GEOLOGICAL SURVEY RESEARCH 1970

Chapter B

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Scientific notes and summaries of investigations in geology, hydrology, and related fields

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GEOLOGICAL SURVEY RESEARCH 1970

This collection of 46 short papers is the first published chapter of "Geological Survey Research 1970." The papers report on scientific and economic results of current work by members of the 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 in fiscal year 1970, together with lists of investigations in progress, reports published, cooperating agencies, and Geological Survey offices.

"Geological Survey Research 1970" is the eleventh volume of the annual series Geological Survey Research. The ten volumes already published are listed below, with their series designations.

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MAFIC AND ULTRAMAFIC ROCKS FROM A LAYERED PLUTON AT MOUNT FAIRWEATHER, ALASKA

By GEORGE PLAFKER and E. M. MacKEVETT, JR.,
Menlo Park, Calif.

Abstract.—Reconnaissance mapping in the Fairweather Range of southeastern Alaska has revealed that a layered mafic and ultramafic pluton, the Fairweather pluton, underlies much of the Mount Fairweather area. The mafic rocks, which constitute most of the pluton, are magnetite- and ilmenite-bearing two-pyroxene gabbros and clinopyroxene-olivine gabbros. The ultramafic rocks consist mainly of sulfide- and chromite-bearing wehrlite, pyroxenite, and dunite, and locally contain significant concentrations of chromium, cobalt, copper, nickel, and platinum-group elements. The pluton is probably a source for ilmenite, magnetite, platinum, and other heavy minerals that have been found as placer beach deposits along the adjacent Gulf of Alaska coast.

During a geochemical sampling program in the Yakutat quadrangle and adjacent areas in 1968, the authors traced float of mafic and ultramafic rocks in glacial moraines to a previously undescribed small layered pluton at Mount Fairweather (fig. 1). The discovery is noteworthy because it extends the known area of a belt of layered mafic plutons in the Fairweather Range some 20 miles northwestward, and because the pluton contains ultramafic rocks with concentrations of chromite, nickel, copper, and platinum-group metals. Ultramafic rocks have possible economic importance at the one other locality in the Fairweather Range where they have been found. The purpose of this paper is to outline the general setting of the Fairweather pluton, as determined from a brief aerial reconnaissance, and to present the results of petrologic and chemical analyses of some samples of float rock that were derived from the pluton.

The Fairweather pluton is the most northerly of three layered mafic intrusives that lie roughly along the axis of the northwest-trending Fairweather Range (fig. 1). Its existence in the general vicinity of Mount Fairweather was correctly inferred by Rossman (1963, p. F11) from float of gabbroic rocks found in the moraines of Fairweather Glacier. However, the location of the source pluton was not known, and no ultramafic rocks were reported in the float. The belt of layered intrusives extends southeastward through Yakobi Island and western Chichagof Island where several smaller bodies of gabbroic rock similar in composition to those of the Fairweather Range are exposed (Rossman, 1963, p. F11). Other than at the Fairweather pluton, ultramafic rocks in the range have been found only in small isolated nunataks at the Brady Glacier nickel-copper prospect (fig. 1), which is believed to lie near the margin of the Crillon-La Perouse pluton (Cornwall, 1967).

SETTING

The Fairweather pluton probably underlies an area of more than 15 square miles along the southwest flank of Mount Fairweather between the trunk stream of Fairweather Glacier and Sea Otter Glacier (fig. 1). Its general configuration and its relation to the adjacent metamorphic and granitic rocks were deduced by close observation from a helicopter. Our knowledge of the lithology of rocks in the pluton and inferences regarding the distribution of ultramafic rocks within it are based entirely on examination of moraines of the glaciers that drain toward the west and southwest from the Mount Fairweather area. The combination of rugged terrain and high altitude precluded landings within the pluton (fig. 2). Technical mountaineering capabilities would be required for a ground study. Virtually all of the pluton, except for the extreme northwestern end, is within the Glacier Bay National Monument.

The Fairweather pluton appears to be at least 6 miles long and 3½ miles wide, the long axis trending approximately northwestward. It is elongated parallel to the structural grain of the adjacent foliated country rocks, which are mainly steeply dipping amphibolite

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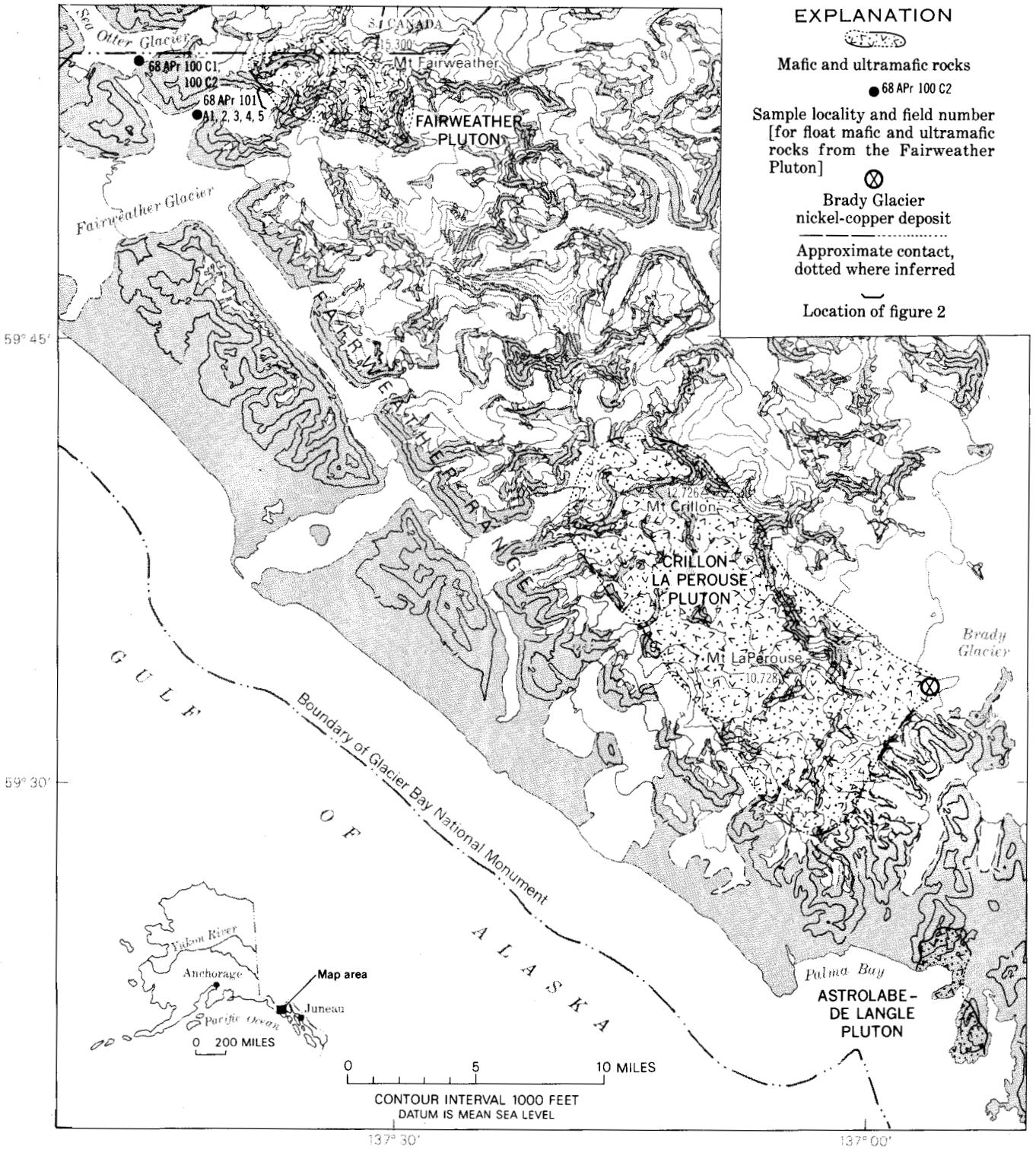

