GEOLOGICAL SURVEY RESEARCH 1965

Chapter D

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Scientific notes and summaries of investigations by members of the Conservation, Geologic, and Water Resources Divisions in geology, hydrology, and related fields

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GEOLOGICAL SURVEY RESEARCH 1965

This collection of 43 short papers is the third published chapter of Geological Survey Research 1965. The papers report on scientific and economic results of current work by members of the Conservation, Geologic, and Water Resources Divisions of the U.S. Geological Survey.

Chapter A, to be published later in the year, will present a summary of significant results of work done during fiscal year 1965, together with lists of investigations in progress, reports published, cooperating agencies, and Geological Survey offices.

Geological Survey Research 1965 is the sixth volume of the annual series Geological Survey Research. The five volumes already published are listed below, with their series designations.

Geological Survey Research 1960—Prof. Paper 400
Geological Survey Research 1961—Prof. Paper 424
Geological Survey Research 1962—Prof. Paper 450
Geological Survey Research 1963—Prof. Paper 475
Geological Survey Research 1964—Prof. Paper 501

JURASSIC PLUTONISM IN THE COOK INLET REGION, ALASKA

By ROBERT L. DETTERMAN, BRUCE L. REED,
and MARVIN A. LANPHERE, Menlo Park, Calif.

Abstract.—Potassium-argon determinations on hornblende and biotite indicate an age of 170 m.y. for emplacement of the Aleutian Range batholith; geologic mapping suggests emplacement between Early Jurassic and early Middle Jurassic time. The age of this batholith agrees closely with the age of the Kosina batholith in the Talkeetna Mountains about 250 miles to the northeast.

A nearly complete Jurassic section in south-central and southwestern Alaska stratigraphically brackets plutonic rocks that occur in a belt extending from the Talkeetna Mountains to the Alaska Peninsula. The stratigraphic data combined with isotopic ages provide the basis for a tie between the stratigraphic and radioactivity time scales. In the eastern Talkeetna Mountains, Grantz and others (1963) reported a tie between the Toarcian-Oxfordian interval (and perhaps the Early-Middle Jurassic boundary) on the stratigraphic time scale and 160–165 million years on the radioactivity time scale (Kulp, 1961). Potassium-argon ages of hornblende and biotite are herein reported for 3 samples from a stratigraphically bracketed pluton on the west side of Cook Inlet (fig. 1), about 250 miles southwest of the eastern Talkeetna Mountains. The ages obtained indicate that emplacement of granitic rocks was practically synchronous for the two areas.

GEOLOGIC SETTING OF THE ALEUTIAN RANGE BATHOLITH

Reconnaissance studies were made on parts of the Aleutian Range batholith by Martin and Katz (1912, p. 74–77), who reported that the pluton is mainly hornblende granite but also includes various kinds of granodiorite and quartz diorite. Juhle (1955, p. 42–59) mapped the eastern margin of the batholith between Chinitna Bay and Tuxedni Bay. He reported that the margin consists dominantly of hornblende quartz diorite which grades westward into biotite-muscovite granodiorite, and that stocks of quartz monzonite intrude the quartz diorite. More detailed current work in the Iliamna area (Detterman and Reed, 1964) has shown the batholith to be a composite body consisting of hornblende quartz diorite, hornblende-biotite quartz diorite, biotite-hornblende quartz diorite, and biotite quartz diorite. Phases of granodiorite, quartz monzonite, and granite are present locally.

The lower stratigraphic limit for the emplacement of the Aleutian Range batholith is set by the Talkeetna Formation of Early Jurassic age (fig. 2). The Talkeetna Formation is widespread in the Cook Inlet region and consists of 6,000 to 9,000 feet of predominantly volcanic rocks with a few interbedded sedimentary rocks. The lower part of the formation as exposed in the mapped area (fig. 1) is intruded by the Aleutian Range batholith near the head of Chinitna Bay. In nearby exposures the lower part of the Talkeetna Formation disconformably overlies beds of Late Triassic (Norian) age. Rocks lithologically similar to the Talkeetna are intruded by the batholith near sample site X^2 at Tuxedni Bay. Fossils have not been found in the Talkeetna Formation west of Cook Inlet, but the formation is correlated on the basis of lithology with rocks in the Talkeetna Mountains that contain a Lower Jurassic fauna (Grantz and others, 1963).

A definite upper stratigraphic limit for emplacement of the Aleutian Range batholith is established by the Chisik Conglomerate Member, the basal member of the Naknek Formation of Late Jurassic age. The Chisik Conglomerate Member contains abundant fresh-appearing granitic cobbles and boulders that are petrographically similar to the rocks of the Aleutian Range batholith. A rapid southeastward thinning of the conglomerate accompanied by a corresponding decrease in size of clasts, plus relict conglomerate-filled stream channels that cut into the underlying rocks, indicates a nearby northwestern source of the granitic detritus. The conglomerate lenses out laterally into sandstone and siltstone between Chisik Island and Iniskin Bay,

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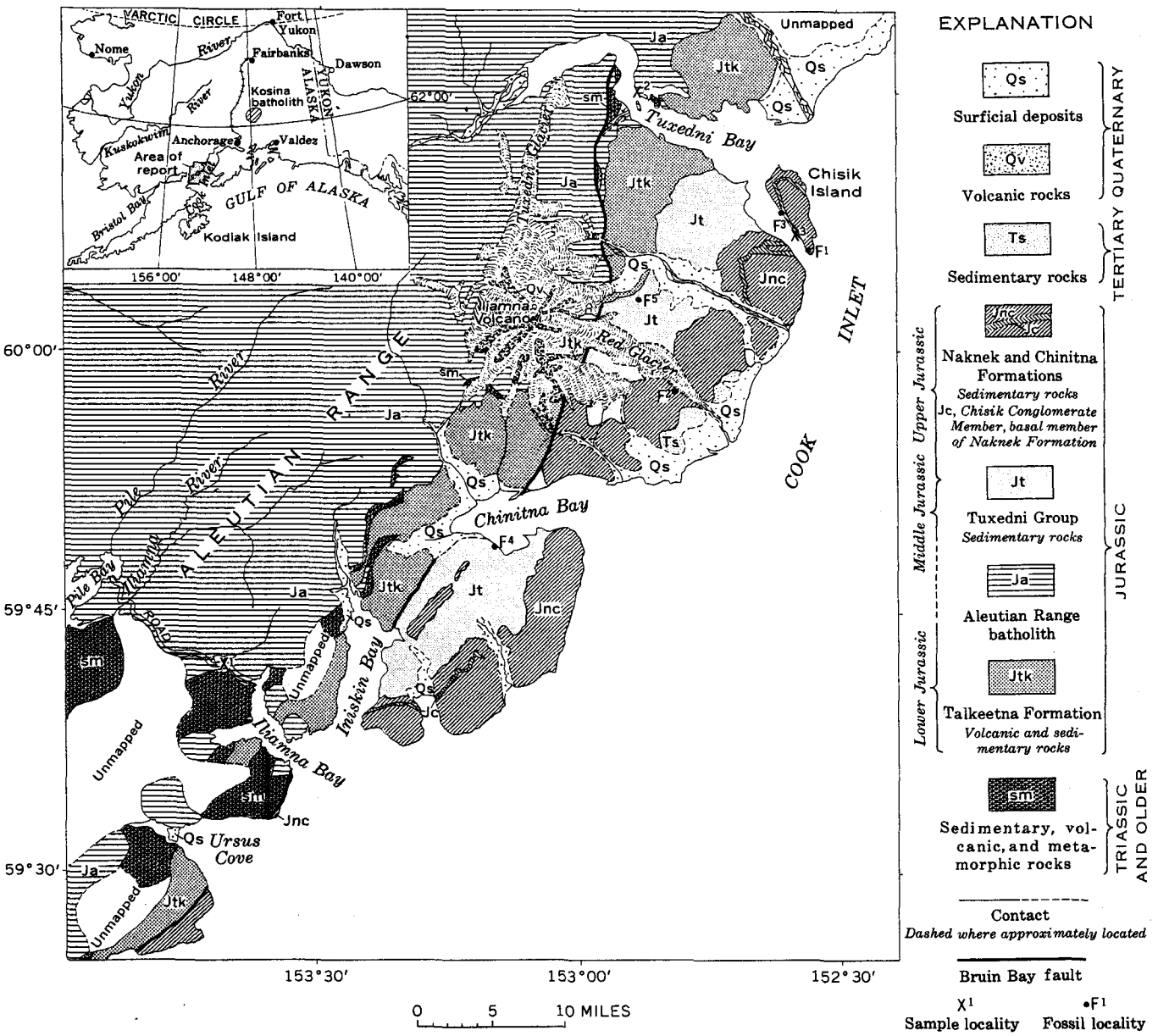

FIGURE 1.—Generalized geologic map of part of the Cook Inlet region, Alaska, showing location of sample and fossil localities.

and the sandstone facies contains a fauna characterized by *Cardioceras* sp. (locality F² in figs. 1 and 2 and table 1) of early Oxfordian age. The Chisik is overlain by fossiliferous siltstone beds in the Naknek Formation (locality F¹) and is underlain by fossiliferous siltstone beds in the Chinitna Formation (locality F³). Naknek siltstone (F¹) contains *Buchia* sp. and *Perisphinctes* sp. of late Oxfordian to early Kimmeridgian age, and the siltstone in the Chinitna Formation (F³) contains *Phylloceras (Partschiceras)* sp. (Imlay, 1953, p. 73), of middle to late Callovian age.

A more restrictive time of emplacement for the batholith is suggested by field evidence west of Cook Inlet. Arkosic sandstone near the base of the Red Glacier Formation (fig. 2) and a few granitic clasts from the overlying Gaikema Sandstone both of Middle Jurassic (Bajocian) age, and parts of the Tuxedni Group (Detterman, 1963) suggest that the batholith was partly unroofed by Bajocian time. We cannot say unequivocally that the granitic detritus from the Red Glacier Formation and Gaikema Sandstone was derived from the Aleutian Range batholith, but there is no evidence of a pre-Jurassic granitic source in southwestern Alaska. Fossils in the Red Glacier Formation includes *Tmetoceras* sp., *Erycites* sp., *Pseudolioceras* sp., *Emilea* sp., and *Sonninia* sp., all of early to middle

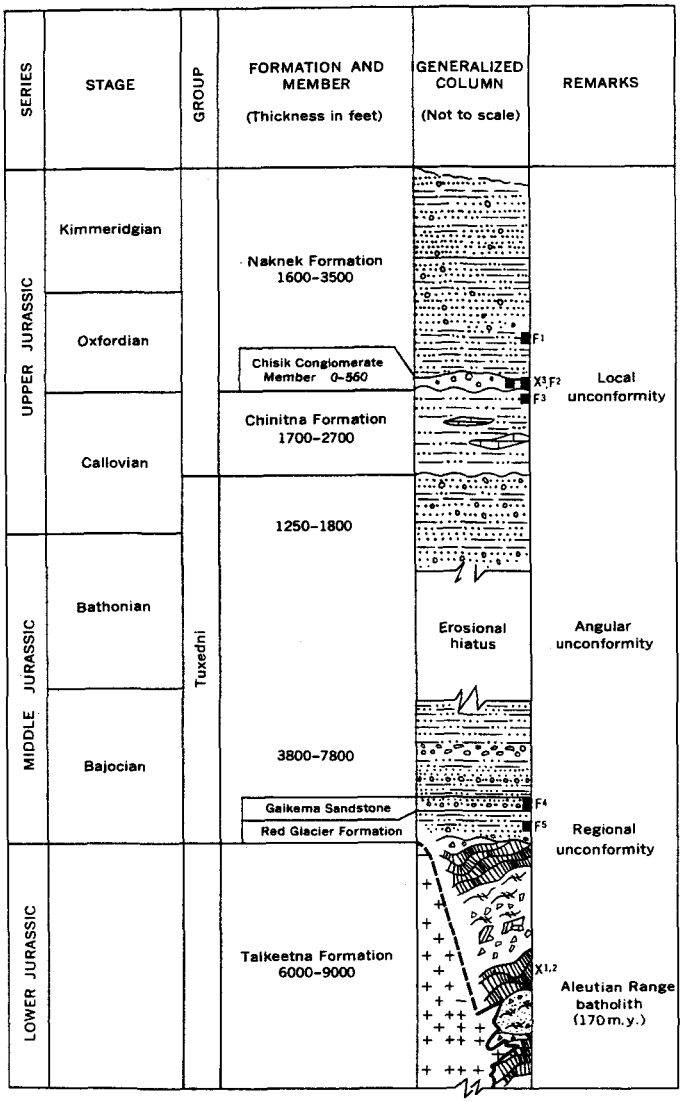

FIGURE 2.—Generalized stratigraphic section, showing location of samples and time of intrusion of Aleutian Range batholith.

