea (Brebisson) William Smith	C	F	C
Cymbella aspera (Ehrenberg) Cleve	C	F	F
cistula (Hemprich) Grunow	C	F	F
cuspidata Kützing	F	R	R
cymbiformis (Agardh) Kützing	------	------	R
ehrenbergii Kützing	F	F	F
lanceolata (Ehrenberg) Van Heurck	C	F	------
mexicana (Ehrenberg) Cleve	C	F	F
reinhardtii Grunow	R	------	------
turgida (Gregory) Cleve	F	F	C
ventricosa Kützing	R	------	R
sp	------	F	------
sp	------	------	R
Diploneis ovalis (Hilse) Cleve [1]	F	R	------
Epithemia intermedia Fricke	------	F	F
sorex Kützing [1]	------	------	F
turgida (Ehrenberg) Kützing [1]	C	F	C
turgida var. *granulata* (Ehrenberg) Kützing [1]	F	F	F
zebra var. *porcellus* Kützing	F	F	------
zebra var. *saxonica* Kützing	C	------	F
Fragilaria leptostauron (Ehrenberg) Hustedt	------	F	------
sp	------	R	R
Gomphoneis herculana (Ehrenberg) Cleve	F	R	------
Gomphonema constrictum var. *capitata* Ehrenberg	R	------	------
intricatum Kützing	R	R	------
lanceolatum Ehrenberg	F	F	F
Gyrosigma attenuatum (Kützing) Rabenhorst	R	R	F
Melosira cf. M. *arenaria* Moore	------	R	------
juergensi Agardh [1]	F	------	------
granulata var. *angustissima* Müller	------	R	------
cf. *M. italica* (Ehrenberg) Kützing	R	------	------
Navicula cuspidata Kützing	R	R	F
dicephala (Ehrenberg) Wm. Smith	------	------	R
oblonga Kützing [1]	------	------	F
peregrina (Ehrenberg) Kützing [1]	------	------	C
placentula (Ehrenberg) Grunow	R	R	R
pupula var. *rectangularis* (Gregory) Grunow	------	R	------
radiosa Kützing	------	------	F
reinhardtii Grunow	R	------	------
scutelloides William Smith	R	------	------
sp	R	R	------
Neidium affine var. *amphirhynchus* (Ehrenberg) Cleve	F	F	------
bisulcatum (Lagerstedt) Cleve	------	------	R
iridis (Ehrenberg) Cleve	F	F	------
Nitzschia sp	------	------	F
Pinnularia borealis Ehrenberg	------	R	------
dactylus Ehrenberg	F	------	F
cf. *P. flexuosa* Cleve	------	R	------
major (Kützing) Cleve	------	C	------
cf. *P. major* (Kützing) Cleve	------	R	------
mesolepta (Ehrenberg) William Smith	R	------	------
microstauron (Ehrenberg) Cleve	------	------	R
nobilis Ehrenberg	F	------	------
cf. *P. obscura* Krasske	R	------	------
streptoraphe Cleve	------	R	------
viridis (Nitzsch) Ehrenberg	R	F	C
cf. *P. viridis* (Nitzsch) Ehrenberg	R	R	------
sp	------	------	R
Rhopalodia gibba (Kützing) Muller	F	F	C
parallela (Grunow) Muller	------	R	------
Stauroneis anceps Ehrenberg	F	------	------
phoenicenteron Ehrenberg	R	R	R
Stenphanodiscus astraea (Ehrenberg) Grunow	C	A	D
Surirella biseriata Brebisson	F	------	------
elegans Ehrenberg	C	F	C
robusta var. *splendida* (Ehrenberg) Van Heurck	C	------	------
Synedra ulna (Nitzsch) Ehrenberg	------	------	R

[1] Species and varieties preferring slightly saline to brackish water.

GEOLOGIC HISTORY

PRE-PLEISTOCENE HISTORY

The pre-Pleistocene history of the Kenai Lowland and adjoining Kenai Mountains is only partly recorded, and numerous problems remain to be solved before a detailed geologic reconstruction of the region can be attempted. The present available record is of geosynclinal sedimentation in the general area of the Kenai Mountains throughout Mesozoic time interrupted by intervals of mountain building and volcanism at the end of the Jurassic period and during one or more intervals within the Cretaceous period (Payne, 1955). During early Tertiary time, it is probable that the Cook Inlet depression existed, and that the significant episodes of deformation, faulting, and intrusion of the Kenai Mountains had been completed. The subsequent history is essentially one of progressive filling of the Cook Inlet basin interrupted by minor episodes of deformation and modification. Whereas at the beginning of Tertiary time the basin could have conceivably been below sea level, during at least part of Eocene time it stood above sea level and was being filled with the nonmarine sediments of the Kenai formation. Deposition was probably slow, and was probably accompanied by gradual crustal subsidence aggregating more than 5,000 feet. The mountain-border fault may have existed at this time, and subsidence of the lowland may have been, at least in part, accommodated by vertical displacement along this fault. Subsequent flexuring of the Kenai formation on the Kenai Lowland probably took place either at the end of Eocene time or later, after a period of continued deposition or erosion, during a Pliocene orogenesis (Cobb, 1952, p. 10). Regardless of the preceding probabilities, by the end of Tertiary time the Cook Inlet basin and surrounding mountain ranges existed approximately in their present form. Their subsequent modification to the present regional landscape is predominantly the product of both glacial erosion and deposition during repeated episodes of Pleistocene glaciation, as detailed below.

This regional interpretation differs from the hypothetical physiographic history of southern Alaska and the Alaska Range proposed by Wahrhaftig (1950, 1958), in which regional geomorphic evidence is adduced for the development of two postmature erosional surfaces in Cenozoic time and for progressive uplift and northward tilting of the Alaska Range in early Pleistocene time. To reconcile his postulated Pleistocene uplift of the Alaska Range with the local glacial record of concomitant lessening of glacial intensity, Wahrhaftig suggests the special hypothesis that the coastal range (Kenai and Chugach Mountains) must also have undergone major uplift so that during early Pleistocene time they would have been lower and thus would not have acted as moisture barriers shutting off precipitation supplies for icefield centers in the Alaska Range. The author found no geomorphic, structural, or stratigraphic evidence in the Cook Inlet region for either Cenozoic peneplanation or Pleistocene uplift of the Kenai Mountains. As previously discussed, the regional distribution of the pre-Naptowne as well as Naptowne moraines (derived from both the Alaska Range and coastal-range sources) in Cook Inlet is consistent with the present orographic climatic pattern of the region and strongly suggests that no major differential uplifts in the region have occurred since middle, if not early, Pleistocene time.

PLEISTOCENE HISTORY

Five Pleistocene glaciations are recognized in the Cook Inlet region (Karlstrom, 1955b; 1957). All are represented by depositional and erosional forms in the Kenai Lowland and the adjoining Kenai Mountains. These glaciations were named from type sections exposed on Mount Susitna in the southern Susitna Lowland, in the Caribou Hills on the Kenai Lowland, in the Eklutna River valley north of Anchorage, along Knik Arm near Anchorage, and near the settlement of Naptowne (now called Sterling) along Sterling Highway near Skilak Lake on the Kenai Lowland. Morainal evidence for a series of post-Pleistocene glacial advances is found throughout the alpine-mountain areas of the state (Péwé and others, 1953; Karlstrom, 1957). These advances are placed within the Alaskan glaciation of the Cook Inlet glacial chronology.

MOUNT SUSITNA GLACIATION

During this, the most extensive glaciation recorded in the Cook Inlet region, icecaps blanketed the surrounding Alaska Range and the Talkeetna, Chugach, and Kenai Mountains, and completely filled Cook Inlet to elevations above 4,000 feet. Projection of the inferred ice surface indicates extensive connections with ice in the Copper River basin across low cols in the upper valley of the Susitna River and the Matanuska Valley, and with ice in the Bristol Bay Lowland across cols in the Aleutian Range east of Iliamna Lake. The Cook Inlet ice in this and succeeding glaciations apparently spilled out to the Pacific Ocean through Shelikof Straits and the straits between Kenai Peninsula and Kodiak Island.