FIGURE 1.—Index map showing the approximate location of the Fairweather pluton and other layered mafic plutons in the Fairweather Range. Crillon-La Perouse and Astrolabe-De Langle plutons after Rossman (1963).

FIGURE 2.—Aerial view of the western part of the Fairweather pluton (location shown on fig. 1). Dashed line indicates the inferred southwest contact. The conspicuously banded rocks in the foreground are probably intertonguing metavolcanic and metasedimentary country rocks. Photograph by Austin Post.

and mica schist cut by granitic stocks and sills. Dark, layered mafic and ultramafic rocks are exposed in sheer cirque walls and knife-edged arêtes along the southwest margin of the pluton from an altitude between 7,000 and 10,000 feet, to the general vicinity of the summit, which rises 15,300 feet above sea level (fig. 2). The layered igneous rocks on the southwest flank of Mount Fairweather appear to dip northeast at a moderate angle. The northeastern contact of the pluton is largely concealed beneath the extensive snow and ice cover on the highest part of the mountain; the contact shown on figure 1 is inferred from the distribution of

schistose country rock at lower elevations. Massive, blocky, light-colored rocks in part border the layered rocks on the southwest in a zone as much as 2 miles wide, and locally seem to crosscut the darker layered rocks. It was not possible to tell from the air whether the light-gray unit represented a felsic granitic intrusive or a relatively nonlayered leucocratic gabbro. However, the general scarcity of felsic rocks in the moraines of glaciers draining this part of the mountain favor the latter alternative, and the light-gray zone was tentatively mapped as part of the pluton.

No data are available on the age of the pluton or of the adjacent foliated rocks. Rossman (1963, p. F10) correlated the schistose rocks of the Fairweather Range with units of Mesozoic age on Chichagof Island. Samples of gabbro from the compositionally and structurally similar Crillon-La Perouse pluton, which have been submitted for radiometric dating (D. A. Brew, oral commun., April 1969), may provide information on the time of intrusion of the layered rocks.

DESCRIPTION OF THE ROCKS

The compositional layering, textures, and mineralogy of the Fairweather pluton are broadly comparable to those of the layered igneous rocks elsewhere in the Fairweather Range (Rossman, 1957) and in many well-known localities throughout the world such as the Skaergaard, Stillwater, and Bushveld Complexes (Wager and Brown, 1968). Such rocks are generally considered to result from fractional crystallization and crystal settling in a magma originally of basaltic composition.

Ultramafic rocks of the Fairweather pluton are restricted to moraines on the south side of Sea Otter Glacier and on the unnamed glacier between Sea Otter and Fairweather Glaciers; gabbroic rocks are abundant in these moraines and in the lateral moraine along the north side of Fairweather Glacier (fig. 1). The distribution of ultramafic float suggests that its source is in the northern part of the pluton in the general area due west of Mount Fairweather.

Samples of float from the Fairweather pluton are composed primarily of virtually unaltered plagioclase, clinopyroxene, olivine, and orthopyroxene. Accessory constituents include sulfides, spinel-group minerals, ilmenite, hornblende, and traces of rutile and apatite. Detailed compositional studies have not been made, but the optical properties suggest that the plagioclase is mostly labradorite (An_{60-70}), the clinopyroxene is probably augite, the olivine has a forsterite content of about 80 percent, and the orthopyroxene is magnesian hypersthene (En_{85}). Augite characteristically is twinned and exhibits schiller structure; the hypersthene contains rare exsolution lamellae and blebs of clinopyroxene. The rock compositions vary from anorthosite or leucocratic gabbro to pyroxenite, wehrlite, and dunite. Chemical analyses of samples of the various rock types are presented in table 1.

Gabbroic rocks are by far the most abundant in the moraines, and probably constitute the great bulk of the pluton. They are leucocratic to melanocratic rocks in which the layering results from variations in the proportions of plagioclase and ferromagnesian minerals. Individual layers in float on the moraines range from a fraction of an inch to several feet in thickness. The rocks that were collected are fine- to medium-grained

TABLE 1.—*Chemical analyses, in weight percent, of six rock samples from the Fairweather pluton*

[Samples analyzed by methods similar to those described in U.S. Geol. Survey Bull. 1144-A, supplemented by atomic absorption. Analysts, Lowell Artis, G. W. Chloe, P. L. Elmore, John Glenn, James Kelsey, and H. Smith]