Bajocian age (Imlay, 1964, p. B6–B11). A specimen of *Tmetoceras regleyi* Dumortier (F^5) was found in a siltstone of the Red Glacier Formation which overlies the arkosic sandstone within 1,000 feet of the unconformity between the Tuxedni Group and the underlying Talkeetna Formation (figs. 1 and 2). This unconformity marked the end of Early Jurassic volcanism and the beginning of marine sedimentary deposition. Stratigraphic relations suggest also that the Aleutian Range batholith was emplaced during this tectonic event.

ANALYTICAL RESULTS

Potassium-argon ages were determined for hornblende and biotite separated from samples of the Aleutian Range and Kosina batholiths and from a boulder in the Chisik Conglomerate Member. The samples from the Kosina batholith are granodiorite and quartz diorite (Grantz and others, 1963). The samples from the Aleutian Range batholith and the Chisik Conglomerate Member are all classified as quartz diorite according to the modal classification of granitic rocks of Williams and others (1954, p. 93–148). Sample X^1 is from along the road between Iliamna Bay and Pile Bay in the southwestern part of the area shown on the map (fig. 1), X^2 is from the north side of Tuxedni Bay, in the northearstern part of the map area, and X^3 is from a boulder in the Chisik along the southwestern side of Chisik Island. The approximate composition of the bedrock samples is plagioclase (mainly sodic andesine) 30–50 percent; orthoclase (mainly interstitial) 5–8 percent; quartz 20–35 percent; hornblende 12–25 percent; and biotite 6–12 percent. Minor accessory minerals include magnetite, apatite, sphene, and zircon. The approximate composition of the boulder from the Chisik is plagioclase (mainly sodic andesine) 40 percent; orthoclase 8 percent; quartz 32 percent; hornblende 12 percent; biotite 7 percent; and accessory minerals about 1 percent (these include opaque minerals, apatite, sphene, and zircon).

The argon analyses were made using standard isotope-dilution techniques, and the potassium analyses were done by flame photometry using a lithium internal standard. For the potassium-argon analyses (table 2) we estimate the standard deviation of analytical precision to be approximately 4 percent. The standard error of the mean (σ_x) of 9 argon analyses of sample-62ALel biotite, which is used as an intralaboratory argon standard, is 0.20 percent, and the total spread is 1.6 percent. The difference between 2 argon analyses of sample-59AGz–M26 hornblende is 0.2 percent. The absolute uncertainty in calibration of the Ar^{38} tracer is considered to be less than 1 percent. Replicate potassium analyses of intralaboratory standard minerals give standard errors of the mean (σ_x) of 0.39 percent for 12 analyses of a biotite (7.71 percent K_2O) and 0.41 percent for 10 analyses of a hornblende (0.493 percent K_2O). On the basis of these data we assign an analytical uncertainty of ±6 million years to the potassium-argon ages reported in this paper (table 2).

As part of our investigation, fragments of two of the bedrock samples from the Kosina batholith collected by Arthur Grantz were crushed; hornblende was separated from one sample and hornblende and biotite were separated from the other sample. The ages previously reported (Evernden and others, 1961; Grantz

and others, 1963) for biotite from these two samples are shown in table 2 together with our results. The 3 ages for sample-59AGz–M26 biotite are the results of analyses, made in 3 different laboratories, of biotite concentrated from 3 different fragments of the granodiorite.

Ages for biotite from the pluton at Lake Iliamna (62ALel) were previously reported by Detterman and Reed (1964). However, these earlier values should be disregarded because additional potassium and argon analyses have been made of this biotite (62ALel), and the value reported here is more precise.

TABLE 1.—*Location and source of samples dated and of fossils*

[Fossils identified by Ralph W. Imlay]

Loc. on figures 1 and 2 and table 2	Field No. or U.S. Geol. Survey Mesozoic locality No.	Rock type or fossil	Source	Locality
X^1	62ALel	Quartz diorite	Aleutian Range batholith, 2,000 ft from its contact.	Iliamna (D–2) quadrangle; lat 59°42′05″ N., long 153°42′ W.
X^2	62ALe5	do	Aleutian Range batholith, ½ mile from its southeast contact.	Kenai (A–8) quadrangle; lat 60°15′10″ N., long 152°53′10″ W.
X^3	62ALe6e	do	Rounded granitic boulders from Chisik Conglomerate Member at base of Naknek Formation. Boulders from about middle of member where it is 560 ft thick.	Kenai (A–7) quadrangle; lat 60°06′50″ N., long 152°35′05″ W.
F^1	22667	*Buchia* cf. *B. concentrica* Lahusen *Perisphinctes* sp.	Siltstone unit in Naknek Formation (Late Jurassic), about 1,000 ft above X^3.	Kenai (A–7) quadrangle; lat 60°05′50″ N., long 152°33′55″ W.
F^2	22701	*Cardioceras martini* Reeside	Sandstone facies of Chisik Conglomerate Member, about same position as X^3.	Seldovia (D–8) quadrangle; lat 59°57′50″ N., long 152°48′50″ W.
F^3	22668	*Phylloceras* (*Partschiceras*) *subobtusiforme* Pompeckj.	Siltstone in upper Chinitna Formation (Late Jurassic), about 350–400 ft below X^3.	Kenai (A–7) quadrangle; lat 60°07′ N., long 152°35′30″ W.
F^4	19961	*Witchellia* sp	Sandstone in Gaikema Sandstone (Middle Jurassic) of Tuxedni Group, about 5,000 ft above contact with Talkeetna Formation (Lower Jurassic).	Iliamna (D–1) quadrangle; lat 59°49′05″ N., long 153°10′ W.
F^5	24335	*Tmetoceras regleyi* Dumortier	Siltstone in Red Glacier Formation (Middle Jurassic) of Tuxedni Group, about 1,000 ft above contact with Talkeetna Formation (Lower Jurassic).	Kenai (A–8) quadrangle; lat 60°13′15″ N., long 152°53′20″ W.

TABLE 2.—*Potassium-argon ages and analytical data*

[Potassium analyses by H. C. Whitehead and L. B. Schlocker; argon analyses by M. A. Lanphere]

Field No.	Loc. on fig. 1	Mineral	K_2O analyses (percent)	Average K_2O (percent)	Ar^{40}_{rad} (10^{-10} moles/g)	$\frac{Ar^{40}_{rad}}{Ar^{40}_{total}}$	Apparent age (m.y.)
62ALel (Aleutian Range batholith).	X^1	Biotite	8.75, 8.77, 8.83	8.78	[1] 21.56	0.82–0.96	160
		Hornblende	0.952, 0.951	.952	2.469	.77	168
62ALe5 (Aleutian Range batholith).	X^2	Biotite	5.59, 5.63	5.61	14.75	.68	170
		Hornblende	0.473, 0.475	.474	1.229	.58	168
62ALe6e (Chisik Conglomerate).	X^3	Biotite	5.64, 5.75	5.70	13.43	.83	153
		Hornblende	0.714, 0.715	.714	1.708	.74	156
59AGz–M26 (Kosina batholith).		Biotite	4.33, 4.37	4.35	11.12	.82	166
		do					[2] 169
		do					[3] 157
		Hornblende	0.498, 0.501	.500	1.227	.68	159
		do			1.225	.77	159
59AGz–M58 (Kosina batholith).		Biotite					[3] 170
		Hornblende	0.399, 0.408	.404	.7627	.69	163

Decay constants for K^{40}: $\lambda_e = 0.585 \times 10^{-10}$ year^{-1}; $\lambda_\beta = 4.72 \times 10^{-10}$ year^{-1}.
Atomic abundance of $K^{40} = 1.19 \times 10^{-4}$.

[1] Mean value of nine Ar determinations. $\sigma_{\bar{x}} = 0.20$ percent.
[2] Evernden and others (1961).
[3] Grantz and others (1963). Age recalculated with the decay constants used in this paper.

All the potassium-argon ages of bedrock samples from the Aleutian Range and Kosina batholiths agree within the analytical uncertainty referred to above. The mean of 4 mineral ages from outcrop samples of the Aleutian Range batholith is 166 m.y., and the mean of 4 mineral ages from outcrop samples of the Kosina batholith (using the mean of the 3 different results reported for sample-59AGz–M26 biotite as a single mineral age) is 164 m.y. The mean of all of the available potassium-argon ages from these batholiths is 165 m.y. However, our data on reproducibility suggest that the scatter in results is not due to analytical uncertainty, but probably reflects differences in the cooling history of the samples analyzed or a slight loss of radiogenic argon since the minerals crystallized. In discussing the results we assume that the potassium-argon ages are minimum ages because there is no evidence that hornblende or biotite from granitic rocks incorporate significant amounts of radiogenic argon during crystallization. Therefore, we consider the higher apparent ages to be the most reliable estimate of the time of emplacement of these plutonic masses, and suggest a probable age of 170 m.y. for the emplacement of the Aleutian Range and Kosina batholiths.

DISCUSSION OF RESULTS

There are no significant differences in the ages of minerals from the Kosina and Aleutian Range batholiths, and we interpret these results to indicate generally synchronous emplacement of the two batholiths. As stated earlier we assume that the potassium-argon ages are minimum values, but we also believe that the ages reported by Grantz and others (1963) and by us closely approximate the age of emplacement of the Aleutian Range and Kosina batholiths. The most compelling evidence supporting this interpretation is the pattern of concordant ages obtained on coexisting hornblende and biotite, which contrasts with discordant ages that commonly are obtained where postcooling thermal metamorphism has affected plutonic rocks. For example, in the Sierra Nevada batholith of California, which had a complex intrusive and cooling history, hornblende and biotite from the older plutonic units yield grossly discordant ages (Kistler and others, 1965, p. 91–92). On the basis of the concordant hornblende-biotite ages from the Aleutian Range and Kosina batholiths we infer that the parts of the batholiths studied reflect a simple history of emplacement and crystallization and that the hornblende and biotite ages approximate the time of crystallization.

The apparent ages of hornblende and biotite from the quartz diorite boulder in the Chisik Conglomerate Member are significantly less than the apparent ages of minerals from outcrop samples of the Aleutian Range batholith. Grantz and others (1963) reported the same type of difference between the ages of biotite from granitic boulders in the Naknek Formation and from outcrop samples of the Kosina batholith. All the outcrop samples were collected within half a mile of the border of the plutons. If the boulders also were derived from the marginal portions of the batholiths, the difference in age between outcrop samples and boulders suggests that loss of radiogenic argon may have occurred during erosion, transportation, and deposition of the boulders. But, if the boulders were derived from the interior of the plutons, the age discrepancy may reflect differences in cooling history of the plutons. Analysis of samples from interior portions of the plutons may yield additional information on this discrepancy.