Evidence for the Mount Susitna glaciation is restricted to surfaces that are at higher elevations than moraines of the next younger glaciation, the Caribou Hills, and which show highly modified ice-scoured slopes and only remnants of what were originally much more continuous mantles of drift and erratic material. Drift and erratic material of Mount Susitna age are present on old glaciated surfaces higher than lateral moraines of Caribou Hills age in the Kenai Mountains just south of Turnagain Arm and near the headwaters of King County Creek south of Skilak Lake. Deposits of Mount Susitna age have not been recognized in the Kenai Lowland; and if present, they are deeply buried beneath younger drift. However, in the adjoining Anchorage area, well data reveal a multiple sequence of tills at depth beneath surface drift of Naptowne age (Frank Trainer, oral communication, 1956), and it is likely that some of the deeper wells penetrate deposits of Mount Susitna age. The present evidence for Mount Susitna glaciation is therefore fragmentary and largely geomorphic, and it is uncertain whether the highest glacial surfaces preserved in the region relate to one or more than one pre-Caribou Hills glaciation. Similarly, in the absence of definitive stratigraphic evidence, the magnitude of the interval between Mount Susitna and Caribou Hills glaciations can only be inferred from geomorphic evidence. Topographic relations and the difference in the degree of dissection and mass wasting of the drifts of Mount Susitna and Caribou Hills age strongly suggest a long interval of time between glaciations. The author believes that this interglacial hiatus was at least as great as those intervening between the Eklutna, Knik, and Naptowne glaciations, but perhaps somewhat less than the one which intervened between the Caribou Hills and Eklutna glaciations.

Capps (1931) early recognized evidence for a high-level glaciation (the Mount Susitna) in the Cook Inlet region and attributed it tentatively to the Wisconsin glacial stage. By this concept, moraines of Caribou Hills, Eklutna, Knik, and Naptowne age would represent recessional phases of the Wisconsin glacial stage. The stratigraphic and geomorphic evidence previously discussed and summarized below is, instead, internally consistent in recording a multiple sequence of major Pleistocene glaciations separated by major retreatal intervals, all of which but the latest (the Naptowne) must be pre-Wisconsin in age, according to radiocarbon-dated stratigraphic boundaries in type localities of both Alaska and the midcontinent.

CARIBOU HILLS GLACIATION

During the Caribou Hills glaciation, Cook Inlet was again completely filled by ice emanating from the surrounding mountains. Highly modified and dissected, but still recognizable, lateral moraines attributed to the Caribou Hills glaciation occur on protected slopes and spurs between elevations of 2,000 and 3,000 feet along the eastern flanks of Mount Susitna, on the flanks of the Talkeetna and Chugach Mountains near the confluence of Matanuska Valley with the Susitna Lowland and Turnagain Arm, and along the Kenai Mountain front just south of Turnagain Arm and north of the Chickaloon River. Between Skilak Lake and Benjamin Creek, lateral moraines of Caribou Hills age rise to elevations between 3,000 and 4,000 feet. Immediately south of this point, drift-covered upland surfaces of the Caribou Hills and the Bear Creek Upland were completely overridden by Caribou Hills ice, indicating an even higher level of the ice surface near Tustumena Lake where ice flowed directly out of the Harding Icefield area. The Caribou Hills area apparently formed a divide that separated the predominantly southwestward-flowing ice within Kachemak Bay and lower Cook Inlet area from the predominantly northwestward- and northward-flowing ice from the icefield north of Tustumena Lake. From the regional distribution of the deposits of Caribou Hills age it is evident that the dominant ice gradient of the Cook Inlet trunk glacier was not everywhere downvalley, but that the gradients of the component ice tongues flowing southward down the Susitna Lowland, southwestward down the Matanuska Valley, westward down Turnagain Arm, and northwestward from centers in the Kenai Mountains were graded to a lower level at their point of confluence within the upper part of Cook Inlet. This is consistent with the morainal patterns of the later glaciations, which also indicate maximum glacial intensity within the lower part of Cook Inlet and a progressive decrease in intensity upvalley. Thus the basic orographic and meteorological factors that determine present-day distribution of glacial ice seem to have persisted throughout most, if not all, of the region's Pleistocene history. Boulder-count ratios suggest that Caribou Hills ice began its retreat from the Skilak platform 155,000 to 190,000 years ago.

EKLUTNA GLACIATION

During Eklutna time, the floor of Cook Inlet basin was completely filled with ice for the last time. Trunk glaciers filled the Susitna, Matanuska, and Turnagain Arm valleys and coalesced with ice spilling off the flanks of the Alaska Range and the Kenai Mountains.

As recorded in the Nikishka Lowland by a terraced interlobate moraine with mixed lithologies from the Alaska Range and Talkeetna, Kenai, and Chugach Mountains, southward- and southeastward-flowing Eklutna ice from the Alaska Range dominated ice flowing northward from Kenai Mountain sources and pushed to within 20 miles of the Kenai Mountains, or at least two-thirds of the distance across the Cook Inlet basin. Lateral moraines attributed to the Eklutna glaciation occur at elevations between 1,000 and 2,000 feet along the flanks of Mount Susitna and the Talkeetna and Chugach Mountains near the head of Cook Inlet and progressively rise in elevation up the Susitna, Matanuska, and Turnagain Arm valleys. South of Turnagain Arm, moraines of Eklutna age can be traced continuously along the front of the Kenai Mountains from an elevation of more than 1,000 feet near the Arm to about 500 feet near the Chickaloon River where they merge with moraines deposited by valley-ice tongues flowing out from Kenai Mountain sources through the Chickaloon River and Dike Creek valleys. Eklutna moraines at an elevation of about 2,000 feet mark the juncture of the major Skilak Lake and Killey River ice lobes. They occur at an elevation of between 1,500 and 2,000 feet along the flanks of the Bear Creek upland, which separated the Killey River and Tustumena Lake lobes in Eklutna time. Eklutna ice almost completely covered the Caribou Hills area except for higher knolls that stood above an ice surface which dropped in elevation from about 2,000 feet near Tustumena Lake to less than 1,000 feet near Homer. The Caribou Hills, therefore, acted as a partly overridden nunatak area separating the trunk glacier that occupied the axis of Cook Inlet from the Kachemak Bay lobe during Eklutna time.

As previously discussed (Karlstrom, 1953), the geomorphic features in the Kenai Mountains record a long interval of subaerial erosion, and perhaps complete deglaciation, between the Caribou Hills and Eklutna glaciations. Along the flanks of the Bear Creek upland, moraines of the Eklutna glaciation form reentrants within broad canyons cut into the Caribou Hills surface and suggest a major erosional hiatus between the retreat of Caribou Hills ice and advance of Eklutna ice. There are similar relations between the moraines of Eklutna age and dissected older glaciated surfaces in the southwestern part of the Talkeetna Mountains. Surface-boulder counts on the Skilak Platform suggest a much greater interglacial hiatus between the Caribou Hills and Eklutna than between the younger glaciations. Definitive stratigraphic relations between drift of Caribou Hills age and that of Eklutna age have yet to be observed in the Cook Inlet region. However, the available geomorphic evidence is consistent in suggesting that the major retreatal interval in the Cook Inlet glacial sequence is marked by the Caribou Hills-Eklutna glaciation boundary. Wood collected from recessional drift of Eklutna age near Boulder Point (carbon–14 loc. 3) dates pre–23,000 B.C. The boulder-count ratios suggest that Eklutna ice began its retreat from the Skilak Platform some 90,000 to 110,000 years ago.