Rock type	Dunite	Wehrlite	Two-pyroxene gabbro		Clinopyroxene olivine gabbro	Dunite (sheared)
Lab No.	M106 872W	M106 873W	M106 874W	M106 875W	M106 876W	M106 877W
Field No.	68 APr 101 A1	68 APr 100 C2	68 APr 101 A2	68 APr 101 A3	68 APr 101 A4	68 APr 101 A5
SiO_2	40.5	44.2	44.4	49.5	46.1	38.8
Al_2O_3	1.3	3.7	13.0	23.0	8.0	.81
Fe_2O_3	1.2	1.7	5.0	1.0	2.2	3.2
FeO	9.4	7.6	11.0	2.8	10.6	7.6
MgO	44.4	29.3	11.3	7.2	18.5	43.8
CaO	1.4	10.6	9.9	13.6	12.4	.70
Na_2O	.07	.32	1.2	1.5	.63	.04
K_2O	.05	.08	.10	.10	.08	.10
H_2O-	.07	.08	.10	.07	.05	.24
H_2O+	.80	1.2	.72	.56	.65	4.9
TiO_2	.04	.21	3.2	.13	.73	.03
P_2O_5	.05	.04	.06	.02	.05	.04
MnO	.16	.15	.21	.20	.21	.16
CO_2	.08	<.05	.05	<.05	.08	.05
Sum	100	99	100	100	100	100

two-pyroxene gabbro and clinopyroxene-olivine gabbro with xenomorphic to hypidiomorphic granular textures. Plagioclase in crystals up to 3.5 mm in length constitutes 10–60 percent of the gabbros analyzed. Rutilated plagioclase makes up an estimated 85 percent of a variant that had a decidedly purplish cast in the hand specimen, and the composition borders on anorthosite. The ferromagnesian minerals are as much as 2.5 mm in size.

The ratio of clinopyroxene to orthopyroxene in the two-pyroxene gabbro is variable, and either mineral may predominate in a given rock. Irregular masses of magnetite and ilmenite(?) in grains 1.5 mm or smaller constitute as much as 10 percent of one sample (68 APr 101 A2). The iron ores occur both interstitially and enclosed within the pyroxenes. The clinopyroxene-olivine gabbro (68 APr 101 A4) is composed mainly of clinopyroxene and olivine in grains as much as 2.5 mm across; the grains contain about 10 percent plagioclase and a few percent interstitial hypersthene. Opaque minerals make up as much as 5 percent of the rock. The predominant ore mineral is interstitial chalcopyrite in grains of less than 0.5 mm. Other accessory minerals in the gabbros are generally less than 0.5 mm in size and include brown hornblende, green spinel, and rare cubanite, pyrrhotite, magnetite, chromite(?), and pentlandite(?).

The float of the ultramafic rock consists of black, greenish-black, and olivine-green crystal cumulates with a faintly layered structure. One sample of dunite (68 APr 101 A1) consists of more than 90 percent fresh euhedral to anhedral olivine in grains ranging from 0.2 to 4.5 mm in size. Some of the grains exhibit twinning and protoclastic textures. The remainder of the rock is composed of euhedral to subhedral chromite crystals 0.1 to 0.5 mm across, a few crystals of pentlandite less than 0.05 mm in size, and minor amounts of interstitial clinopyroxene and hornblende. One sheared dunite specimen (68 APr 101 A5) was cut by cross-fiber serpentine in closely spaced veinlets less than 0.02 mm wide that make up as much as 20 percent of the rock. The essential mineral of a pyroxenite sample (68 APr 100 C1) is anhedral clinopyroxene in grains 0.5 to 3.0 mm across with about 25 percent anhedral to subhedral hypersthene that is less than 1.0 mm in size. A sample of wehrlite (68 APr 100 C2) consists of about equal amounts of subhedral and anhedral olivine in grains as much as 2.5 mm across and anhedral, partially poikilitic clinopyroxene as much as 5.0 mm. The clinopyroxene is commonly altered along grain boundaries and cracks to a mixture of fibrous green actinolite and antigorite. The pyroxenite and wehrlite contain as much as 15 percent interstitial sulfides and minor scattered crystals of chromite and spinel from a few microns to 1 mm in size. The sulfide minerals, which occur in irregular scattered masses and microveinlets, are cubanite intergrown with chalcopyrite and pyrrhotite. Some pentlandite is intergrown with chalcopyrite or cubanite, or, more rarely, it occurs in isolated masses.

SPECTROGRAPHIC ANALYSES

Seven isolated float samples were analyzed for total metals by semiquantitative spectrographic methods, and of these, five ultramafic rocks and one gabbro were analyzed for platinum-group elements by quantitative spectrographic methods (table 2). The rocks analyzed include all the lithologic types described in the preceding section, and some of them had the highest content of disseminated opaque minerals found in the float. With the exception of the pyroxenite (68 APr 100 C1), chemical analyses are given for these same rocks in table 2.

The analyses indicate concentrations of titanium (2 percent) and vanadium (2,000 ppm) in the magnetite- and ilmenite-bearing two-pyroxene gabbro that are not unusual for rocks of this type. As much as 5,000 ppm chromium, 5,000 ppm copper, and 5,000 ppm nickel are present in the richest samples of sulfide- and chromite-bearing pyroxenite and wehrlite, as much as 5,000 ppm chromium, and 3,000 ppm nickel, in the chromite-bearing dunite. Noteworthy amounts of cobalt and platinum-group elements were also found in the ultramafic rocks and, to a lesser extent, in the gabbros. The largest amounts of these elements, which were in the sheared dunite (68 APr 101 A5), totaled 200 ppm cobalt and 0.184 ppm palladium, 0.171 ppm platinum, and detectable rhodium (0.004 ppm).

Disseminated opaque minerals occur in all the float collected from the Fairweather pluton. These minerals are mainly magnetite, ilmenite, sulfides, and chromite, which undoubtedly account for the anomalous metal content of these rocks. Combined magnetite and ilmenite constitute as much as 10 percent by volume of some gabbros. The wehrlite and pyroxenite contain up to 15 percent sulfides with minor chromite, and some dunites contain a few percent of chromite with minor sulfides. The sulfides identified in polished section include cubanite, chalcopyrite, pyrrhotite, and pentlandite. No chromitites or massive sulfides were found. The nickel and copper content of the highest grade rocks sampled is about 0.5 percent each. This may be compared with a content of 1.5 percent nickel and 2 percent copper in selected samples of ultramafic rocks from the Brady Glacier prospect which is cur-

TABLE 2.—*Spectrographic analyses of selected float ultramafic and mafic rocks from the Fairweather pluton*

[Asterisk indicates quantitative analysis, A. F. Dorrzapf and Marian Schnepfe, analysts; all other analyses are semiquantitative, Chris Heropoulos, analyst. G, major constituents greater than 10 percent; N, not detected. Other elements looked for but not found: As, Au, B, Be, Bi, Cd, La, Mo, Nb, Pb, Sb, Sn, Te, U, W, Zn, Zr, Ce, Ge, Hf, In, Li, Re, Ta, Th, Tl, Eu]