The data obtained by Grantz and others (1963) for the Kosina batholith and by us for the Aleutian Range batholith indicate a generally synchronous emplacement of the granitic rocks for the two widely separated areas. The accumulated stratigraphic evidence also indicates that this emplacement occurred during the Toarcian-Oxfordian interval and that it may have occurred at the Early-Middle Jurassic boundary.

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RADIOCARBON DATES FROM ILIAMNA LAKE, ALASKA

By ROBERT L. DETTERMAN, BRUCE L. REED, and MEYER RUBIN,
Menlo Park, Calif.; Washington, D.C.

Abstract.—A radiocarbon date of 8,520±350 years Before Present from a lacustrine sand deposit in a terrace at the west end of Iliamna Lake establishes a minimum age for the second major advance of the Brooks Lake Glaciation. The advance must be considerably older than 8,520 years, as other terraces are cut into the moraine as much as 49 feet above the dated terrace.

Iliamna Lake, Alaska (fig. 1), is one of many large lakes in southern and southwestern Alaska that occupy basins enclosed by moraines of Wisconsin age. Muller [1]

[1] E. H. Muller, 1952, The glacial geology of the Naknek district, the Bristol Bay region, Alaska: Illinois Univ., thesis, 97 p.; microfilm copy available from University Microfilms, Inc, Ann Arbor, Mich.

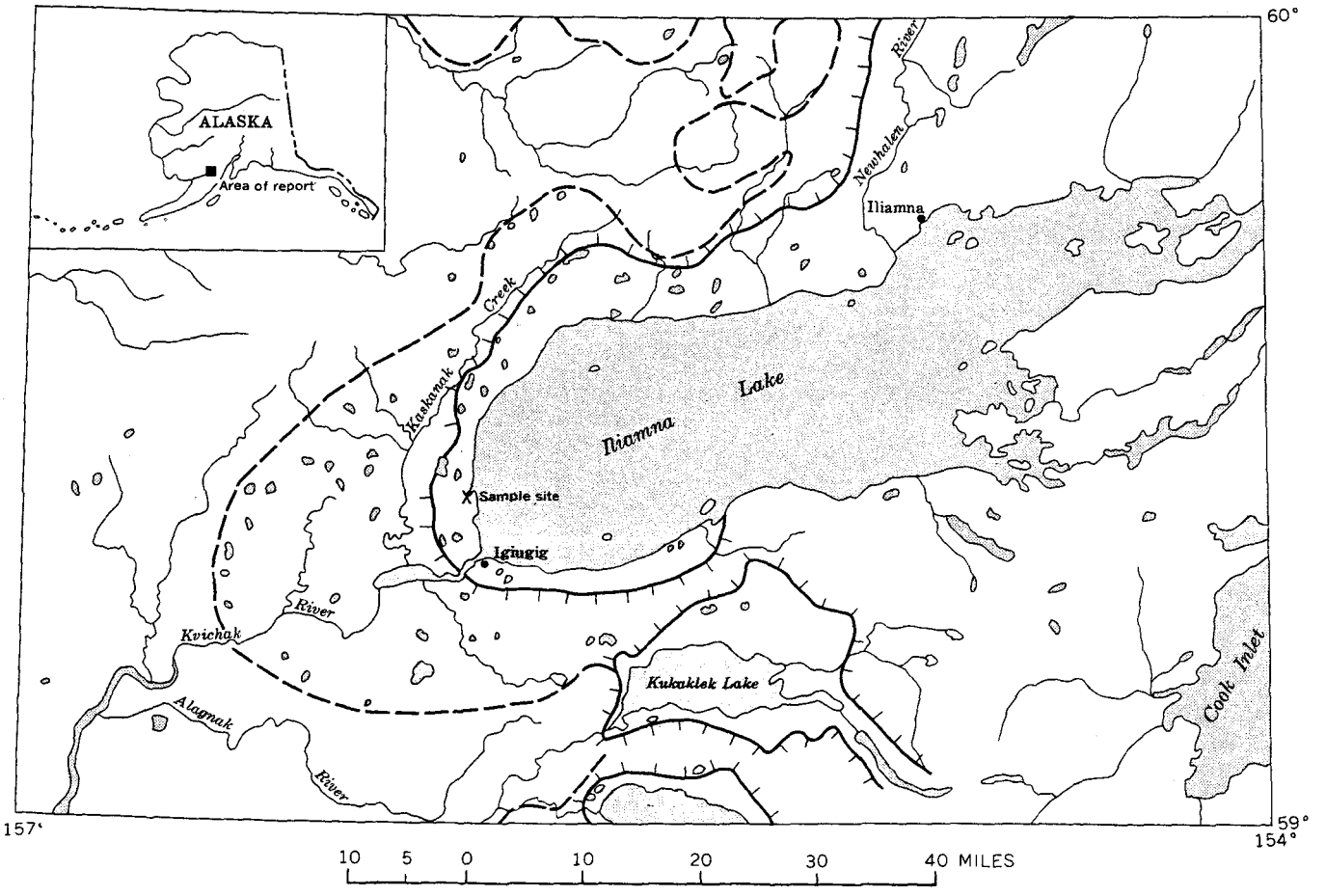

FIGURE 1.—Maximum extent of the Brooks Lake Glaciation in the Iliamna Lake region, Alaska. Dashed line, extent of first major glacial advance; glaciated area lies on the east side of line. Hachured line, extent of second major glacial advance; glaciated area lies opposite the hachured side of line.

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(1953) named the glacial episode during which these lake-enclosing moraines were built the Brooks Lake Glaciation. In the Iliamna Lake area the Brooks Lake Glaciation, as mapped by Detterman and Reed, is recorded by moraines of 4, or possibly 5, major advances that were separated by several minor periods of recession and readvance. The major advances of the Brooks Lake Glaciation probably correspond to the advances of the Naptowne Glaciation as distinguished by Karlstrom (1957; 1964, p. 56–57; Karlstrom and others, 1964).

The moraine of the second major advance of the Brooks Lake Glaciation (fig. 1) encloses the basin of the modern Iliamna Lake. A prominent wave-cut terrace is present on the inner side of this moraine. The altitude of this terrace is about 127 feet above mean sea level; that of the present lake surface is 47 feet. A series of younger terraces with beach ridges and escarpments is present between the 127-foot level and the present lake.

The dates presented herein, the first from the Iliamna Lake area, are from deposits at an altitude of about 78 feet in a terrace that has several beach ridges and a lakeward escarpment. Silt deposits and oriented lakes now occupy a former lagoon on the terrace. Locally, sand dunes obscure the beach ridges and escarpment.

Two pits (fig. 2) were excavated in an area of generally stabilized sand dunes that now is covered by a sparse stand of spruce and brush. The pits, about 20 feet apart, both struck the white volcanic ash layer shown just above zone 3 in figure 2. The sediments penetrated are interpreted as being in part lacustrine and in part eolian. The upper 54 inches, considered to be an eolian deposit, includes dated zones 4 (200±200 years old) and 3 (400±200 years old). The sand is light tan, unstratified, and has well-frosted grains; minor silt is present. Zone 4 has many pieces of rotted wood, some of which are carbonized, probably as a result of a forest fire. Zone 3 is an organic layer containing many carbonized small seed pods, small twigs, and grass(?); it is overlain by the thin bed of white volcanic ash.

Material in the interval between zones 3 and 2b may be either eolian or lacustrine; some of the sand grains are frosted, but many are not, and there is more silt mixed with the sand than is present above zone 3. Zone 2a and b (1,980±250 years old) appears to be in a lacustrine deposit and probably marks the highest stand of water on this terrace; it is composed of 2 layers of organic material about 6 inches apart, separated by sand. The organic material is concentrated in the troughs of probable oscillation ripples.

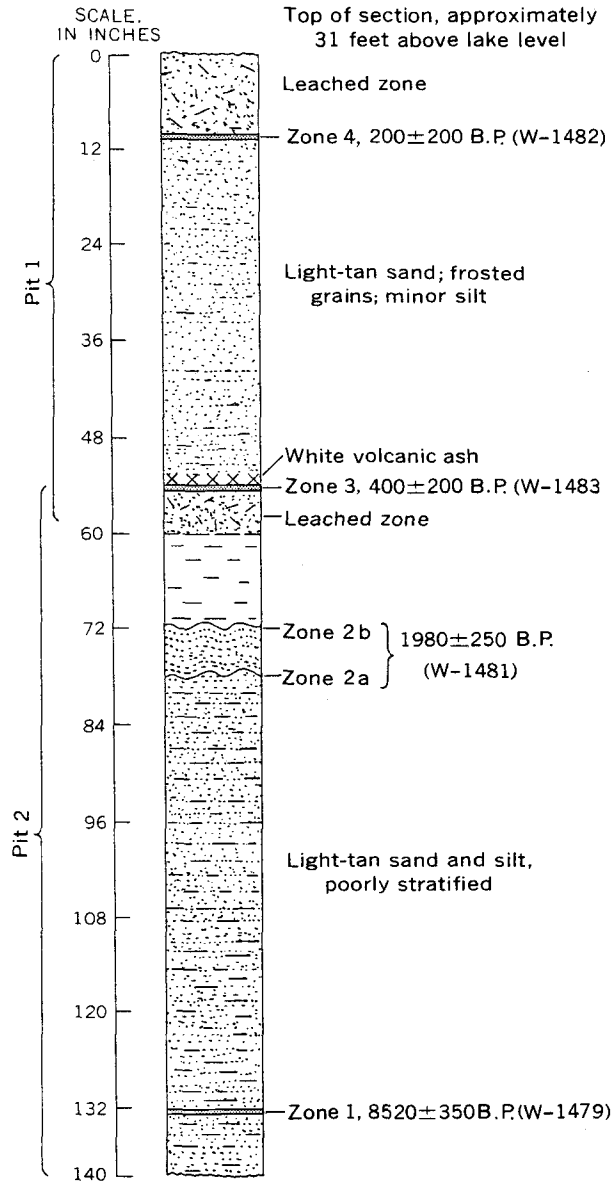

FIGURE 2.—Stratigraphic section in two pits in lake terrace at Iliamna Lake, Alaska. Numbers in parentheses are numbers of samples on which age determinations were made by Rubin at the U.S. Geological Survey radiocarbon laboratory, Washington, D.C. B.P., years Before Present (that is, before A.D. 1950).

The paucity of frosted sand grains and the presence of what are probably oscillation ripple marks suggest water rather than the wind as the agent of deposition. Sand below zone 2a is poorly stratified, finer grained, and contains more silt than the overlying units; it is of probable lacustrine origin. The unit appears to lack depositional breaks, and probably marks a prolonged stand of the lake at this level. Zone 1 is thin (0.25–0.75 in.) and contains very fine organic material without identifiable plant remains. The age (8,520±350 years)

obtained from zone 1 is regarded as a minimum age for the second major advance of the Brooks Lake Glaciation. Because there are older terraces to a height of 49 feet above the dated terrace, and because the terrace cutting took some time to accomplish, the moraine into which these terraces are cut is believed to be considerably older than the dated terrace. The advance which deposited the moraine is probably equivalent to the Killey Stade of the Naptowne Glaciation (Karlstrom, 1964, p. 59). The Killey is thought to have occurred between 12,500 and 19,000 years ago.