KNIK GLACIATION

During the succeeding Knik and Naptowne glaciations, piedmont glacial lobes draining major ice centers extended into, but did not coalesce to completely fill, the Cook Inlet basin. As recorded by moraines in the Kenai Lowland and by stratigraphic relations in the sea bluffs in the Knik Arm area north of Anchorage and near Boulder Point on the Kenai Lowland, the Knik glaciation was from 3 to 6 miles more extensive than the succeeding Naptowne glaciation. Major ice lobes draining through the Kenai, Skilak, Killey, and Tustumena valleys from the Harding Icefield coalesced along the margins of the Kenai Lowland to form a continuous ice shelf 25 miles wide and 50 miles long parallel to the Kenai Mountain front north of the Caribou Hills. Whereas ice of the compound Killey, Skilak, and Kenai valley lobes reached elevations just above 1,000 feet along the mountain front, the Tustumena Valley lobe reached an elevation of 1,500 to 2,000 feet near the head of Tustumena Lake. During the Knik glaciation, the Tustumena Valley lobe spilled across the low divide at the head of Kachemak Bay and joined the Kachemak Bay lobe which partly covered the Caribou Hills, and pushed out around the southern end of the hills for an unknown distance westward and for about 15 miles northward into the Cook Inlet trough. Lateral projections of Knik ice across the axis of the Caribou Hills in the upper reaches of Deep Creek provide a direct explanation for the broad swamp-covered valley sections upstream from the end moraines and the deep canyons cut below the dissected terrace surfaces developed downstream from these moraines. The indicated lateral projections of Knik ice up tributary valleys of the south branch of the Anchor River also provide a logical explanation for the drainage diversion and the superposition across a bedrock ridge recorded near the head of the north fork of the Anchor River. The maximum extent of the Turnagain Arm ice lobe during Knik time is marked by the arcuate morainal belt south of Point Possession that transects the general trend of the interlobate moraine of Eklutna age and, according to the author's interpretation, by a comparable arcuate belt of moraines in the Anchorage area between Potter and Point Campbell.

The moraines now mapped as Knik in age were originally considered by the author on the basis of photointerpretation to represent a retreatal phase of the Swan Lake (Eklutna) glaciation preceding the Naptowne glaciation (Karlstrom, 1953). Stratigraphic relations near Boulder Point, Point Possession, and Point MacKenzie clearly record major erosional and weathering hiatuses preceding as well as following this intermediate glacial advance. Deposits of Knik age rest unconformably on deposits of Eklutna age that are weathered through vertical intervals of more than 40 feet. The deposits of Knik age are in turn weathered to depths generally between 10 and 20 feet and are overlain by deposits of Naptowne age with weathering profiles less than 10 feet deep. In keeping with this stratigraphic evidence of a separate major glaciation preceding the Naptowne and postdating the Eklutna is the surface-boulder evidence from Skilak Platform. The boulder ratios suggest that the intermediate moraines of Knik age are roughly twice as old as the moraines of Naptowne age and roughly one-half as old as the moraines of Eklutna age. Radiocarbon samples collected from zones within or directly overlying drift of Knik age near Goose Bay (carbon–14 loc. 1), Eagle River (carbon–14 loc. 2), and on the Kenai Lowland near Nikishka No. 1 (carbon–14 loc. 4), Nikishka No. 1—Salamato (carbon–14 loc. 5), Salamato (carbon–14 loc. 6), Kenai (carbon–14 loc. 7), and Tustumena Lake (carbon–14 loc. 8) all date older than the dating range and indicate that the Knik glaciation predates at least 36,000 B.C. The ionium-uranium-ratio date of between 31,000 and 46,000 B.C. for the marine zone overlying till of Knik age in the Knik Arm area suggests that it may predate 46,000 B.C. The boulder ratios suggest that Knik ice began its retreat from Skilak Platform some 50,000 to 65,000 years ago.

Coalescence of the Kachemak Bay lobe with ice from the Aleutian Range in the lower part of the inlet created an interior lake during the extended phases of the Knik glaciation. The existence of this lake is recorded stratigraphically in weathered proglacial-lake sediments underlying and overlying till of Knik age near Point Possession and underlying proglacial-lake sediments of Naptowne age between Point Possession and Boulder Point and elsewhere in the lowland outside the limits of Naptowne glaciation. Just when the ice lobes of Knik age coalesced and dammed the interior drainage of Cook Inlet or when this iced dam was breached during retreat is not known; but from the evidence at hand, it is apparent that the lake was in existence long before the maximum extension of the Turnagain Arm ice lobe of Knik age. The weathered proglacial-lake silt deposit exposed at an elevation of between 500 and 600 feet beneath till of Naptowne age near Jean Lake further suggests that the lake persisted with relatively high lake levels into late Knik time. Strandline benches that transect morainal and structural trends along the flanks of the Caribou Hills and along the Kenai Mountain front north of Jean Lake may represent one of the highest, if not the highest, lake stands of the proglacial lake of Knik age. Surface deposits of fine-grained laminated silt exposed at an elevation of between 800 and 900 feet in Rabbit Creek valley and coarser grained stratified sand and gravel exposed at an elevation of about 1,000 feet in Campbell Creek canyon are believed to represent proglacial-lake deposition during Knik time in the Anchorage area.

NAPTOWNE GLACIATION

The youngest major glaciation recognized in the Cook Inlet region is the Naptowne. It is represented by conspicuous spatulate end moraines in the vicinity of Skilak Lake near Naptowne Lodge at Sterling, Tustumena Lake near Kasilof, and Kachemak Bay near the Anchor River on the Kenai Lowland; and by morainal belts of similar appearance at the mouth of Matanuska Valley (Karlstrom, unpublished data; Trainer, 1955; Miller and Dobrovolny, 1959) and on the margin of the lowland in front of trunk valleys heading in major icefields of the Alaska Range west and north of Cook Inlet. Additional work is required to precisely determine the extent of Naptowne glaciation in the northern part of the Susitna Lowland between Talkeetna and McDougall. The extent of Naptowne glaciation in Turnagain Arm is also uncertain, but it is probably represented by a remnant of a lateral moraine along the north shore of Turnagain Arm near Bird Creek. The absence of till or moraines of Naptowne age in the northern part of the *Nikishka Lowland strongly suggests* that the Turnagain Arm lobe of Naptowne age did not extend much, if any, farther west than the front of the Kenai Mountains.

During Naptowne time, northward expansion of the Harding Icefield filled the Kenai River and Resurrection Creek valleys with ice to elevations of more than 1,000 feet. This ice fed westward into the lowland as a compound piedmont lobe 20 miles long and 12 to 15 miles wide fronting the Kenai Mountains. Expansion of the outlet glaciers from Indian, Tustumena, and Chernof valleys created a separate piedmont lobe. This lobe, as much as 15 miles wide, completely filled the Tustumena Lake trough to elevations between 500 and more than 1,000 feet and extended more than 30 miles from the Kenai Mountain front. This ice lobe was coextensive with ice filling Kachemak Bay and extended an unknown distance into the lower part of Cook Inlet. As marked by conspicuous lateral moraines and major drainage divides on the eastern flanks of Caribou Hills, the surface of the Kachemak ice lobe of Naptowne age decreased in elevation from about 1,500 feet near the head of the bay to less than 500 feet west of Homer.

During Naptowne time, ice from the Alaska and Aleutian Ranges pushed eastward across Cook Inlet and deposited end moraines near Boulder Point and East Foreland. As previously discussed, the end moraine near East Foreland is bordered on the south by a channeled gravel plain underlain by water-laid deposits of Naptowne age unconformably overlying more deeply weathered and contorted silt, sand, and gravel of Knik age. The intensity of deformation in the deposits of Knik age increases northward toward the end moraines of Naptowne age and, where overridden by the Naptowne ice, these deposits are extremely contorted and locally infolded into the basal till. The till of Naptowne age at Boulder Point and East Foreland is intensely sheared and contorted, recording deformation following retreat from the Naptowne glacial maximum. The bordering surface drift of Naptowne age south of East Foreland is also deformed near the moraine margin. These deformational relations are interpreted as the result of a series of successively less extensive Naptowne advances, the most recent of which not only deformed the end-moraine deposits of Naptowne age but also affected surface sedimentation in the area immediately to the south. Near the top of the section just south of East Foreland are local exposures of two buried and folded peat and organic-silt deposits separated by laminated silt and sand and overlain unconformably by undisturbed surface-bog deposits of organic silt and peat. Another series of surface-bog deposits is exposed east of Boulder Point in a comparable position marginal to the moraines of Naptowne age. Here, the bog deposits floor at or below beach level, and only the upper undisturbed part of the organic deposits is exposed. The base of the lower and most intensely folded of two deformed organic beds at radiocarbon locality J (W–416) was dated at 10,950 B.C. ± 300 years; the base of the undisturbed upper bog unit at carbon-14 locality H (L–117 O) was dated at 6250 B.C. ± 900 years, and N (L–163B), at 6700 B.C. ± 450 years. These dated layers are interpreted as closely bracketing two readvances of ice across the inlet from the Alaska Range side in the time interval following the Naptowne maximum between 11,000 and 7000 B.C. and just prior to final withdrawal of the Trading Bay ice lobe from the area.