Rock type	Dunite	Dunite (sheared)	Wehrlite	Clinopyroxene olivine gabbro	Two-pyroxene gabbro	Two-pyroxene gabbro	Pyroxenite
Field No.	68 APr 101 A1	68 APr 101 A5	68 APr 100 C2	68 APr 101 A4	68 APr 101 A3	68 APr 101 A2	68 APr 100 C1
Laboratory No.	M4949 M106892W	M106877W	M4949 M106873W	M106876W	M106875W	M4949 M106874W	M4949
Weight percent							
Fe	10	10	10	G	3	G	7
Mg	G	G	G	10	5	7	10
Ca	0.7	0.5	7	7	7	5	7
Ti	0.05	0.02	0.2	0.5	0.1	2	0.2
Si	G	G	G	G	G	G	G
Al	1.0	0.7	2.0	5.0	G	7.0	2
Na	N	0.02	0.2	0.7	1.0	1.0	0.15
Parts per million							
Mn	1,500	1,500	1,000	3,000	700	3,000	1,000
Ag	N	N	1	N	N	N	2
Ba	20	15	30	30	50	50	N
Co	150	200	150	100	30	70	150
Cr	5,000	3,000	5,000	700	300	150	3,000
Cu	50	30	3,000	700	100	200	5,000
Ni	3,000	2,000	5,000	500	150	100	5,000
Sc	15	7	70	150	30	70	70
Sr	N	N	15	100	500	200	10
V	50	30	150	500	150	2,000	300
Y	N	N	10	10	N	10	N
Ga	3	N	3	7	15	15	N
Yb	1	N	1.5	1	N	N	N
*Pd	[2] 0.006	0.184	[1] 0.056	0.002	----------	[1] 0.006	0.006
*Pt	[2] 0.010	0.171	[1] 0.048	0.003	----------	[1] 0.009	0.043
*Rh	0.002	0.004	[1] 0.002	N	----------	<0.002	<0.002

[1] Average of two analyses. [2] Average of three analyses.

rently being actively explored by the Newmont Mining Co. (Cornwall, 1967, p. 153, table 15).

The Fairweather pluton is probably a major source for magnetite, ilmenite, platinum, and other heavy minerals that occur in association with placer gold in beach deposits along the adjacent Gulf of Alaska coast (Rossman, 1957, 1963; Thomas and Berryhill, 1962).

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BLUESCHIST AND RELATED GREENSCHIST FACIES ROCKS OF THE SEWARD PENINSULA, ALASKA

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Abstract.—Blueschist facies rocks of Precambrian age are exposed in thrust slices over an area of more than 10,000 square miles of the Seaward Peninsula, Alaska. Rocks with mineral assemblages characteristic of high-grade blueschist facies and retrograde blueschist facies occur juxtaposed against low-rank metamorphic pelitic and carbonate rocks, possibly because of thrust faults. From west to east over the Seward Peninsula, progressive regional metamorphism of Cretaceous(?) age and extensive overthrust faulting of pre-mid-Cretaceous age have complicated the metamorphic assemblages. Field evidence proves that the blueschist rocks represent metavolcanic rocks and metamorphosed mafic rocks of late Precambrian age. Mineral assemblages are strongly influenced by the original chemical composition of the rocks.

Glaucophane-bearing rocks have long been known in the south-central Seward Peninsula (Smith, 1910; Moffit, 1913); mapping by the senior author from 1960 to 1968 has shown that similar rocks are exposed over much of the central and eastern Seward Peninsula. In view of the intense current interest in such rocks and problems of interpretation of their origin (Essene and others, 1965; Ernst, 1963; Coleman, 1967; Miyashiro, 1961), this preliminary report describes the general field relations of the Seward Peninsula rocks, summarizes the tectonic setting, and briefly describes the mineralogy and metamorphic classification of some of the rocks collected at widely scattered localities. Because of the importance of assigning the blueschist rocks to the Precambrian — blueschist rocks are uncommon in Precambrian rocks—the discussion of the stratigraphy and age relations of rocks of the Seward Peninsula is rather complete. The Precambrian rocks are similar to those of the Soviet Arctic (Rabkin and Ravich, 1961).

REGIONAL GEOLOGY

Except for small areas near Nome, which were mapped in detail by Smith (1910) and Moffit (1913), the geology of Seward Peninsula has been imperfectly known. Since 1960, mapping by the senior author, assisted in 1967–68 by Kachadoorian, has clarified the stratigraphy and structural setting. The stratigraphy is merely summarized here and is depicted in broad outline on figure 1.

Older Precambrian rocks

Rocks of Precambrian age form the cores of the Kigluaik and Bendeleben Mountains and crop out over wide areas elsewhere on the Seward Peninsula. The oldest rocks, exposed in the Kigluaik arch which trends east along the axis of the range, consist of plagioclase-orthoclase-quartz-biotite-hornblende paragneisses with local beds of calc-silicate rock. These paragneisses grade upward into marble gneisses with forsterite, monticellite, and muscovite, which are formed by chemical reconstitution of the impurities. Because of intense flowage and deformation, the marble gneiss varies greatly in thickness; where best exposed in the Kigluaik arch, it locally exceeds 700 feet, but it thins rapidly by tectonic squeezing. The marble gneiss is transitional with the overlying biotite-orthoclase-plagioclase-quartz paragneiss; this paragneiss is several hundred feet thick and is interbedded with thin layers of calc-silicate rocks. These upper gneisses, which have been dated by Carl Hedge (oral commun., 1969) by the whole-rock rubidium-strontium method as 750 m.y. (million years), the probable age of the metamorphism, grade upward into andalusite-garnet schists, locally gneissic, and thence into biotite-garnet schists and intercalated marble and calc-silicate rocks. Rocks equivalent to these upper schists extend continuously from the east end of the Kigluaik Mountains (fig. 1) and form the bedrock of the western and central Bendeleben Mountains. These rocks were in-