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OCCURRENCE AND STRATIGRAPHIC SIGNIFICANCE OF *OLDHAMIA*, A CAMBRIAN TRACE FOSSIL, IN EAST-CENTRAL ALASKA

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Abstract.—Abundant specimens of *Oldhamia*, a fan-shaped trace fossil of probable Cambrian age, were found in the Charley River quadrangle, near the Alaska-Canada boundary. Although no other fossils have been found associated with *Oldhamia* there, the rocks in which it occurs can be correlated with an archaeocyathid-bearing unit of Early Cambrian age nearby. Assignment of this Alaskan *Oldhamia* to the Lower Cambrian is consistent with the Cambrian or possibly latest Precambrian age of *Oldhamia* in Europe and eastern North America. Occurrences of *Oldhamia* in the Mount Schwatka area and in the Crazy Mountains, about 180 and 100 miles, respectively, west of the Charley River quadrangle, suggest that rocks of Cambrian age, much older than previously reported, are probably present in the central interior of Alaska.

During mapping of the Charley River quadrangle (1: 250,000) in east-central Alaska (Brabb and Churkin, 1964), abundant specimens of *Oldhamia*, a fan-shaped trace fossil[1] of probable Cambrian age, were found in rocks originally thought to be the Nation River Formation of Late Devonian age. Additional mapping and laboratory work indicated that the rocks containing *Oldhamia* are different from those of the Nation River Formation but are very similar both lithologically and in stratigraphic position to those bearing Lower Cambrian archaeocyathids in another part of the quadrangle. If this correlation is correct the areal extent inferred for Cambrian rocks in east-central Alaska is about doubled. Moreover, the earlier discovery by Mertie (1937) of a similar *Oldhamia* in the Mt. Schwatka area (locality 3, fig. 1), about 175 miles west of the mouth of the Nation River, suggests that the rocks there are much older than reported and that rocks of Cambrian age are probably present in the central interior of Alaska (fig. 1).

[1] A trace fossil is a sedimentary structure resulting from the activity of an animal moving on or in the sediment at the time of accumulation of the sediment. Trace fossils include tracks, burrows, feeding marks, and other traces (Simpson, 1957).

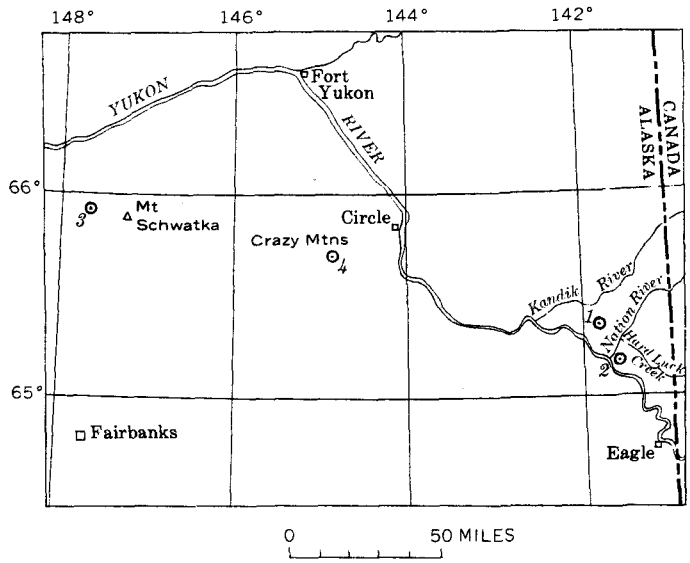

FIGURE 1.—Index map of central and east-central Alaska, showing numbered *Oldhamia* localities.

OLDHAMIA FROM THE CHARLEY RIVER QUADRANGLE

The specimens of *Oldhamia* from the Charley River quadrangle were first identified by Preston E. Cloud, Jr., of the University of Minnesota (written communication, 1963). They consist of gently curved ridges and furrows ½ to 1 mm in width that radiate from centers to form fan-shaped impressions as much as 3 cm in diameter on bedding planes in quartzite and siltstone (fig. 2). Many of the specimens seem to cross each other, but this overlap is probably the result of imprints from one layer being preserved in the succeeding layer, as Ruedemann (1942a) pointed out in relating *Oldhamia* to worm trails. Each fan-shaped

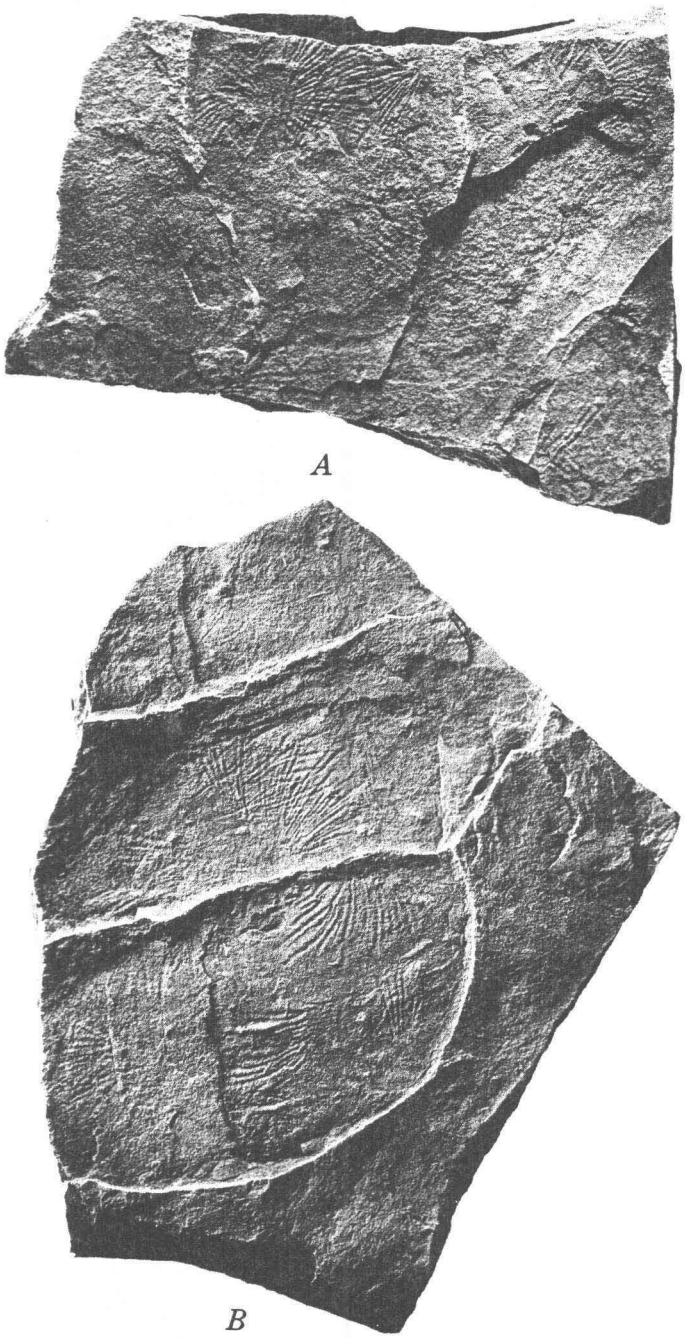

FIGURE 2.—*Oldhamia* from the area between the Kandik and Nation Rivers (loc. *1*, fig. 1), Charley River quadrangle, east-central Alaska. *A*, USNM specimen 146373; natural size. *B*, USNM specimen 146374; natural size.

cluster of ridges in the Alaskan species seems to be disconnected from adjacent clusters, as it is in *Oldhamia radiata* Forbes (Ruedemann, 1942a, fig. 3, photographs 2 and 3) from Ireland and *Oldhamia smithi* Ruedemann (Neuman, 1962, fig. 2) from Maine. The arrangement of the fan-shaped clusters in an interconnected zigzag pattern, as in *Oldhamia antiqua* Forbes (Ruedemann, 1942a, fig. 3, photograph 1) from Ireland or *Oldhamia occidens* (Walcott) (Ruedemann, 1942a, fig. 3, photograph 4) from New York, was not found in the Alaskan material, but the close spacing and apparent overlap of specimens from successive sedimentary laminae has partly obscured their original pattern. The ridges and furrows of the *Oldhamia* from the Charley River quadrangle are more curved than those of *O. radiata* but seem identical to those of *O. smithi* and of the *Oldhamia* illustrated by Mertie (1937, pl. 9A) from Alaska.

All the specimens of *Oldhamia* found in the Charley River quadrangle are from two small areas of outcrop (locs. *1* and *2*, fig. 1) of a distinctive formation of thinly interbedded and cross-laminated quartzite, quartzose siltstone, and silty argillite. The quartzitic layers are pale olive, and the fine-grained, more argillaceous interbeds are light olive gray. The distinct and very thin and laminated bedding, together with well-developed scour-and-fill structures and various small sole marks of undetermined origin, characterize this formation. White mica is usually abundant on the bedding planes, and in thin section abundant chloritic material, sericite, and strained quartz sand grains with well-developed quartz overgrowths collectively serve to distinguish the *Oldhamia*-bearing rocks from other formations in the Charley River quadrangle. In particular, the presence of white mica and abundant laminae and cross-laminae in the *Oldhamia*-bearing rocks, and the absence from these rocks of thick beds of chert-rich sandstone and chert-pebble conglomerate and of ubiquitous plant fragments, distinguish the *Oldhamia*-bearing rocks from those of the Nation River Formation.

CORRELATION AND AGE OF THE *OLDHAMIA*-BEARING ROCKS

Although no other fossils have been found at the two *Oldhamia* localities, the distinctive unit of argillite and quartzite in which *Oldhamia* occurs can be correlated (fig. 3) with a similar unit of Lower Cambrian argillite in a fossiliferous sequence exposed between Hard Luck Creek and the Yukon River, 10 to 25 miles east of the mouth of the Nation River. The unnamed argillite and quartzite unit in the fossiliferous sequence (Brabb and Churkin, 1964) contains archaeocyathids of Early Cambrian age, according to A. R. Palmer, of the U.S. Geological Survey (written communication, 1965), and is overlain by a limestone unit that contains, according to Palmer, trilobites of uppermost Cambrian age in its upper part and of Middle or possibly Lower Cambrian age in its lower