Advances.—On the eastern margin of the Kenai Lowland the morainal record is of at least four major Naptowne advances: the Moosehorn (most extensive), Killey, Skilak, and Tanya. A partly buried morainal knoll immediately outside the boundary of Naptowne glaciation near Naptowne Lodge may represent a recessional phase of Knik age or an advance that just preceded the Moosehorn advance. These subordinate Naptowne advances are recorded by morainal belts of the compound moraines of Naptowne age near Skilak and Tustumena Lake, in the Killey River valley, and marginal to Kachemak Bay; and they are considered to represent events of regional rather than local climatic significance. There are slight, if any, recognizably consistent soil and topographic differences between the four morainal belts. These geomorphic differences are to be contrasted with the much more pronounced break represented by the boundary between moraines of the Naptowne and Knik glaciations and by the significant, but somewhat less distinctive, geomorphic break between the moraines of Naptowne age and those of the succeeding Alaskan glaciation. Whereas soils developed on moraines of Naptowne age in the Tustumena Lake area are generally characterized by oxidation profiles from 2 to 5 feet deep, the soils on moraines of Alaskan age are characteristically less than 1 foot deep.

Radiocarbon-dating of moraines.—The lower time boundary of the Naptowne glaciation is most closely established by the carbon-14 samples collected from pro-Naptowne deposits near Goose Bay (carbon-14 loc. 1; W–644, >36,000 B.C.) and near East Foreland (carbon-14 loc. 5; L–163A, 37,000 B.C. ±2,000 years). All other samples collected from stratigraphically lower zones in Cook Inlet are beyond the range of the dating method. The only finite date in this older group (L–163A) was obtained by reanalyses in new counters at the Lamont Laboratory that extend the range of the radiocarbon-dating method back to 40,000 to 60,000 years ago. Reanalyses of sample W–644 and related samples, now pending, give promise of providing other finite dates that will permit more precise dating of the boundary beteen Knik and Naptowne glaciations in the Cook Inlet region, and which should answer the question as to when other ice lobes in the region attained their Naptowne maxima. According to stratigraphic position, the date of 37,000 B.C., obtained from sample L–163A, predates the maximum extension of the Trading Bay ice lobe in Naptowne time. The preliminary ionium-uranium date of from 31,000 to 46,000 B.C. for shells collected from the marine zone marking the interglacial period preceding the Naptowne advance in the Knik Arm area is thus apparently consistent with the carbon-14 dating of the pro-Naptowne sediments near East Foreland.

No radiocarbon samples have been collected as yet from Cook Inlet that can be directly related to deposits of the Moosehorn and Killey advances of the Naptowne glaciation. However, the basal sample from the bog overlying till of Naptowne (Skilak) age in the Homer area (L–137W; carbon-14 loc. L) provides a close minimum date of 7000 B.C. for the end moraines of the Skilak advance. This date combined with the pro-Naptowne date thus provides a time bracket of between 37,000 and 7000 B.C. for the Moosehorn, Killey, and Skilak advances. Culmination of Tanya retreat just prior to the climatic deterioration that initiated the Alaskan glaciation is dated between 4850 B.C. (L–237; carbon-14 loc. P) and 2550 B.C. (L–237G; carbon-14 loc. Q). The interval of bog drying recorded in the upland bog near Homer (L–137T; carbon-14 loc. N) dates within this time interval and may provide a more precise date of ca. 3500 B.C. for the boundary between Naptowne and Alaskan glaciations. The Naptowne glaciation may therefore be dated on the basis of these radiocarbon samples as between 37,000 and 3500 B.C. If the maximum extension of Naptowne ice occurred halfway between these maximum and minimum dates, an average of between 20,000 and 25,000 years ago is obtained for the Naptowne maximum. In the absence of more precise dating, these figures have been applied to the maximum extension of Naptowne ice on Skilak Platform for the purpose of converting the surface boulder ratios into calendar years as a first approximation to the actual ages of pre-Naptowne moraines.

ALASKAN GLACIATION

The most recent series of glacial advances recorded in the Cook Inlet region is represented by a sequence of fresh-looking moraines that lie between more modified moraines of Naptowne age and the fronts of existing glaciers throughout the Kenai Peninsula. These post-Naptowne climatic events are placed within the Alaskan glaciation of the Cook Inlet chronology. Differences in topographic expression and position, soil development, and vegetation cover indicate two distinctly separate ages for the recent moraines. From type sections near the head of Tustumena Lake on the Kenai Lowland, and near the section house of the Alaska Railroad at Tunnel in the Kenai Mountains, the glacial advances represented by the older moraines are named the Tustumena advances; those represented by the younger moraines are named the "Tunnel advances." The morainal record is of at least 3 major Tustumena advances (Tustumena I, II, and III) and 2 major (Tunnel I and II) and several smaller (Tunnel II) readvances. In numerous ice-free upland-valley heads in the Kenai Mountains, events of Alaskan age are also recorded in a multiple sequence of little-modified rock glaciers, talus cones, alluvial fans, and valley-bottom terraces.

On the basis of the previously discussed radiocarbon-dated stratigraphy, the moraines and related deposits of Alaskan age are dated as follows: Tustumena I, post-Tanya and therefore post-3500 B.C. (L–137T; carbon-14 loc. N), also post-2550 B.C. (L–237G, carbon-14 loc. Q); Tustumena II, post-1250 B.C. (L–117B, carbon-14 loc. M); Tustumena III, post-420 B.C. (W–78, carbon-14 loc. R), and post-300 B.C. (L–137K, carbon-14 loc. K); Tunnel I, post-A.D. 550 (W–318, carbon-14 loc. R); Tunnel II, post-A.D. 1550 (L–117K, carbon-14 loc. O) and post-A.D. 1500 (L–137E, carbon-14 loc. H); and including evidence of at least two subordinate glacial readvances following retreat from the Tunnel II end moraines, as well as historically recorded readvances in about the late 1890's, 1916, ca. 1940, and ca. 1950.

RADIOCARBON-DATED COOK INLET GLACIAL CHRONOLOGY

Reconstruction of the detailed glacial chronology shown in plate 7 is based on an integration of the partly dated morainal sequence with the more detailed and continuous depositional record of the radiocarbon-dated coastal-bog stratigraphy (table 3). The coastal bogs exposed near East Foreland, Point Possession, Boulder Point, and Girdwood provide sensitive stratigraphic records from which major and synchronous hydrologic changes in the Cook Inlet region can be inferred. These changes are correlated with the morainal record on the basis of parallel sequence and radiocarbon cross-dating. By this means the character of climatic and environmental controls that determined the recorded hydrologic changes can be directly judged and interpreted as the product of the same climatic changes that affected glaciation in the region.