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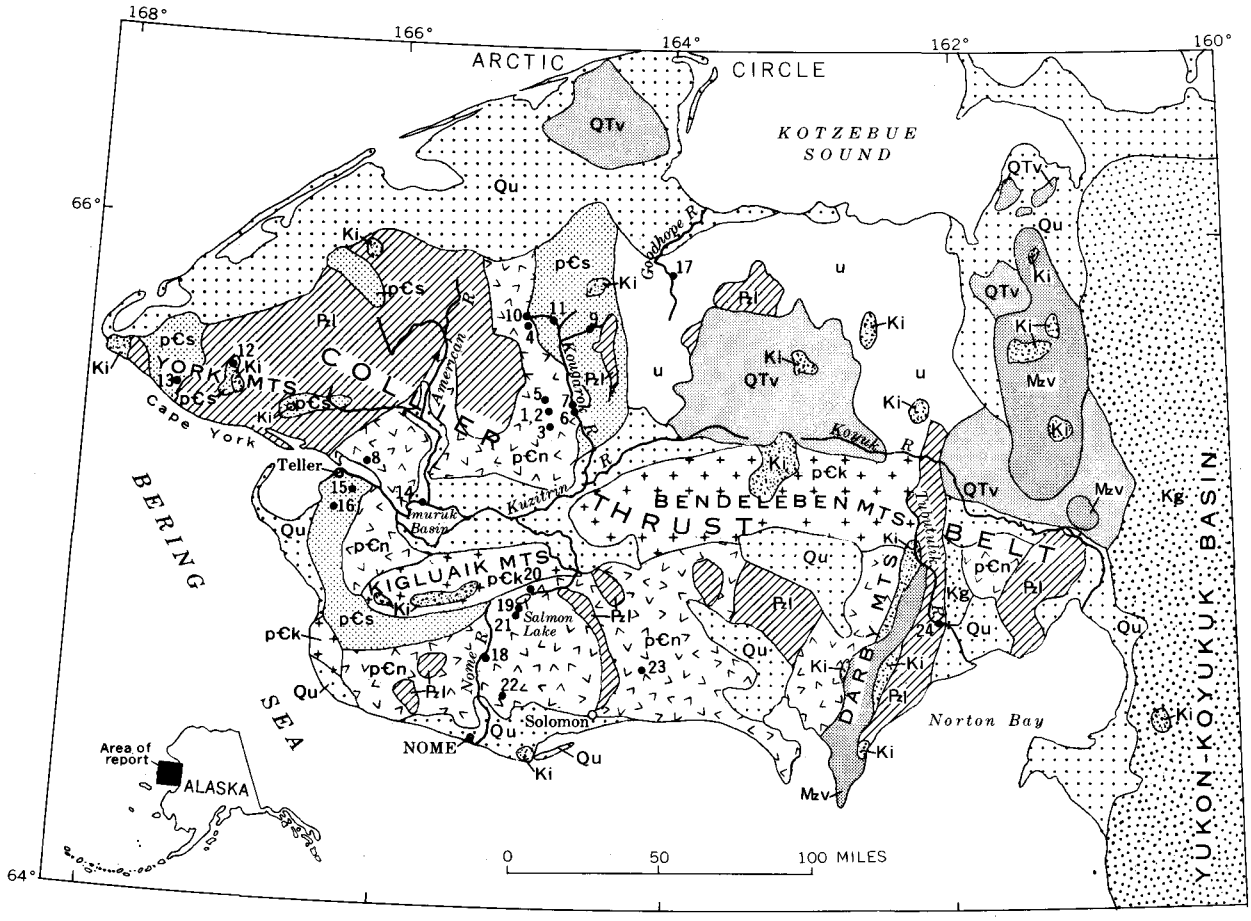

EXPLANATION

Qu — Unconsolidated deposits	QUATERNARY	
QTv — Volcanic rocks	TERTIARY OR QUATERNARY	
Ki — Granitic intrusives	CRETACEOUS	
Kg — Graywacke, conglomerate, and andesite	CRETACEOUS	
Mzv — Volcanic rocks	MESOZOIC	
Pzl — Limestone, dolomite, and marble *Includes local areas of older rocks*	PALEOZOIC	
p€s — Slate, graphitic siltite, and quartz-mica schist	*Upper Precambrian*	PRECAMBRIAN
p€n — Nome Group *Garnet-glaucophane-epidote-chlorite schists and schistose marble*	*Upper Precambrian*	PRECAMBRIAN
p€k — Kigluaik Group *High-rank metamorphics, including biotite-andalusite schists, orthogneiss and paragneiss, calc-silicate rocks, and marble*	*Upper Precambrian*	PRECAMBRIAN
u — Undifferentiated rocks of Paleozoic and Precambrian age		
Contact *Approximately located*		
•8 Sample locality and number		

FIGURE 1.—Generalized geologic map of the Seward Peninsula, Alaska, showing sample localities. Geology modified by C. L. Sainsbury from Dutro and Payne (1957). Geology will be modified further when current work has been completed.

cluded in the Kigluaik Group by Moffit (1913), and this name is retained in this report.

All the metamorphic rocks described above are intruded by biotite-orthoclase-quartz orthogneiss, which forms extensive masses in the Kigluaik Mountains, and by gneissic biotite granite, which is cataclastic in texture and which is associated with numerous coarse-grained pegmatites. All these intrusive rocks are believed to be of Precambrian age, principally because they are not known to have intruded younger Precambrian rocks.

Younger Precambrian rocks

Younger rocks which represent metamorphosed volcanic rocks, including tuffaceous sediments and mafic intrusives probably related to the volcanics, and a thick sequence of graphitic pelitic rocks crop out widely over the Seward Peninsula both in thrust slices and as wide expanses of bedrock that exceed hundreds of square miles in area. The older metavolcanic rocks are of principal interest to this report, for they include the blueschist facies rocks; they have been called the Nome Group by Brooks, Richardson, and Collier (1901), by Collier (1902), by Moffit (1913), and by Smith (1910). Although the Nome Group was generally considered to be of Paleozoic age, certain puzzling features of it (principally the wide disparity in metamorphic rank in rocks close to each other) have led some workers (for example, Moffit, 1913, p. 23) to believe that rock of Precambrian age may be included therein.