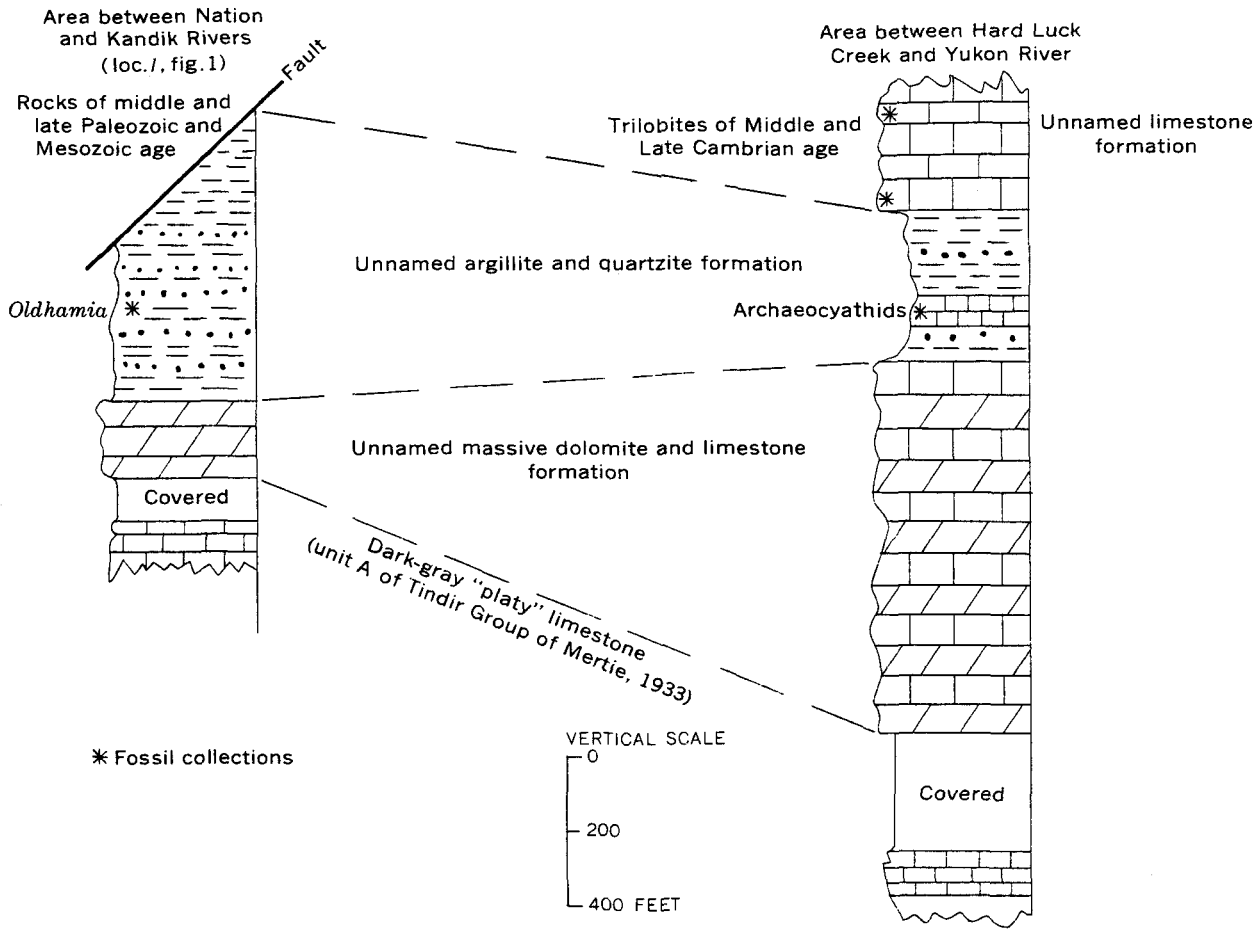

FIGURE 3.—Geologic sections showing the correlation of argillite and quartzite sequences in two areas of east-central Alaska.

part. It is underlain by an unnamed massive dolomite unit which in turn is underlain by dark-gray laminated and platy limestone characteristic of Mertie's (1933, p. 370-372) unit A of the Tindir Group of late Precambrian and Early Cambrian(?) age. This platy limestone is underlain by a succession of rocks characteristic of the older units of the Tindir Group. In the area between the Kandik and Nation Rivers (loc. *1*, fig. 1), the *Oldhamia*-bearing argillite unit rests accordantly on a sequence of massive dolomite underlain by dark-gray platy limestone and older rocks of the Tindir Group similar to the sequence that underlies the archaeocyathid-bearing Lower Cambrian argillite in the area between Hard Luck Creek and the Yukon River. The upper part of the *Oldhamia*-bearing unit in the area between the Kandik and Nation Rivers is faulted against middle and upper Paelozoic and Mesozoic rocks, so that no direct correlation can be made with the Middle and Upper Cambrian limestone beds that overlie the Lower Cambrian argillite unit of the fossiliferous sequence. A limestone that seems to be stratigraphically above the *Oldhamia*-bearing argillite about 3 miles northeast of the mouth of the Nation River (just north of loc. *2*, fig. 1) is lithologically similar to, and may be correlative with, the Middle and Upper Cambrian limestone; but no fossils were found in this unit, and the structure in the area is so complicated that the limestone may not be in superpositional sequence.

Greenstone occurs in the *Oldhamia*-bearing rocks 3 miles east of the mouth of the Nation River (loc. *2*, fig. 1). Except for the older part of the Tindir Group, the only other greenstone known in the immediate area is in the argillite and quartzite formation exposed directly below fossiliferous Middle and Upper Cambrian limestone near the Alaska-Yukon boundary. This joint occurrence of greenstone in the two areas further supports the correlation of the enclosing argillite and quartzite.

In summary, similar lithology and similar sequence suggest that the *Oldhamia*-bearing rocks are correlative with Brabb and Churkin's (1964) unnamed argillite unit of Early Cambrian age.

The assignment of this *Oldhamia* to the Lower Cambrian is consistent with the following known occurrences of the genus in Europe and eastern North America: Cambrian of Ireland, the type area for the genus (Forbes, 1848–50); Nassau Formation of Early Cambrian age in eastern New York (Walcott, 1894); Grand Pitch Formation of Cambrian(?) age in northeastern Maine (Smith, 1928; Neuman, 1962); and Weymouth Formation of Early Cambrian age in Massachusetts (Howell, 1922). One of two species of *Oldhamia* reported in rocks of Ordovician age (*Oldhamia keithi* Ruedemann, 1942b, fig. 5, photographs 1 and 2) is substantially different in appearance and probably is not the same genus; the other, *Oldhamia pedemontana* Rusconi, has recently been shown to be a bryozoan (Fritz, 1965). Although *Oldhamia* is widely distributed it has been reported only in argillaceous rock interbedded with quartzite. In spite of the dangers of using a facies-restricted trace fossil for determining the age of a formation, *Oldhamia* appears to be restricted to rocks of Cambrian age, or as Neuman (1962) points out, may range downward into rocks as old as latest Precambrian.

OTHER OCCURRENCES OF *OLDHAMIA* IN ALASKA

In Alaska, trace fossils questionably assigned to *Oldhamia* had previously been found by Mertie (1937, p. 121, pl. 9A) near Mount Schwatka (loc. *3*, fig. 1). These fossils have all the structural details of the *Oldhamia* found in the Charley River quadrangle, and they belong unquestionably to the same genus. Mertie included his *Oldhamia*-bearing rocks in a belt of "undifferentiated noncalcareous rocks of Mississippian age." The Mississippian age for these rocks was based mainly on a few widely scattered fossil collections from similar rocks in neighboring areas. The new occurrence of *Oldhamia* from probable Lower Cambrian rocks in the Charley River quadrangle suggests that at least some of the rocks previously considered Mississippian by Mertie are probably Cambrian.

The only other *Oldhamia* known from Alaska was collected in 1962 in the Crazy Mountains (loc. *4*, fig. 1), 100 miles northwest of the mouth of the Nation River, by geologists of BP Exploration Co. (Alaska), Inc., who kindly loaned us the specimen (fig. 4). This *Oldhamia* is somewhat smaller and has correspondingly finer ridges and furrows than that from the Charley River quadrangle, but otherwise it has the same structure. The fossils were found in mudstone interbedded with quartzite that was originally mapped by Mertie (1937) as "undifferentiated noncalcareous rocks of Devonian age." The Devonian age was evidently based on a lithologic correlation inasmuch as

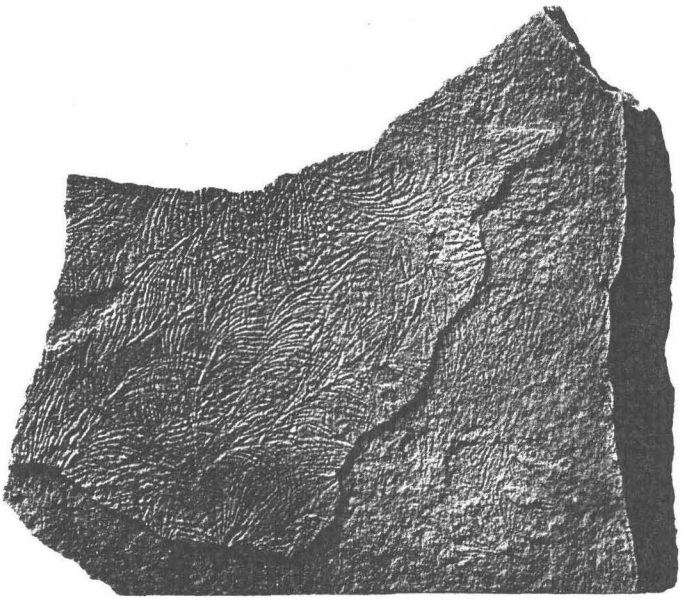

FIGURE 4.—*Oldhamia* from the Crazy Mountains (loc. *4*, fig. 1) east-central Alaska. Specimen loaned by BP Exploration Co. (Alaska) Inc. Enlarged × 1.5.

Mertie apparently did not find fossils in the area. The discovery of *Oldhamia* from the Crazy Mountains partly bridges the distance between the Mount Schwatka locality on the west and the Nation River area on the east and suggests that some of the rocks there are probably also Cambrian.

The geographic location of all known occurrences of *Oldhamia* is shown in the accompanying list.

Geographic location of Oldhamia *collections in Alaska*

Area between the Kandik and Nation Rivers, 10 miles north of the mouth of the Nation River (loc. *1*, fig. 1). Charley River B–2 quadrangle (1:63,360):

62ACn 851[1] (M1024–CO).[2] From top of ridge at elev 3,000 ft in NE¼ sec. 21, T. 6 N., R. 29 E., lat 65°20.2′ N., long 141°46.0′ W.

62ACn 891 (M1025–CO). NE¼SE¼ sec. 21, T. 6 N., R. 29 E., lat 65°20.0′ N., long 141°45.7′ W.

62ACn 1081 (M1026–CO and USNM 146374,[3] see fig. 2*B*). From top of ridge at elev 2,500 ft in NE¼NE¼ sec. 30, T. 6 N., R. 29 E., lat 65°19.4′ N., long 141°50.1′ W.

63ACn 2091 (M1027–CO and USNM 146373, see fig. 2*A*). From top of ridge at elev 2,500 ft in NE¼NE¼ sec. 30, T. 6 N., R. 29 E., lat 65°19.4′ N., long 141°50.1′ W.

63ACn 2126 (M1028–CO). SW¼SW¼ sec. 23, T. 6 N., R. 29 E., lat 65°19.7′ N., long 141°43.4′ W.

Area about 3 miles east of the mouth of the Nation River (loc. *2*, fig. 1). Charley River A–2 quadrangle (1:63,360):

63ACn 2212 (M1029–CO). From top of ridge at elev 2,100 ft in NW¼NW¼ sec. 32, T. 5 N., R. 30 E., lat 65°13.4′ N., long 141°37.0′ W.

[1] U.S. Geological Survey field locality number.
[2] U.S. Geological Survey fossil collection number.
[3] U.S. National Museum specimen number.

63AGs 344B (M1030–CO). At elev 1,000 ft in SW¼ sec. 19, T. 5 N., R. 30 E., lat 65°14.7′ N., long 141°37.6′ W.

Vicinity of Mount Schwatka (loc. *3*, fig. 1). Livengood D–2 quadrangle (1:63,360):

21AMt 152. At elev 3,000 ft on top of ridge east of Lost Creek. About 15.4 miles N. 39° E. from junction of Grouse and Bear Creeks. Collector, J. B. Mertie, Jr., 1921.

Crazy Mountains (loc. *4*, fig. 1). Circle C–3 quadrangle (1:63,360):

Mountain crest 0.9 mile northeast of BM3728 (Craz), lat 65°43′ N., long 145°4.3′ W. Collected by geologists of BP Exploration Co. (Alaska) Inc. (fig. 4).

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SUBSURFACE STRATIGRAPHY OF GLACIAL DRIFT AT ANCHORAGE, ALASKA

By FRANK W. TRAINER and ROGER M. WALLER, Washington, D.C.