TABLE 3.—*Summary of radiocarbon data, Cook Inlet and adjoining coastal areas, Alaska*

[Sample numbers: L, analyzed by the Lamont Laboratory; W, numbers by the Washington Laboratory; I, numbers by the Isotopes Inc. Laboratory. Conversion of B.P. to A.D.–B.C. dates based on 1950 as reference year]

Sample	Date A.D.–B.C.	Locality	Collector and date collected	Stratigraphic assignment	References
L–117K	A.D. 1550±150 yr	Tustumena glacier, Kenai Lowland (loc. 0).	Karlstrom, 1951	Tunnel II	Kulp and others, 1952, p. 412.
L–163G	Post A.D. 1650	Spencer glacier, Kenai Mountains (loc. S).	Marshal and Karlstrom, 1950	do	Kulp (written communication, 1954).
L–137E	A.D. 1500±200 yr	Kenai-Kasilof, Aaa, Kenai Lowland (loc. H).	Karlstrom, 1952	do	Broecker and others, 1956, p. 156.
W–175	A.D. 1250±250 yr	Girdwood, Aaa, Turnagain Arm (loc. A–1).	Karlstrom, 1954	Tunnel I	Rubin and Suess, 1955, p. 486.
W–541 [1]	A.D. 1330±200 yr	Fire Island (loc. C–1)	Miller, Dobrovolny, and Hansen, 1956.	do	Rubin and Alexander 1960, p. 165.
W–318	A.D. 565±200 yr	Tunnel, Aaa, Kenai Mountains (loc. R).	Karlstrom, 1953	do	Rubin and Alexander, 1958, p. 1480.
W–78	420 B.C.±100 yr	Tunnel, Aaa, Kenai Mountains (loc. R).	Karlstrom, 1953	Tustumena III	Suess, 1954, p. 471.
L–137K	300 B.C.±300 yr	Homer, Aaa, Kenai Lowland (loc. K).	Krinsley and Karlstrom, 1950	do	Broecker and others, 1956, p. 156.
L–117B	1250 B.C.±150 yr	Homer, Aaa, Kenai Lowland (loc. M).	Benninghoff, 1950	Tustumena II	Kulp and others, 1952, p. 412.
W–299	850 B.C.±180 yr	Girdwood, Aaa, Turnagain Arm (loc. A–1).	Karlstrom, 1954	do	Rubin and Suess, 1956, p. 445.
I–A65–1 [1]	1520 B.C.±180 yr	Karluk, Kodiak Islands (loc. W).	Heusser and Hawbecker, 1956	Tustumena I	Heusser, C. J., 1959.
L–117N	1850 B.C.±400 yr	Boulder Point, Kenai Lowland (loc. E–1).	Karlstrom, 1950	do	Kulp and others, 1952, p. 412.
L–434	1750 B.C.±150 yr	do	do	do	Olson and Broecker, 1959, p. 6.
L–163E	1600 B.C.±170 yr	Boulder Point, Kenai Lowland (loc. E–4).	do	do	Do
L–163F	2000 B.C.±200 yr	do	do	do	Do
L–237G	2550 B.C.±450 yr	Ingram Creek, Kenai Mountains (loc. Q).	Karlstrom, 1953	Pro-Tustumena	Broecker and others, 1956, p. 156.
L–101A [1]	3390 B.C.±300 yr	Anchorage, Aaa (loc. B)	Eckles, 1949	Tanya III	Kulp and others, 1951, p. 568.
L–137T [1]	3850 B.C.±500 yr	Caribou Hills, Kenai Lowland (loc. N).	Benninghoff, 1951	do	Kulp (written communication, 1954).

See footnotes at end of table.

TABLE 3.—*Summary of radiocarbon data, Cook Inlet and adjoining coastal areas, Alaska*—Continued

Sample numbers: L, analyzed by the Lamont Laboratory; W, numbers by the Washington Laboratory; I, numbers by the Isotopes Inc. Laboratory. Conversion of B.P. to A.D.–B.C. dates based on 1950 as reference year]

Sample	Date A.D.–B.C.	Locality	Collector and date collected	Stratigraphic assignment	References
L-237F	4850 B.C.±550 yr	East Fork, Kenai Mountains (loc. P).	Karlstrom, 1952	Tanya II	Broecker and others, 1956, p. 156.
L-137U [1]	5350 B.C.±600 yr	Anchor River Kenai Lowland (loc. J).	Benninghoff, 1951	do	Kulp (written communication, 1954).
W-431 [1]	6050 B.C.±300 yr	Matanuska glacier (loc. V)	Williams and Ferrians, 1954	Tanya I	Rubin and Alexander, 1958, p. 1481; Williams and Ferrians, 1958, p. 91.
L-163B	6700 B.C.±450 yr	Boulder Point, Kenai Lowland (loc. E-1).	Karlstrom, 1950	do	Olson and Broecker, 1959, p. 6.
L-1170	6250 B.C.±900 yr	do	do	do	Do.
W-603	6690 B.C.±280 yr	Point Possession, Kenai Lowland (loc. D-1).	Karlstrom, 1954	do	Rubin and Alexander, 1960, p. 169.
W-602	6470 B.C.±300 yr	do	do	do	Olson and Broecker, 1959, p. 6; Rubin and Alexander, 1960, p. 169.
I-AGS-2 [1]	6920 B.C.±300 yr	Kodiak, Kodiak Islands (loc. X).	Heusser and Hawbecker, 1956	do	Heusser, 1959, p. 30.
L-137W [2]	7050 B.C.±750 yr	Homer, Aaa (loc. L)	Benninghoff, 1951	Skilak III	Kulp (written communication, 1954).
W-536	7350 B.C.±250 yr	Fire Island, Anchorage Area (loc. C-2).	Miller and Hansen, 1956	do	Miller and Dobrovolny, (1959.)
I-AGS-3	7400 B.C.±320 yr	Afognak, Kodiak Islands (loc. Y).	Heusser and Hawbecker, 1956	do	Heusser, 1959, p. 30.
I-AGS-4 [1]	7490 B.C.±350 yr	Perry Island, Prince William Sound (loc. Z).	do	do	Do.
L-137D	7550 B.C.±650 yr	Point Possession, Kenai Lowland (loc. D-3).	Karlstrom, 1951	do	Broecker and others, 1956, p. 156.
L-163D	7250 B.C.±600 yr	Point Possession, Kenai Lowland (loc. D-2).	do	do	Do.
L-137L [1]	7650 B.C.±650 yr	Ninilchik Aaa Kenai Lowland (loc. I).	Krinsley, 1951	do	Do.
W-336 [1]	7920 B.C.±250 yr	Talkeetna Mountains (loc. U)	Bjørn Andersen, 1955	do	Rubin and Alexander, 1958, p. 1483.
W-474	8420 B.C.±350 yr	Point Possession, Kenai Lowland (loc. D-1).	Karlstrom, 1954	Skilak II	Rubin and Alexander, 1958, p. 1479.
W-540	9650 B.C.±300 yr	Anchorage, Aaa (loc. B-1)	Miller, Dobrovolny, and Hansen, 1956.	Skilak I	Miller and Dobrovolny, 1957a, p. 1908.
W-360 [1]	9980 B.C.±250 yr	Talkeetna Mountains (loc. T)	Bjørn Andersen, 1955	do	Rubin and Alexander, 1958, p. 1483.
W-416	10,950 B.C.±300 yr	East Foreland, Kenai Lowland (loc. F-2).	Karlstrom, 1954	Killey III	Rubin and Alexander, 1958, p. 1479.
W-748	11,550 B.C.±400 yr	Salamato Creek, Kenai Lowland (loc. G-1).	Karlstrom, 1958	do	Rubin and Alexander, 1960, p. 169.
L-163A	37,000 B.C.±2,000 yr	Nikishka-Salamato, Kenai Lowland (loc. 5).	Karlstrom, 1950	Pro-Naptowne	Olson and Broecker, 1959, p. 5.
L-163A [3]	20,000 B.C.±2,000 yr	do	do	do	Do.
W-644	Pre-38,000 B.C.	Goose Bay, Knik Arm (loc. 1)	Karlstrom, 1957	do	Rubin and Alexander, 1960, p. 169.
W-294	Pre-35,000 B.C.	Salamato Creek, Kenai Lowland (loc. 6).	Karlstrom, 1954	Pre- or pro-Naptowne	Rubin and Suess, 1956, p. 444.
L-117L	Pre-42,000 B.C.	Nikishka No. 1, Kenai Lowland (loc. 4).	Karlstrom, 1950	do	Olson and Broecker, 1959, p. 5.
L-117L [3]	17,250 B.C.±1,000 yr	do	do	do	Kulp and others, 1952, p. 412.
L-137D [2]	Pre-22,000 B.C.	Kenai, Aaa Kenai Lowland (loc. 7).	Karlstrom, 1951	do	Broecker and others, 1956, p. 156.
W-174	Pre-36,000 B.C.	Goose Bay Knik Arm (loc. L)	Karlstrom, 1954	Pre-Naptowne	Rubin and Suess, 1955, p. 486.
W-77	Pre-30,000 B.C.	do	Karlstrom, 1950	do	Suess, 1954, p. 471.
L-117A [3]	17,150 B.C.±900 yr	do	do	do	Kulp and others, 1952, p. 412.
W-76	Pre-30,000 B.C.	Tustumena Lake, Kenai Lowland (loc. 8).	do	do	Suess, 1954, p. 471.
L-117J [3]	13,850 B.C.±400 yr	do	do	do	Kulp and other, 1951, p. 568.
W-535	Pre-36,000 B.C.	Eagle River, Anchorage Area (loc. 2).	Miller, Dobrovolny, and Hansen, 1956.	Pre-Naptowne (or pro-Naptowne).	Miller and Dobrovolny, 1957a, p.1908.
L-101B [3]	12,350 B.C.±600 yr	do	Eckles, 1949	do	Kulp and others, 1951, p. 568.
L-117M [2]	Pre-23,000 B.C.	Boulder Point Kenai Lowland (loc. 3).	Karlstrom, 1950	Pre-Knik	Broecker and others, 1956, p. 156.