The younger graphitic rocks have been called the slate of the York region on the western Seward Peninsula by Collier (1902) and by Knopf (1908), and the Kuzitrin Series in the Kigluaik Mountains area by Brooks, Richardson, and Collier (1901); they are probably correlative with the Hurrah Slate and Puckmummie Schist (Smith, 1910) in the Solomon and Casadepaga areas east of Nome. Although several variants are well established, these graphitic or slaty rocks wherever seen exhibit the common characteristic of being composed principally of silt-size quartz grains in a graphitic matrix. The percentages of quartz, graphite, carbonate, and less common albite, chlorite, and muscovite vary from place to place, but in general appearance the rocks are remarkably similar. In contrast to the older Nome Group rocks, which everywhere are intensely deformed into recumbent isoclinal folds, sheared, and completely recrystallized, the graphitic slates not deformed by thrust faulting commonly exhibit a clearly definable clastic texture with angular quartz grains of silt size. Tectonism, thermal metamorphism, and hydrothermal alteration quickly obliterate the sedimentary texture. Nevertheless, the siliceous composition of the slates of the York region is always apparent. Although the normal contact with the Nome Group rocks has not been observed, the disparity in degree of deformation between Nome Group rocks and the slates of the York region suggests that the slates are unconformable above the Nome Group rocks. An unconformable relation is suggested, too, by the fact that Nome Group rocks are intruded by intensely deformed mafic dikes, as well as by the gabbros which alone intrude the slates.

Latest Precambrian rocks

In the York Mountains of the western Seward Peninsula, detailed mapping by Sainsbury (1965, 1969b) has demonstrated that the slates of the York region are overlain by more than 2,300 feet of thin-bedded argillaceous and dolomitic limestone, which is completely unmetamorphosed and utterly devoid of fossils. The contact between slate and limestone in at least one locality appears to be gradational and conformable; elsewhere over wide areas it is definitely a thrust-fault contact. These limestones are not delineated separately on the geologic map (fig. 1). At other places on the Seward Peninsula, a thick sequence of thin- to medium-bedded limestones, argillaceous limestone, and dolomitic limestone devoid of fossils overlies the thin-bedded dolomitic limestone. All these carbonate rocks are clearly of pre-Ordovician age (Sainsbury, 1965). Because they are not intruded by any of the numerous gabbros that intrude the slate of the York region, they are unquestionably younger than the slates and are, therefore, probably of latest Precambrian age.

Paleozoic rocks

Detailed and reconnaissance geologic mapping in the Teller, Bendeleben, and Solomon 1:250,000 quadrangles has shown that carbonate rocks of tremendous thickness were deposited on the Seward Peninsula without a major lithologic change from Early Ordovician at least through Mississippian time. The paleostratigraphy has been deciphered from disconnected exposures in thrust plates at widely scattered localities and hence is incomplete. Nevertheless, abundant fossil collections have firmly established that the Ordovician, Silurian, Devonian, and Mississippian Systems are represented by carbonate rocks throughout the Seward Peninsula. It can be stated emphatically that no fossiliferous noncarbonate rocks of early or middle Paleozoic age are known on the Seward Peninsula and, moreover, that the known stratigraphy allows no appreciable time for deposition of noncarbonate rocks from Ordovician through Mississippian time. No rocks of late Paleozoic age are known on the Seward Peninsula.

Post-Paleozoic rocks

Throughout most of the Seward Peninsula, rocks of post-Paleozoic age consist mainly of intrusive rocks, which comprise biotite granites of middle to Late Cretaceous age and granitic and mafic dikes (including lamprophyres) of Late Cretaceous to early Tertiary age. The geologic map of Alaska (Dutro and Payne, 1957) shows rocks of Triassic age on the Seward Peninsula; this age assignment is erroneous, for these rocks are the slates of the York region, which are of pre-Ordovician age. During the Tertiary, small local basins were filled, giving rise to coal-bearing beds; and during the Quaternary, extensive lava fields were formed in the Imuruk Basin and lowlands. East of the Seward Peninsula, volcanic rocks and eugeosynclinal graywackes of Jurassic and Cretaceous age filled the subsiding Yukon-Koyukuk basin (Miller and others, 1959). The Mesozoic rocks extended west only to the Darby Mountains, east of the main Seward Peninsula areas where blueschist facies rocks were studied by the senior author. Some Mesozoic volcanic rocks occur west of the Tubutulik River, where blueschist rocks occur.

Summary of age relations

The above discussion shows clearly that the rocks of the Nome Group, which contain the glaucophane-bearing rocks to be discussed, are intensely deformed and underlie unmetamorphosed pre-Ordovician limestones. The field relations and stratigraphy allow but one conclusion: the Nome Group rocks are considerably older than the slates of the York region, which themselves are older than the pre-Ordovician limestones. Hence, it is concluded that the blueschist facies rocks are of Precambrian age.

STRUCTURE

Throughout the Seward Peninsula, the geologic structure is dominated by thrust sheets. Thrusting was first inferred by Collier (1902, p. 18), and proved in the Nome area by Moffit (1913) and Smith (1910). Detailed mapping by Sainsbury (1965, 1969a, b) in the York Mountains showed the great extent of the thrusting and demonstrated the existence of imbricate thrust faults as the dominant structure of the western Seward Peninsula. Reconnaissance mapping to the east for 150 miles and low-level aerial reconnaissance and spot ground checks as far east as Norton Bay have demonstrated that rocks of the entire Seward Peninsula are involved in thrust sheets of tremendous extent and complexity. This thrust belt has been named the Collier thrust belt (Sainsbury, 1969b), to honor A. J. Collier, who first recognized that the limestones of the York Mountains were not in normal stratigraphic position above the older rocks (Collier, 1902, p. 18).

In the York Mountains of the western Seward Peninsula, the thrusts mainly are horizontal or dip gently south, and the Paleozoic rocks are completely unmetamorphosed. Eastward from the York Mountains, the thrusting becomes more complex, thrusts are folded, and a weak regional metamorphism begins near the American River (fig. 1) and becomes progressively stronger eastward and southward. East of the Kougarok River, imbricate thrust sheets are intricately folded, and the Paleozoic carbonate rocks are recrystallized to sugary-textured marble in which bedding is largely obliterated. In this area, thrust sheets involve the Precambrian rocks as well as the Paleozoic, fold axes generally trend northward, and thrusting was eastward. Mapping in 1969 by Sainsbury has shown that the York Mountains thrust sheets, where thrusting was northward, are succeeded to the west by thrust sheets with intensely folded limestones of Mississippian age. The Mississippian rocks are thrust northeastward. Seemingly, then, two distinct cycles of thrusting are represented; the earlier was characterized by intense folding and eastward transport, the younger was characterized by imbricate thrusting without major folding and by northward transport.