Abstract.—Glacial drift at Anchorage, which is situated at an edge of a wide glaciated lowland, reaches a thickness greater than 500 feet. The drift includes till, outwash-stream deposits, and estuarine and lake sediments which represent at least five glacial episodes, and it thickens progressively from the mountain wall on the east toward the deeper, axial part of the valley. Its constitution changes in the same direction, from predominant till near the mountain wall to till, sand and gravel, and clay in an intermediate region and then to till and clay near two estuaries which border the area. These changes are attributed to areal differences in dominant modes of sedimentation. The expression of the same topographic features in several buried surfaces (unconformities) is believed to reflect continuing, indirect influence of the preglacial topography on deposition of the drift. Disastrous slides during the Alaska earthquake of March 27, 1964, were caused by failure of a thick clay unit exposed in bluffs at Anchorage.

Pleistocene deposits at Anchorage, in south-central Alaska, represent at least five episodes of glaciation and include all the types of sediments commonly found in glacial drift. The stratigraphy of the drift is described in this report, and the areal distribution of the separate units is outlined. The distribution of one unit, the Bootlegger Cove Clay, provides background information helpful in the interpretation of why landslides occurred where they did during the Alaska earthquake of March 27, 1964. The results reported in this paper are based upon surface investigations coupled with study of the detailed logs of 21 deep test wells and of the logs of 400 domestic and industrial wells and 93 test borings; and study of samples from many of the wells. The logs studied range from 35 to 540 feet in depth and average 160 feet. A total of 81,500 feet of logs was studied. Criteria for the recognition of different types of glacial drift in the logs are given by Cederstrom and others (1964, p. 16–20).

Anchorage is situated on a triangular tract of lowland that is bounded on the east by high mountains and on the southwest and northwest by two estuaries (fig. 1). The area described in this report is entirely in the lowland except at the southeast, where it extends a short distance up the mountain slope. Local relief is less than 100 feet except near some stream valleys and hilly tracts. The land surface is underlain generally by glacial drift. The drift comprises (1) till, and associated till-like sediments believed to have been somewhat sorted during deposition by mudflow, by meltwater streams, or in standing water at glacier margins;

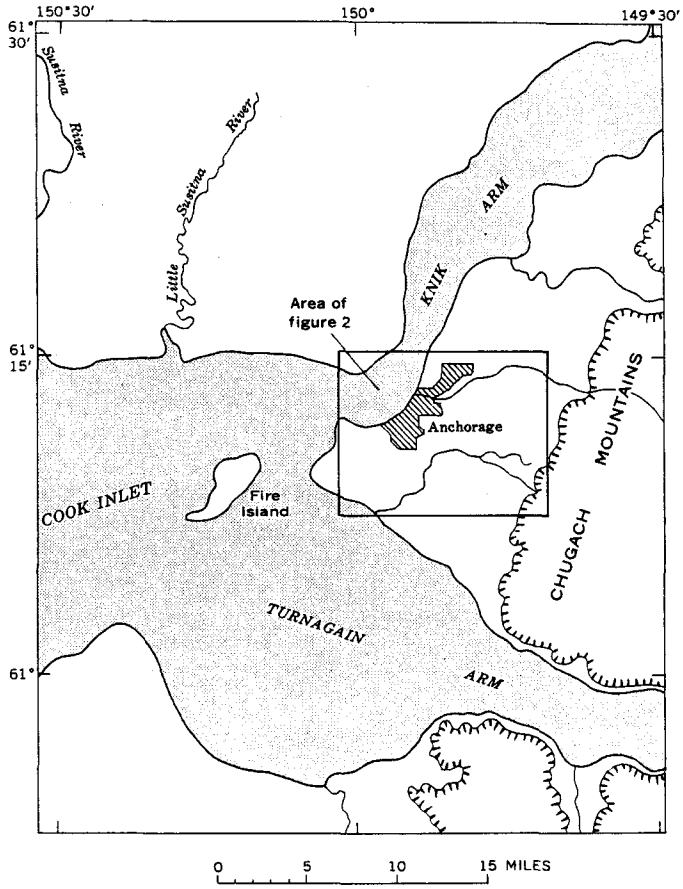

FIGURE 1.—Index map showing approximate boundaries of Anchorage area, Alaska. Diagonal pattern shows Anchorage and heavily settled adjacent areas.

(2) outwash sand and gravel deposited by melt-water streams; and (3) sand, silt, and clay deposited in standing water (fig. 2).

CHARACTER AND SUBDIVISION OF THE GLACIAL DRIFT

Two sheets of glacial drift are exposed at the land surface (fig. 2). The younger of these was formed during the last glaciation of the upper Cook Inlet lowland, the Naptowne Glaciation of Wisconsin age (Karlstrom, 1964). This drift sheet consists of the Elmendorf end moraine (Miller and Dobrovolny, 1959) formed by a large valley glacier that advanced into this area from the east-northeast, and of outwash-plain and lake deposits which cover most of the central part of the area south of the end moraine. Older ground-moraine and associated deposits, exposed in the southern and eastern parts of the area, represent the next-older Knik Glaciation (Miller and Dobrovolny, 1959, p. 12–14) or the Knik and an older glaciation as well (Karlstrom, 1964, pl. 6). Subsurface data from the records of wells and test borings reported in this paper provide evidence of older drift deposits which are not exposed. Miller and Dobrovolny (1959) and Cederstrom and others (1964) have described the Pleistocene deposits, and these authors and Karlstrom (1964) have discussed their stratigraphy and history.

The fence diagram (fig. 3*B*), based on the logs of selected wells, summarizes our interpretation of the stratigraphy of the drift. The diagram is a revision, at a new scale and with added data, of one prepared as part of a study of ground water in the Anchorage area. Part of the older diagram was published in Cederstrom and others (1964, fig. 11), and part of it was reproduced in an engineering-geology report on landslides which occurred after the earthquake.[1] Most of the logs have been published: Waller and others (1961) is the most complete reference; others are Miller and Dobrovolny (1959), Cederstrom and others (1964), and Shannon and Wilson (1964). All the logs are in the files of the Water Resources Division of the U.S. Geological Survey at Anchorage.

Problems of identification and of the adequacy of the data affect the reliability of interpretation of the drillers' logs, on which figure 3*B* is based. The common types of materials can be identified readily from drillers' reports for most wells, and the materials are sufficiently different that the boundaries of till and clay-silt units probably were located within a few feet of their true positions in one-half to two-thirds of the logs. In most of the remaining logs our error in locating contacts was probably less than 20 to 30 feet. The buried deposits of sand and gravel present a different type of problem. They generally can be identified with confidence, but their thickness is poorly known because most wells do not penetrate them completely. The water wells commonly were drilled into sand and gravel only far enough to obtain the desired yield, and the test borings commonly were terminated in the upper part of the sand and gravel, just below the overlying clay or till.

Figure 3*B* shows that the deposits at Anchorage form several drift sheets of wide extent. We believe that each of 6 wells (197, 64, 111A, 177, 590, and 291, listed from east to west) penetrates 4 till sheets that are separated by sand and gravel, clay, or a weathered zone (Cederstrom and others, 1964, p. 26). Another well (163) appears to penetrate 4 or 5 till sheets, and several shallower wells penetrate at least 3 tills thought to be part of the same sequence of beds. Because the boundary between each pair of till sheets, as we have correlated them, is marked by a weathered zone that must have required an appreciable ice-free interval for its formation, we believe that the buried till sheets represent at least four glacial episodes. This interpretation, with the additional evidence of the Elmendorf end moraine, implies that the Anchorage area has been glaciated at least five times. Karlstrom (1964) has identified five glaciations in the Cook Inlet region on the basis of surface observations interpreted partly in the light of radiocarbon dates. We believe that the 2 drift sheets exposed in this area represent the 2 youngest members of the sequence — the Knik (older) and Naptowne Glaciations. We hesitate, however, to assign the older tills in the subsurface to the first 3 of his glaciations, because of uncertainty in the correlation of the older tills and because we cannot eliminate the possibility that more than five tills are present.

The composition of the drift section changes progressively with increasing distance from the mountain wall toward the center of the valley. At the wall the drift is largely till. Farther west, near wells 114, 163, and 177, beds of sand and gravel of appreciable thickness, and some of clay, are interbedded with the till. Still farther west (as far as wells 291, 427, and 624, for example) the sand and gravel are thin or absent and the section consists chiefly of clay and till.

The drift also thickens toward the center of the valley. The logs of 9 wells which reach bedrock near Anchorage record total thicknesses of drift of (1) about 100 to 230 feet on and near the slope south and

[1] Engineering Geology Evaluation Group, 1964, Geologic report, 27 March 1964 earthquake in the Greater Anchorage area: Alaska State Housing Authority, 41 p. [Duplicated report]

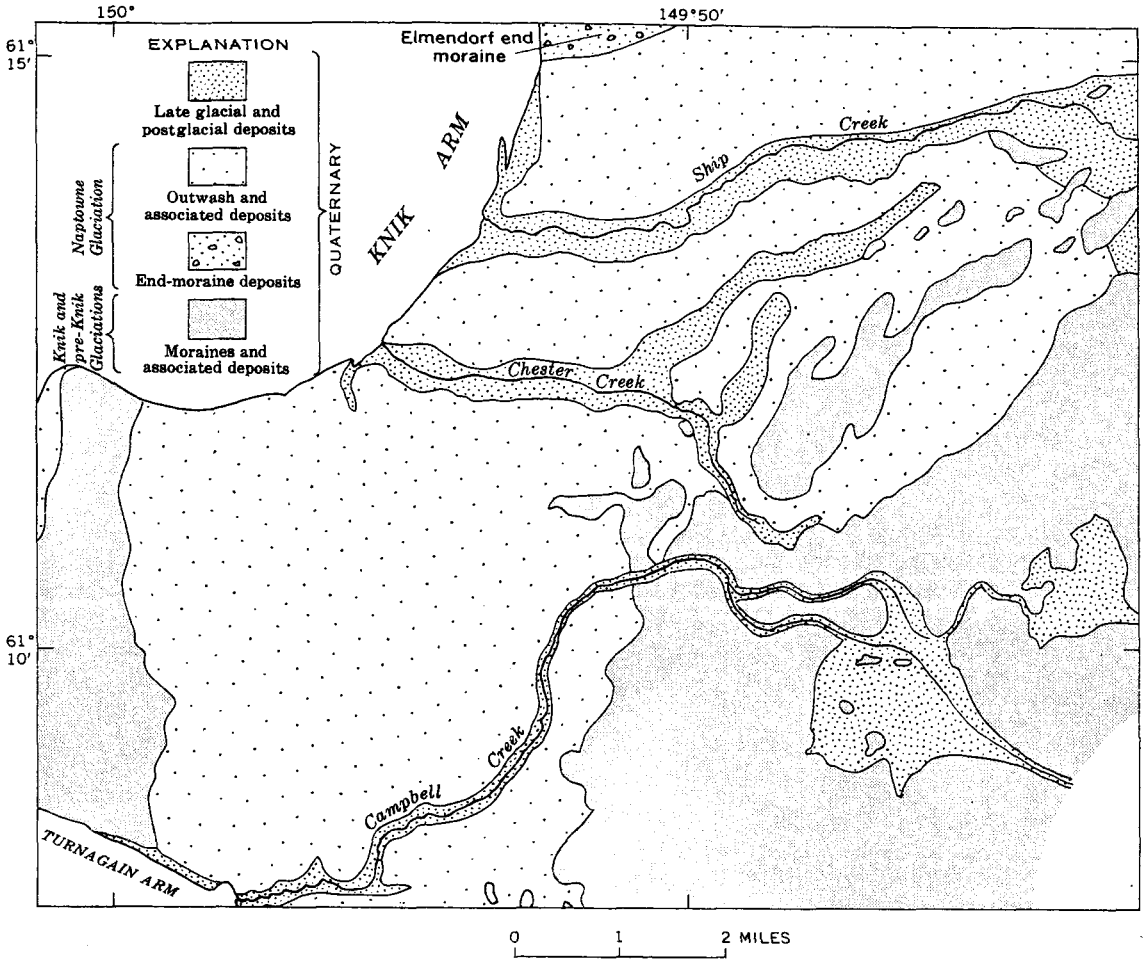

FIGURE 2.—Surficial geology of part of the Anchorage area, Alaska (generalized after Miller and Dobrovolny, 1959, pl. 1, and Cederstrom and others, 1964, pl. 1). Bootlegger Cove Clay, which crops out in bluffs along Knik Arm and Ship Creek and locally elsewhere, is not shown.

east of the region shown in figure 3*B*; (2) about 350 to 450 feet farther out in the lowland (wells 64 and 197, fig. 3*B*, and a well northeast of 64 that is not shown on the diagram); and (3) more than 540 feet but less than 700 feet near Knik Arm (well 28; the top of the bedrock is difficult to identify in the log).