[1] Samples from stratigraphic section not studied by author; stratigraphic assignment tentative, and based solely on radiocarbon age.

[2] Tentative solid-carbon results; samples to be rerun by the more accurate gas-counting method.

[3] Preliminary solid-carbon results of samples dated pre-12,000 B.C. which have been discarded on the basis of more accurate gas-counting results. In all rerun samples in this age group, the new results give older dates. On the other hand samples dated post-12,000 B.C. by the solid-carbon method, have checked out consistent with the newer gas-counting results on comparable samples, and are therefore considered to be generally valid (Olson and Broecker, 1959, p. 5–6).

This integrated record is the basis of the author's summarized geoclimatic chronology for the past 12,000 years as presented in a recent publication (Karlstrom, 1956). Not all the boundaries of the reconstructed glacial sequence are radiocarbon dated. However, as the chronology is based on continuous sedimentation records, the author feels that the age of intermediate events can be closely estimated by careful stratigraphic interpolations between radiocarbon-dated boundaries. The validity of the resulting chronology is supported by (1) the compatibility with geologic theory of two separate continuous and correlative geoclimatic sequences, (2) the internal consistency of the more than 25 radiocarbon dates with each other and with stratigraphic position, and (3) the parallel climatic pattern between the radiocarbon-dated Cook Inlet record and the varve- and archeologically-dated Scandinavian climatic sequence (Karlstrom, 1956). However, the chronology is preliminary in the sense that continued geologic mapping in the region and analyses of carefully selected radiocarbon samples will provide additional and more accurately dated boundaries as a critical test of present interregional and extraregional correlations.

NAPTOWNE PROGLACIAL-LAKE EVENTS

The history of the proglacial lake that occupied the upper part of Cook Inlet during the Naptowne glaciation is recorded by surficial deposits and strandlines that are best developed outside the boundaries of the moraines of Naptowne age. Insofar as the spillway threshold of this lake was determined by a glacial-ice dam, the history of lake-level fluctuations is complicated and directly related to major events in the glacial history. In general the ice lobes from the Aleutian and Alaska Ranges and from the Kenai Mountains coalesced in the lower part of Cook Inlet during extended advances and formed an effective ice barrier to exterior drainage from the ice-free upper part of the Cook Inlet basin. After coalescence, minor pulsations in the glacial regimen could reasonably be expected to cause rapidly changing lake levels by raising or lowering the ice threshold for over-ice spillways or by opening and closing the interice or subice drainageways. In the absence of stable bedrock-threshold conditions, poorly to fairly well-developed multiple-terraced strandline levels characteristic of the Cook Inlet evolved instead of one or several well-developed and simple strandline levels. During significant intervals of ice retreat and downmelting, the lake drained partly or completely only to be re-formed during the next significant impulse or advance. Although many uncertainties remain concerning the details of the lake sequence, sufficient data are now available to suggest major events in its life history and, in combination with the radiocarbon-dated bog sequences associated with the lower strandline levels, to date some of these events.

Abandoned melt-water channels emanating from end moraines of Naptowne age and graded to strandline levels suggest significant static stands or lake level near the 750-foot elevation (perhaps the highest attained during Naptowne time) during the maximum Moosehorn advance, about the 500- and 600-foot elevations during the Killey advance, and about 250- to 300-foot elevations (275-ft. lake level) during the Skilak advance. The series of terrace levels cut on ridge slopes in the lowland below the 275-foot level (the 125-ft. and 50-ft. levels are particularly well developed) record fluctuating and final recession of lake level following the Skilak maximum and prior to the Tanya advance. Lake-bottom sediments include numerous disastems, disconformities, unconformities, and buried organic layers recording depositional hiatuses relating to partial or complete lake drainages between the higher lake-level stands.

The Point Possession coastal bogs (Bog group D) are on a lowland surface that lies between the 275-foot and 125-foot strandline levels; the East Foreland bogs (Bog group F), on a surface that lies between the 125-foot and 50-foot strandline levels; and the Boulder Point bogs (Bog group E) and Homer bog (Bog L), on terrace surfaces at and just below the 50-foot strandline level.

By combining these geomorphic relations with the radiocarbon cross-dated stratigraphic records, the following dated lake-level sequence may be inferred, as shown graphically in plate 7.

1. Recession of Glacial Lake Cook levels below the 80-foot elevation ca. 11,000 B.C. (East Foreland bogs).
2. Lake transgression accompanying glacial advance and deformation near East Foreland, rising above the 125- to 150-foot level (Point Possession bogs), and presumably to the 275-foot strandline ca. 10,000 B.C.
3. Recession of lake levels below the 80-foot level and concomitant drop in ground-water levels just prior to 8420 B.C., or ca. 9000 B.C. (East Foreland and Point Possession bogs).
4. Lake transgression accompanying glacial advance and deformation near East Foreland and rising of lake level above the 80-foot level but not to the 150-foot level (thus, presumably to the 125-ft. strandline level) ca. 8500 B.C. (Point Possession bogs).
5. Lake recession below the 80-foot level (East Foreland bogs) between 8420 and 7400 B.C., or ca. 8000 B.C.
6. Lake transgression to the 50-foot strandline level (Boulder Point bogs) just before 7400 B.C., or ca. 7500 B.C.
7. Lake recession below the 20-foot level (Homer Bog L) ca. 7000 B.C., leading to final drainage of Glacial Lake Cook prior to the Tanya advance.

By this reconstruction, the radiocarbon-dated intervals of presumed ice-shove deformation near East Foreland by the Trading Bay ice lobe are directly correlated with the 275-foot strandline associated with the end moraines of Skilak age deposited by the Skilak Lake and Tustumena Lake ice lobes. By this correlation, dates of ca. 10,000 B.C. are provided for the Skilak maximum and ca. 10,500 B.C. for the culmination of the preceding Killey retreatal interval of low-lake levels. Two important subordinate Skilak advances, ca. 8500 and 7500 B.C., are suggested by intervals of rising proglacial-lake levels prior to the final drainage of Glacial Lake Cook. These may, with further study, be correlated with individual recessional moraines in the morainal lobes of Skilak age on the lowland. As indicated by the stratigraphic record, and as strongly suggested by the withdrawn position of the moraines of Tanya age in Kachemak Bay, the lower Cook Inlet ice dam did not re-form during the Tanya glaciation; and the post-Skilak hydrologic history of the Cook Inlet trough must be related to base-level changes in an environment including direct connections with the sea.