Because the thrust sheets have been intruded by granite stocks of middle to Late Cretaceous age, the thrusting is earlier than middle Cretaceous. As the thrust belt is probably buried by the Cretaceous rocks of the Yukon-Koyukuk basin, the thrusting is apparently of pre-mid-Cretaceous age, for the Jurassic and Lower Cretaceous rocks are intimately folded. No upper Paleozoic or lower Mesozoic rocks being known in the thrust belt, the thrusting cannot be dated more precisely than post-Mississippian and pre-Late Cretaceous, although it most likely is of Early Cretaceous age. The regional thermal metamorphism impressed upon the thrust sheets in the eastern Seward Peninsula is probably related to the intrusion of large batholiths and stocks of granite and related syenites, which have been dated as of mid-Cretaceous age (Miller and others, 1966). Biotite separated from Precambrian schists in the Kougarok River area, where Paleozoic limestones of thrust sheets are metamorphosed to marble, gave a "re-set" age date of 100 m.y., on the basis of the potassium-argon method (J. D. Obradovich, oral commun., 1969). Apparently, regional metamorphism and intrusion of granitic batholiths were related and occurred generally in the Cretaceous. This regional thermal metamorphism probably caused the marked retrograde metamorphism of the blueschist facies rocks.

BLUESCHIST ROCKS

The blueschist and related rocks to be described were sampled at widely scattered localities on the Seward Peninsula—all samples, however, came from rocks belonging to the Nome Group (p. B35). Wherever seen, the Nome Group rocks consist of greenish schists and intercalated beds of schistose marble. Locally, dark-green rocks intrude both the limestones and the schists and are themselves locally converted to blueschist rocks. Where exposures are good, color banding and lithologic variations in the Nome Group rocks suggest that the Nome Group represents old volcanic rocks, tuffs, and tuffaceous limestones. Locally, as in the Nome River valley, where samples 68–ASn–566 to 566H (p. B41) were collected, irregular masses of rock related to the blueschist facies are isolated within schistose marble (fig. 2), thus showing unquestionable contemporaneity of calcareous muds and material most logically interpreted as tuff or volcanic bombs. Similar relations have been observed in southeastern Alaska (Sainsbury, 1961, p. 315), where pyritized volcanic bombs are encased in unaltered limestone. For comparison with the blueschist rocks, altered mafic intrusive rocks from west of the main blueschist belt are described. All sample localities are shown on figure 1.

Petrography

For this preliminary report, Coleman has classified rocks collected by Sainsbury in 1967, and determined to be glaucophane-bearing, into four groups that are correlative with types originally defined by Coleman and Lee (1963) in the Cazadero area, California. Rocks collected by F. H. Moffit from the Solomon area and by W. C. Mendenhall from the Darby Mountains on the eastern Seward Peninsula are described briefly, and reference is made to probable blueschist rocks discussed by Smith (1910). The suite of related rocks (group 6) from a small area in the Salmon Lake area (fig. 1) was classified by Sainsbury.

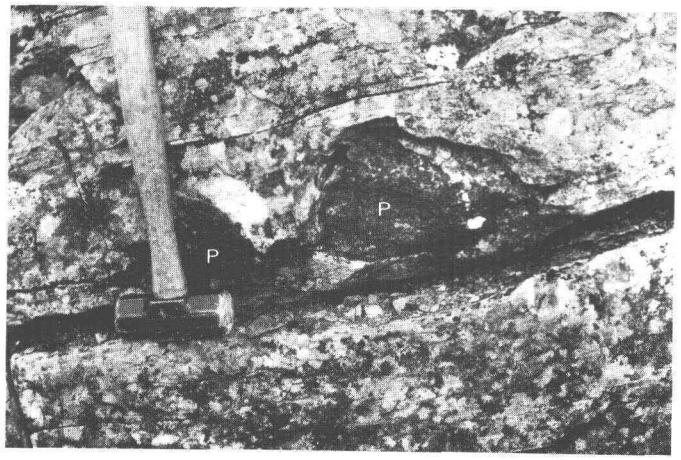

FIGURE 2.—Pods (P) of rock related to the blueschist facies in schistose marble of the Nome Group.

Five groups of rocks are recognized: (1) glaucophane schists, (2) retrograde glaucophane schists, (3) metasedimentary rocks, (4) metagabbros not converted to blueschist rocks, and (5) metagabbros or metavolcanic rocks intrusive into Precambrian limestones and belonging to the blueschist facies. The detailed collection localities of all the samples to be described are given in table 1.

Group 1 rocks represent the following mineral assemblages:

Field No.	*Description*
67–ASN–264	Glaucophane–actinolite–chlorite–epidote–garnet–sphene–white mica–quartz.
67–ASn–264A	Glaucophane–epidote–garnet–sphene–rutile–chlorite.
67–ASn–503	Glaucophane–epidote–garnet–chlorite–sphene–white mica–quartz–rutile.
67–ASn–595	Glaucophane–garnet–sphene–white mica.

These rocks are foliated because of orientation of the platy minerals; garnets are euhedral to subhedral porphyroblasts (nonhelical), which contain abundant inclusions of the other minerals that make up the rest of the rock. The blue amphibole was identified as glaucophane on the basis of the following optical constants: $2V=30\text{–}40°(-)$, $Z\wedge C$ less than 7°, x=colorless, y=purple, and z=blue. In sample 67–ASn–264, the actinolite coexists with the glaucophane and is not retrograde. The epidote forms anhedral masses, and individual grains have iron-rich cores as deduced by birefringence and color. Sphene is common, generally forming anhedral masses—euhedra are very rare. The rutile occurs within the sphene masses and may be retrograding to sphene. Some of the minor chlorite may be retrograde, but much of it is intergrown with glaucophane and probably is in equilibrium with it. The sparse white mica may be phengitic. The small amount of quartz commonly occurs in the pressure shadows behind garnets. Apatite is a minor accessory; small opaque grains associated with rutile may be ilmenite.

The textures (fig. 3) and mineral assemblages are nearly identical with those of the "high-grade" type IV blueschists from California and New Caledonia (Coleman, 1967). However, these Seward Peninsula glaucophane schists lack omphacite, which is common in type IV blueschists of California (Coleman and Lee, 1963).