These changes in the constitution and thickness of the drift reflect areal differences in the dominant modes of sedimentation. Where the mountain slope and adjacent lowland were not covered by ice, meltwater streams (flowing mainly across the lowland) deposited sand and gravel that represented part of the sediment carried from the glacier. In contrast, much of the deeper part of the valley lay under water during periods when it was not covered by ice, and most of the sediment carried into the standing water was deposited there. Thus, the nontill deposits to the west are much thicker, and contain much more clay and silt, than those to the east.

YOUNGEST DRIFT SHEETS

Figure 3*B* illustrates several drift sheets, each of which appears to be a composite of (1) till, (2) sand and gravel, and (3) clay and silt that represent a single glaciation. The younger deposits are better preserved than the older ones and are much better known because many more wells penetrate them. Two units, the Knik Till and the Bootlegger Cove Clay which overlies the till, are sufficiently well known to be mapped in some detail. Contour maps of the base of the till and of the base of the clay reveal the gross form of the land surface before and after the next-to-last glaciation of the area. The maps agree in their portrayal of several former topographic features (now parts of unconformities), and this agreement lends credence to our interpretation of the subsurface data. It is important to note, however, that the maps are based largely on the same logs, so that if one map is in error at a given place the other probably is also in

error. Thus, if the upper till in a sequence (in ascending order) of till, clay, till, and clay had locally been removed by erosion before deposition of the upper clay, the two clays might be interpreted as being the upper clay alone, and the lower till identified as the upper till unit. Consequently the inferred altitudes of the bases of both map units would be in error. However, this type of error seems unlikely because the wells are numerous and closely spaced.

Knik Till

Figure 4 is a contour map of the base of the Knik Till. This till is exposed as ground (and lateral?) moraine in the eastern part of the map area but is buried by younger deposits in most of the area shown. The pattern of contour lines shows that the till was deposited on a gently sloping surface which in the south-central part of the area flattens and extends westward as a broad, low hill. We interpret this hill as an expression of the preglacial divide (undoubtedly greatly eroded) between the major valleys now occupied by Knik Arm and Turnagain Arm. The hill is bounded on the north and west by deep valleys. The valley to the west is thought to be the northward extension of the Turnagain valley. That to the north may represent the westward extension of the preglacial Ship Creek valley into the lowland.

Figure 5 is a contour map of the base of the next younger extensive stratigraphic unit, the Bootlegger Cove Clay. That surface can be considered to approximate the upper surface of the Knik Till because sand and gravel are present between the till and clay only locally. Comparison of figures 4 and 5 shows that the till is commonly about 50 feet thick and that the form of its upper surface is a rather close replica of that of its base. The prominent topographic features of the surface beneath the till — the wide hill in the central part of the area and the valleys north and west of it — are all repeated on its upper surface. Thus, except for small buried hills such as those shown in generalized form at wells 333 and 398, in the northwestern part of figure 3*B*, and in somewhat more detail in figure 5, the configuration of the till sheet reflects that of the topography on which the till was deposited; it is not due to erosion.

Bootlegger Cove Clay

The Bootlegger Cove Clay is a deposit of clay, silt, and subordinate material which underlies the surficial sand and gravel in much of the Anchorage area (Miller and Dobrovolny, 1959, p. 35–48, pl. 5–6; additional data and discussions of the character, distribution, fossil content, and origin of the clay are given by Schmidt, 1963; Cederstrom and others, 1964; Karlstrom, 1964;

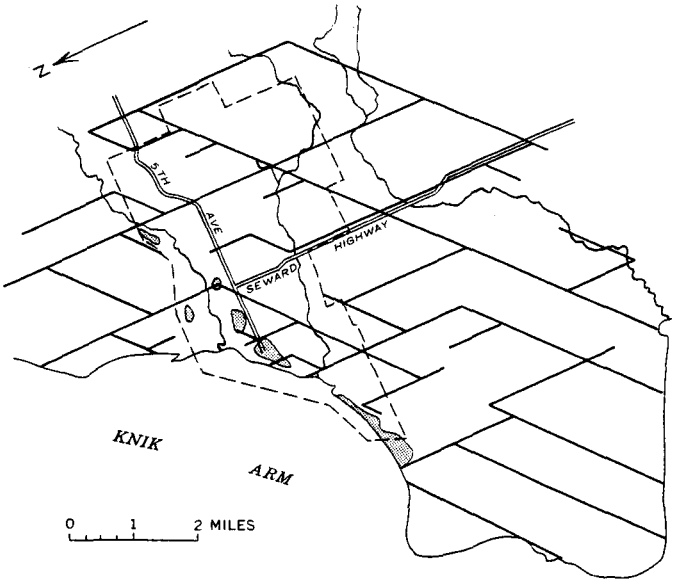

FIGURE 3

A, Index map to fence diagram on facing page, showing location of lines of section, landslides of March 1964 (shaded areas), and boundary of Anchorage (dashed lines).

B, Fence diagram, based on selected well logs, that shows the stratigraphy of glacial drift in part of the Anchorage area, Alaska. Diagram is oriented with view southeastward, from above Cook Inlet, to show deposits in central part of area to best advantage; it is somewhat distorted by projection. Well logs numbered with letter prefixes from Shannon and Wilson (1964); other well logs from Waller and others (1961) and unpublished records in files of Water Resources Division, U.S. Geological Survey, Anchorage.

and Shannon and Wilson, 1964). The clay is younger than part of the Knik drift; in part it extends beneath the Elmendorf end moraine, and, in part, adjacent to the end moraine, it contains what appears to be water-laid till and has been deformed. Evidently the Naptowne glacier advanced into the water body in which the clay was deposited. Karlstrom (1964, p. 37–38) believes that the clay consists of three units. According to his interpretation, which we think reasonable, the lower beds were deposited in a Knik proglacial lake formed when water was ponded in the upper Cook Inlet region by coalescent glaciers to the southwest; the middle beds represent estuarine deposition during the Knik-Naptowne Interglaciation; and the upper beds were laid down in a Naptowne proglacial lake.

In gross form the upper surface of the Bootlegger Cove Clay (fig. 6), with a broad hill in the central part of the area bordered by valleys to the west and north, resembles the form of each of the older unconformities shown in figures 4 and 5. It is inferred that the same strong control operated throughout the separate cycles of sedimentation in this area, giving a simi-

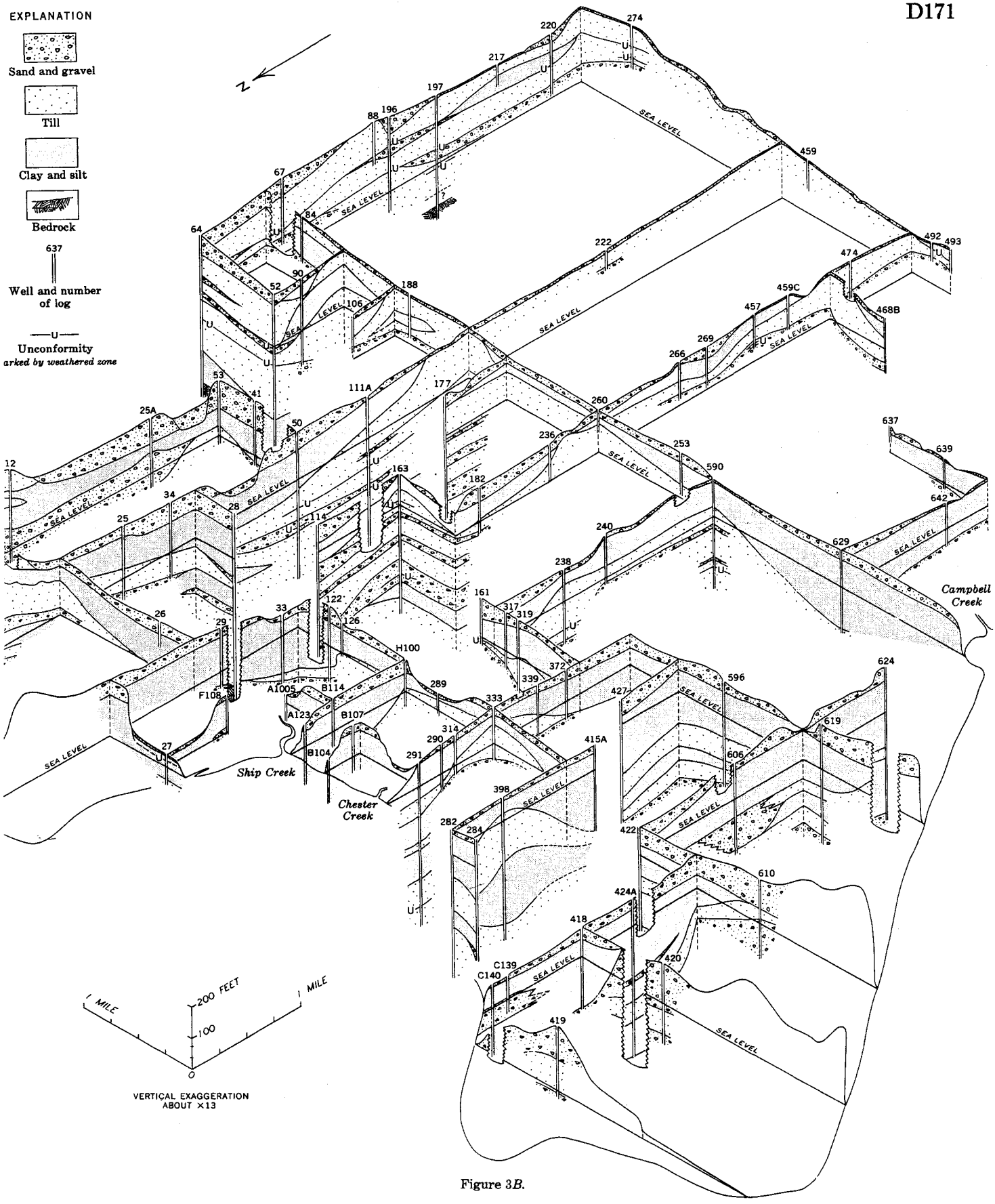
EXPLANATION
Sand and gravel
Till
Clay and silt
Bedrock
637
Well and number of log
—U—
Unconformity
arked by weathered zone
N
SEA LEVEL
Campbell Creek
Ship Creek
Chester Creek
1 MILE
200 FEET
100
0
1 MILE
VERTICAL EXAGGERATION ABOUT ×13

Figure 3*B*.