GLACIOEUSTATIC RECORD OF LATE NAPTOWNE AND ALASKAN TIME

The postglacial-lake hydrologic sequence recorded by the lowland bogs near Point Possession and Boulder Point and by the tidal bog in Turnagain Arm near Girdwood is as follows: lowest fluctuating regional water levels between 7000 and 4500 B.C. following final drainage of Glacial Lake Cook; highest water levels betwen 4500 and 3500 B.C.; general lowering of water levels between 3500 and 2500 B.C.; fluctuating lower water levels between 2500 B.C. and the beginning of the Christian Era; higher water levels in about A.D. 500; lower water levels in about A.D. 1000; a brief interval of higher water levels in about A.D. 1500; lower water levels between A.D. 1500 and ca. 1850; and general rise in water levels since 1850.

Radiocarbon cross-dating of the coastal-lowland-basin type bog sequence with the shorter tidal-bog sea-level sequence indicates broadly parallel and contemporaneous water-level fluctuations in the period of overlapping records and suggests that the regional ground-water-level changes recorded in the coastal bogs were also in direct response to sea-level changes. Radiocarbon cross-dating of this composite hydrologic sequence with the dated morainal sequence further indicates essential contemporaneity of lower water-level intervals with glacial advance and higher water-level intervals with glacial retreat. Thus glacioeustatic sea-level controls are indicated. As previously discussed (Karlstrom, 1956), this glacioeustatic interpretation is enhanced by evidence from other coastal areas in the Northern Hemisphere that suggests a pattern of sea-level changes for the Atlantic Ocean comparable to that inferred from the Cook Inlet hydrologic sequence for the Pacific Ocean.

The seeming synchronism of recorded sea-level changes in two ocean basins and the parallelism with the glacial changes in Cook Inlet emphasize the probable climatic and glacioeustatic origin of the changes and in effect eliminate tectonic and isostatic adjustments as significant factors in the recorded hydrologic sequence. To conclude that the coastal-bog hydrologic record reflects glacioeustatic controls, however, does not eliminate the possibility that the Cook Inlet region has suffered either isostatic rebound or tectonic changes in land-sea relations during the time interval in question. Nevertheless, in view of the available evidence, it seems quite clear that if such adjustments took place, they must have been of much smaller magnitude than the recorded eustatic shifts.

The general stability of the Cook Inlet coastal region is further suggested by the following relations:

1. Uplifted marine terraces comparable to those recording both tectonic and isostatic adjustments of great magnitude in southeastern Alaska are absent in the Cook Inlet region. No marine fossils have been found anywhere associated with the uplifted strandline deposits of Cook Inlet.
2. Proglacial-lake strandlines that closely follow contours throughout the length of the Kenai Lowland are traceable at the same elevations as far north as along the western flanks of the Talkeetna Mountains. This suggests that if differential uplift has affected Cook Inlet since early or middle Naptowne time, it has been less than can be shown by the present accuracy of mapping from aerial photographs onto 1:63,360 base maps.
3. The radiocarbon-dated coastal bog at Homer indicates that Homer Bench became ice free prior to 7000 B.C. and that surfaces as low as 20 to 25 feet in elevation have remained above sea level since that date. This evidence severely restricts the magnitude of both tectonic and isostatic adjustments that could possibly have taken place during this interval at the southern tip of the Kenai Lowland.
4. The fault cutting deposits of Naptowne age in the Susitna Lowland provides evidence of some tectonic displacement following the Naptowne maximum. Measurable displacement along this fault, however, is slight (less than 10 feet of measurable dip-slip displacement); and it apparently reflects minor movement along an ancient fault zone that parallels the western shore of Cook Inlet. This recent faulting has no recognizable reflection in the coastal-bog stratigraphy, although it conceivably could be recorded in one of the sea-level shifts. More likely, the faulting took place prior to the oldest event recorded in the bog stratigraphy.
5. In contrast to the continental glaciers that formed ice masses of vast extent during the Wisconsin stage in areas that today are free of ice, the relative difference between the ice load during the Naptowne glaciation and the existing icefields in Cook Inlet is extremely small. Thus major isostatic

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suppression of Cook Inlet under ice load and major rebound following retreat from Naptowne maximum is not likely. In keeping with the isostatic theory that rebound is most rapid immediately after releases of ice load and falls off rapidly in time, minor isostatic compensation can be expected to have affected Cook Inlet during the late interval in the coastal stratigraphic record.

In the absence of a fixed reference point, the absolute shifts in either land or sea-level positions cannot be directly measured from coastal stratigraphic evidence. However, the problem does lend itself to an indirect solution. Careful studies of stratigraphy and geomorphology in stable coastal areas of the world should provide sea-level records that primarily reflect eustatic sea-level shifts. When a sufficient number of such studies are completed, it should be possible to eliminate local and noneustatic factors that may be represented and to reconstruct a quantitative glacioeustatic sea-level curve.

By correlation with the inferred glacioeustatic sea-level changes, the end moraines of the Tanya advance are dated between 7000 and 4500 B.C.; an upper boundary of ca. 3500 B.C. is obtained for the culmination of Tanya retreat just prior to the initial advance phases of the succeeding Alaskan glaciation; and end moraines of the Tustumena I advance, representing the maximum extension of Alaskan ice, are dated ca. 2000 B.C., or contemporaneous with the maximum inferred marine regression in post-Tanya time. Late Tanya retreat is therefore marked by the preceding maximum rise in sea level, which implies maximum glacial retreat and optimal climatic conditions just following Skilak time. This interpretation is supported by the pedologic evidence in the Cook Inlet region that indicates much deeper soil development on the moraines of the Tanya advance than on the younger moraines of the Alaskan glaciation, and by the independently dated upland-bog sequence that records maximum glacial retreat, and dry ground and climatic conditions, during the same interval in which the eustatically controlled ground-water levels in the lowland rose to their highest post-Skilak position. Conspicuous uplifted tidal flats recording a sea-level stand at least 5 to 10 feet higher than present datum are near the mouths of the Kenai, Kasilof, and Chickaloon Rivers and are attributed to the maximum marine transgression of late Tanya age in the region.

Insofar as the Girdwood tidal-bog stratigraphy faithfully records relative, if not absolute, glacioeustatic shifts in sea level, it provides a detailed geoclimatic record of the past 3,000 years that should closely reflect average climatic conditions affecting the regimen of the world glaciers. The record is of general sea levels below $-15\frac{1}{2}$ to $-14\frac{1}{2}$ feet relative to present datum during the Tustumena II advance; a marine transgression to above $-13\frac{1}{2}$ feet during the Tustumena II retreat (ca. 500 B.C.); a pulsatory marine regression with four fluctuations above and below $-13\frac{1}{2}$ to $-9\frac{1}{2}$ feet during the Tustumena III advances (about the beginning of the Christian Era); marine transgression to above -4 feet during the Tustumena III retreat (ca. A.D. 500); a marine regression with three fluctuations above and below $-4\frac{1}{2}$ to $-2\frac{1}{2}$ feet during Tunnel I advances (ca. A.D. 1000); a marine transgression above -2 feet during Tunnel I retreat (ca. A.D. 1500); a marine regression with three fluctuations generally below $-\frac{1}{2}$ to -2 feet during Tunnel II advances (ca. 1700); a marine transgression from below -1 foot to present datum during the interval ca. 1850 to 1953; and a progressive rise from 1953 to 1958.

The maximum lowering of sea level during Tustumena I time is not known; but from the coastal-bog record, it is likely that it was lower than the $-15\frac{1}{2}$ feet recorded for Tustumena II time. A sea-level drop of more than 20 feet is therefore suggested between late Tanya time, when sea level was from 5 to 10 feet above present datum, and Tustumena I time, when sea level was probably more than 15 feet below present datum.