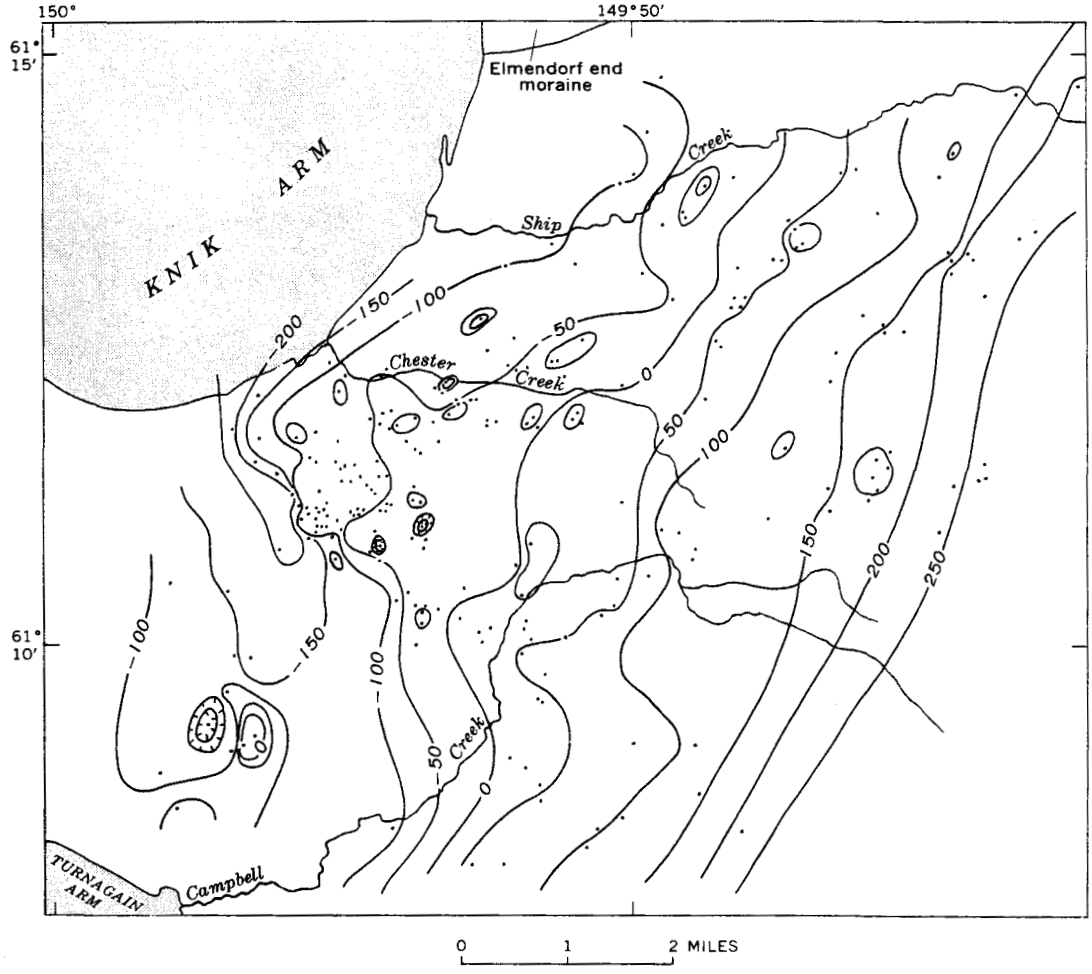

FIGURE 4.—Contour map of the base (unconformity) of the Knik Till in part of the Anchorage area. Datum is mean sea level; contour interval, 50 feet. Dots show location of wells from which data were obtained for drawing contour lines.

larity in form to deposits otherwise quite dissimilar, as for example the Knik Till and the Bootlegger Cove Clay. Apparently the controlling influence was the land surface, and the form of each successive land surface reflected that of the preceding one. It follows that the ultimate control upon deposition would be the preglacial topography. Once this preglacial surface had imposed its symmetry upon the first-formed deposits, that symmetry was repeated in all subsequent deposition.

Other topographic features of the top of the clay are narrow west-trending valleys and several small hills and closed depressions. These valleys are coincident with stream valleys in the present land surface and must be due to stream erosion. Land-surface depressions in the western part of figure 6, some of which are

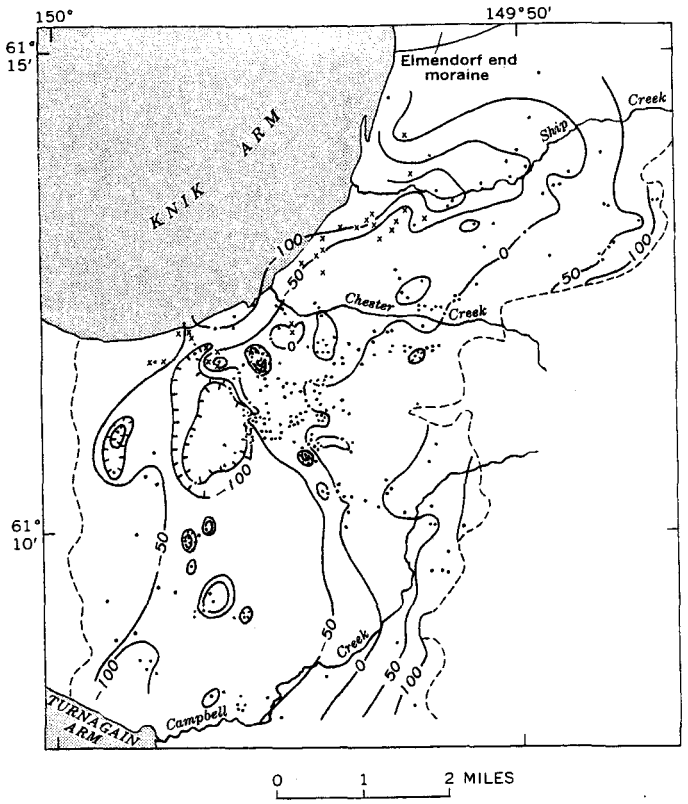

FIGURE 5.—Contour map of the base (unconformity) of the Bootlegger Cove Clay in part of the Anchorage area. Datum is mean sea level; contour interval, 50 feet. Dots show location of wells from which data were obtained for drawing contour lines. Dashed lines show inferred boundaries of the clay.

indicated on this map, have been explained by the melting of buried glacial ice (Miller and Dobrovolny, 1959, p. 54; Cederstrom and others, 1964, p. 39) and by other processes such as differential compaction or the melting of ground ice (Karlstrom, 1964, p. 38–39). The similarity of land-surface form here and in the pitted outwash deposits west of the western clay boundary favors explanation by ice-block melting. The fact that some of the depressions on figure 6 are located where the clay is thicker than it is nearby suggests localization by differential compaction. The small hills on the upper surface of the clay, in which the clay stands 30 feet or more higher than nearby and which are capped by sand and gravel, are chiefly in the central and southwestern parts of the area. During our earlier work (Cederstrom and others, 1964, p. 34) these hills were interpreted as erosional remnants of a higher level of the outwash plain. Comparison of figures 5 and 6 suggests that differential compaction of the clay offers an adequate explanation of the hills.

The Bootlegger Cove Clay is covered by sand and gravel deposited by outwash streams that flowed into this area from the northeast, from mountain valleys outside the Elmendorf end moraine. Toward the west these outwash deposits were deposited in the Naptowne proglacial lake. During westward regression of the lake, streams from the mountains (particularly Ship Creek, which may still have had a glacial source) flowed across the emerging plain, building alluvial fans near the mountains and trenching the plain near the shore. With draining of the lake and return to estuarine conditions the deposits in what is now Knik Arm were also trenched. During this episode of downcutting, Ship Creek flowed in several distributary channels which were abandoned in turn until only the present creek valley contained a through-going stream. Thus, the estuary and the channels of different ages were cut to different depths into the sand and gravel or into the underlying Bootlegger Cove Clay. The presence of the clay near the modern shore, and its exposure in bluffs along Knik Arm and along the deeper stream valleys (especially the deepest one, that of the modern Ship Creek), provided the setting for the disastrous landslides caused by the earthquake of March 27, 1964 (fig. 3*A*).

During or after drainage of the proglacial lake, and before the postglacial rise of sea level reversed the downcutting trend, the Ship Creek valley was trenched as much as 9 feet below the present sea level. In postglacial time, estuarine water flooded the valley to a level somewhat above present sea level, depositing a relatively thin clay upon the trenched older clay and the alluvial deposits in the valley bottom. Finally, during and after decline of sea level to its present position the clay was covered by modern alluvium.

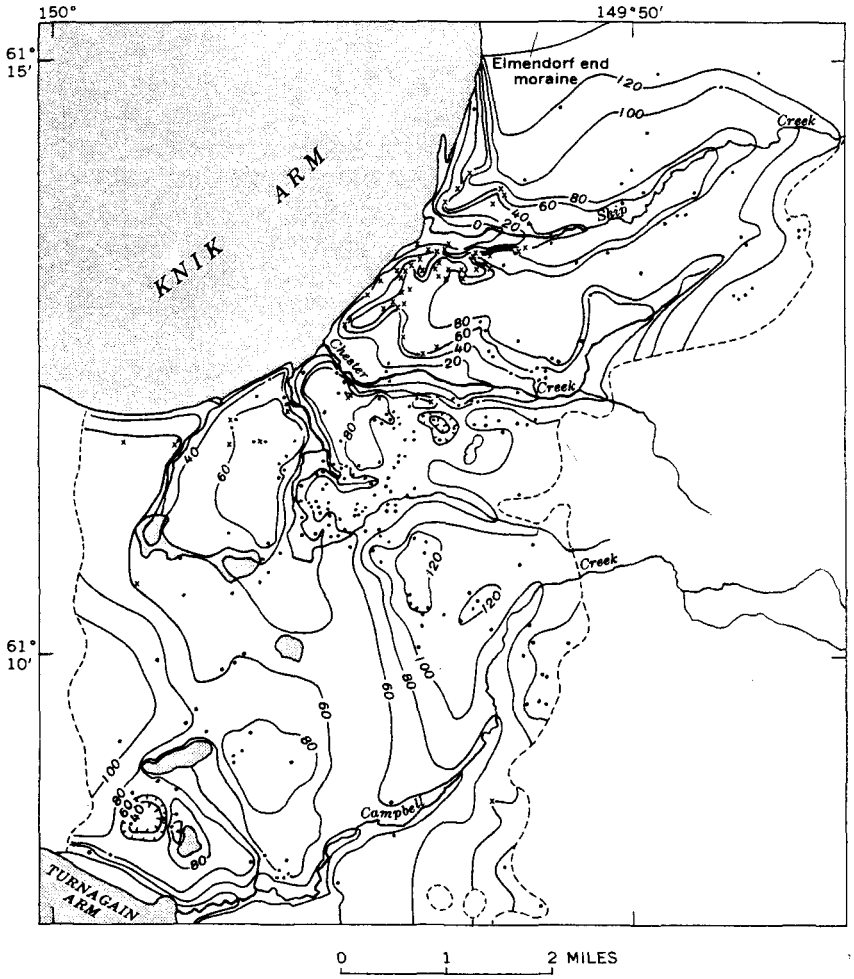

FIGURE 6.—Contour map of the top of the Bootlegger Cove Clay in part of the Anchorage area. Datum is mean sea level; contour interval, 20 feet. Dots show location of wells from which data were obtained for drawing contour lines. Dashed lines show inferred boundaries of the clay. Larger lakes in land area underlain by the clay are shown by stippled pattern.

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