No direct Cook Inlet evidence is available for establishing sea-level positions in pre-Tanya III time. As it is generally accepted that eustatic sea-level positions during the culmination of the last ice age were, in general, around 300 feet lower than at present, it is probable that sea level in the north Pacific Ocean also transgressed from around 300 feet below to more than 5 feet above present sea level between early and late Naptowne time. The configuration of this sea-level rise is conjectural, however; and it is likely that the transgression was not uniform but interrupted by static or regressive phases comparable to those recorded for the post-Tanya interval. If so, major sea-level oscillations below present datum would have taken place between 37,000 and 4000 B.C. during the culminations of pro-Naptowne, Moosehorn, Killey, Skilak, and Tanya advances. In stable coastal areas, evidence of these earlier glacioeustatically controlled sea-level oscillations would have to be sought in submerged wave-cut benches or strandline features and in cores of submerged sediments.

SUMMARY OF COOK INLET GLACIAL CHRONOLOGY

The dated glacial history of the Cook Inlet region may be conveniently summarized by graphic portrayal of the glacial oscillations recorded by the morainal sequence deposited in the Kenai Lowland by the Tustumena Lake ice lobe (fig. 14). The positions of named

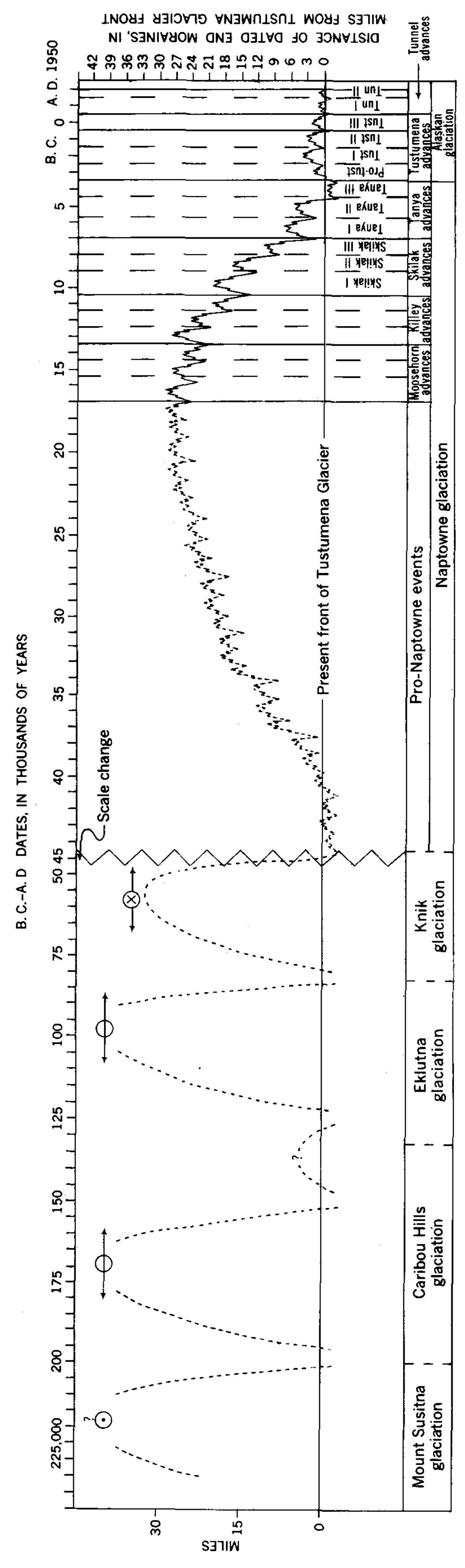

FIGURE 14.—Graphic summary of Cook Inlet glacial chronology.

ice advances are plotted according to distances of terminal moraines from the present front of Tustumena glacier. The morainal complex of the Tustumena Lake ice lobe includes end moraines of Knik age; Naptowne end moraines of the Moosehorn, Killey, Skilak, and Tanya advances; and Alaskan end moraines of the Tustumena and Tunnel advances. During pre-Knik and more extensive glacial advances, the Tustumena Lake ice lobe coalesced with ice that filled Cook Inlet from valley wall to valley wall. Therefore, no end moraines of Eklutna, Caribou Hills, or Mount Susitna age were deposited in the lowlands, and this part of the glacial chronology is recorded by lateral moraines and high-level drift on upland and mountain slopes flanking Tustumena Lake.

The dating of post-Killey moraines and the schematic configuration of this part of the graphed glacial curve are derived from the integrated chronology developed in plate 7. This closely-dated part of the chronology expresses a systematic pattern of glacial oscillations with major retreatal intervals recurring every 3,000 to 4,000 years (about 3500) and with important but subordinate retreatal intervals recurring every 1,000 to 1,200 years (about 1,100). Lesser oscillations, recorded by a complex of minor morainal ridges and by coastal stratigraphy, are superposed on these larger glacial oscillations. The detailed tidal-bog record suggests the possibility of a systematic fourfold subdivision of the about 1100-year glacioeustatic oscillations. It is reasonable to assume that the pre-Skilak glacial oscillations were also subject to the same pulsatory climatic regimen as is recorded by the deposits of post-Killey age. The plotting of the pre-Skilak part of the Naptowne curve is based on this assumption, and the following extrapolated dates are obtained: ca. 13,500 B.C. for the Moosehorn retreatal culmination, ca. 17,000 B.C. for the retreatal culmination preceding the Moosehorn advance, and ca. 20,500 B.C., 24,000 B.C., and so on for important retreatal culminations that presumably interrupted the general advance of the Tustumena Lake ice lobe during its maximum extension in Moosehorn time. As previously discussed, other ice lobes in the region attained their Naptowne maxima either during earlier or later advances, and in this regard their glacial curves would differ from the constructed curve shown in figure 14.

The beginnning of the Naptowne glaciation is provisionally dated between 46,000 and 37,000 B.C. on the basis of the ionium-uranium-ratio date of 46,000 to 31,000 B.C. for marine sediments recording a high interglacial sea of late Knik age and the radiocarbon date of 37,000 B.C. for wood collected from stratigraphically higher proglacial-lake sediments of early Naptowne or pro-Naptowne age. The termination of the Naptowne glaciation is placed at ca. 3500 B.C., or coincident with the inferred culmination in late Tanya time of a comparable sea-level stand higher than present datum. As dated, the Naptowne glaciation therefore suggests an about 40,000-year complete glacial cycle.

Less precise datings of the Knik, Eklutna, and Caribou Hills glaciations at maxima respectively between 50,000 and 65,000; 90,000 and 110,000; and 155,000 and 190,000 years age are derived from the surface-boulder ratios of upland moraines near Skilak Lake (table 1). The Mount Susitna glaciation remains undated by any direct means. However, because the regional geomorphic relations suggest that the interval represented between the Mount Susitna and Caribou Hills glaciations is of the same order of magnitude as those between the Eklutna, Knik, and Naptowne glaciations, a minimum age of between 200,000 and 230,000 years can be suggested for the culmination of the Mount Susitna glaciation.

There is no direct geologic evidence supporting the plotted distances of retreats shown between many of the advances on the glacial curve. From the geomorphic and stratigraphic evidence it is clear that the major retreatal intervals separating the Mount Susitna, Caribou Hills, Eklutna, Knik, and Naptowne glaciations were of an entirely different order of magnitude than those separating the subordinate glacial oscillations. As previously discussed, it is inferred that the distances of retreats separating the subordinate advances of Naptowne and Alaskan age were probably about several miles at the most, rather than tens of miles; and it seems certain that they do not represent complete deglaciation of the bordering alpine areas. The evidence of higher sea levels in Cook Inlet during late Knik and late Tanya time clearly implies that during these intervals the alpine ice areas in the region were much more contracted than today. The relatively greater duration and weathering intensity recorded by the deposits for the interval between the Caribou Hills and Eklutna glaciations further suggest that this interglacial marks a major Pleistocene period of alpine ice contraction. The author leaves open the possibility that alpine ice may have completely disappeared during one or more of the recorded interglacials. However, he is inclined to believe with Capps (1931) that glaciers have survived continuously in the higher mountain areas of Alaska from the beginning of Pleistocene time to the present; and that the Pleistocene ice advances were merely expansions, and the interglacials, contractions, of continuously existing glaciers.

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