TABLE 1.—*Localities and descriptions of samples referred to in this report*

Group	Map No.	Field No.	Locality	Latitude (N.)	Longitude (W.)	General description of sampled rock body
1	1	67–ASn–264	West of Kougarok River	65°26′20″	164°55′30″	Frost-riven massive boulders on surface of tundra-covered ridge.
	2	67–ASn–264A	do	65°26′20″	164°55′30″	Schistose frost-riven boulders surrounding 67–ASn–264.
	3	67–ASn–503	do	65°24′20″	164°54′30″	Frost-riven massive boulders on surfaces of tundra-covered ridge.
	4	67–ASn–595	West headwaters of Kougarok River.	65°42′20″	164°59′50″	Float boulders in creek bed, surrounded by tundra-covered hills.
2	5	67–ASn–373	West of Kougarok River	65°30′35″	164°55′50″	Frost-riven boulders on tundra-covered ridgeline.
	6	67–ASn–438	Bed of Kougarok River	65°28′	164°42′30″	Small outcrop on east bank of river, massive-appearing blueschist.
	7	67–ASn–439	do	65°29′	164°43′	Outcrop on west bank of River, relatively sheared, pyrrhotite noticeable.
3	8	67–ASn–137	North of Grantley Harbor.	65°19′	166°06′30″	Graphitic slate band in chloritic schist, float on ridgeline.
	9	67–ASn–326	East of Kougarok River, top of Harris Dome.	65°37′30″	164°33′40″	Thrust "xenolith" in marble.
	10	67–ASn–369	West headwaters of Kougarok River, north bank of Washington Creek.	65°44′	164°58′	Outcrop of calcareous, lineated slate.
	11	67–ASn–434	West fork of Kougarok River, north bank of Washington Creek.	65°44′20″	164°52′	Outcrop of sheared calcareous slate.
	12	62–ASn–652D	Northeast shoulder, Brooks Mountain.	65°33′	167°04′	Outcrop, siliceous graphitic bed with numerous quartz pods.
4	13	61–ASn–477	West bank, Kanauguk River.	65°32′	167°31′30″	Outcrop in creek bed, graphitic siltite.
	14	67–ASn–65	North shore, Imuruk Basin.	65°11′40″	165°46′30″	Outcrop at beach level, gray-green mafic dike, sheared.
	15	67–ASn–135E	South of Grantley Harbor.	65°12′	166°12′	Frost-riven rubble of mafic intrusive.
	16	67–ASn–242	Southeast of Gantley Harbor.	65°08′30″	166°22′	Altered gabbro body intrusive into limestone and slate.
	17	68–ASn–136	East bank, Goodhope River.	65°53′	164°03′	Altered gabbro dike intrusive into chloritic schist.
5	18	67–ASn–41	Headwaters of Nome River.	64°50′12″	165°12′20″	Sheared gabbro intruding limestone schist.
	19	68–ASn–567	Southeast of Salmon Lake.	64°52′	165°10′	Lenticular body (tuff?) in limestone schist.
	20	68–ASn–444	Northeast of Salmon Lake.	64°57′30″	164°50′20″	Mafic inclusion in limestone schist.
6	21	68–ASn–566	Southeast of Salmon Lake.	64°52′04″	165°10′	Well-exposed outcrop of chloritic schist, faint color banding.
		68–ASn–566B	do	do	do	Do.
		68–ASn–566C	do	do	do	Do.
		68–ASn–566D	do	do	do	Do.
		68–ASn–566E	do	do	do	Do.
		68–ASn–566F	do	do	do	Do.
		68–ASn–566G	do	do	do	Do.
		68–ASn–566H	do	do	do	Do.
(None)	22	Moffit's (1913) area.	Between Nome and Solomon.			Chloritic schist of the Nome Group, especially intrusives in marble.
(None)	23	Smith's (1910) area.	Northeast of Solomon			"Greenstones" and chloritic schists of the Nome Group.
(None)	24	Mendenhall's (1901) area.	Tubutulik River, eastern Seward Peninsula.			Chloritic schist within or beneath thrust slices of marble.

The absence of lawsonite and aragonite in the Alaskan rocks indicates that these rocks are not similar to the lower grade type III rocks of the Cazadero area, where the mineral assemblage is glaucophane-lawsonite-chlorite±phengite±aragonite±jadetic pyroxene-sphene.

Group 2 rocks clearly are retrograde blueschists. Specimens and mineral assemblages are listed below, with the unusual minerals in italic:

Field No.	*Description*
67–ASn–373	*Chlorite–actinolite*–white mica–*albite*–garnet–epidote–sphene–(aragonite?).
67–ASn–438	*Albite–chlorite–actinolite*–garnet–epidote–sphene.
67–ASn–439	*Albite–chlorite–actinolite*–epidote–garnet–sphene–glaucophane–calcite.

These rocks clearly show a strong retrogression to greenschist facies under static conditions; some original foliation remains but is not inherited by the retrograde

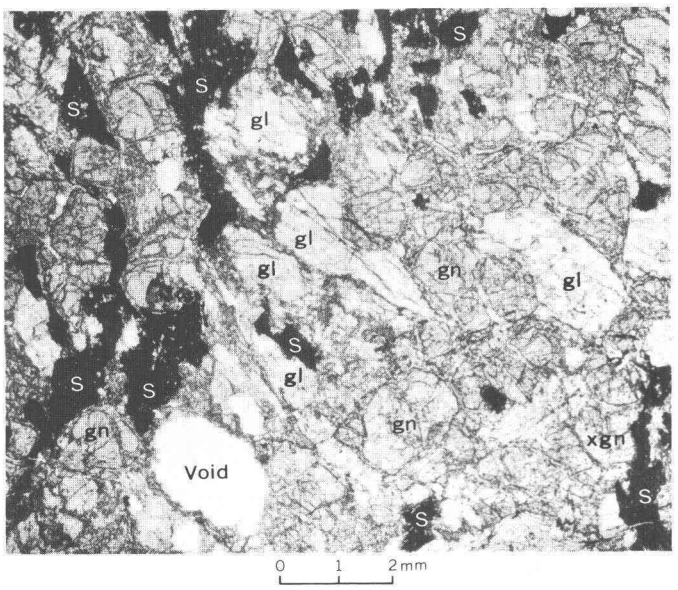

FIGURE 3.—Photomicrograph of typical coarse-grained garnet-glaucophane rock from the Kougarok River drainage; gl, glaucophane; gn, garnet; S, sphene; xgn, garnet with glaucophane in fractures. Plain light. Photomicrograph by Ernest Krier, U.S. Geological Survey.

minerals. The apparent original blueschist minerals are glaucophane-epidote-garnet-sphene; of these, glaucophane and garnet have been most altered, glaucophane being virtually absent. The glaucophane relicts are being replaced and surrounded by a pale-green amphibole, which is set in a matrix of chlorite and albite. The new amphibole looks like actinolite but with detailed study may prove to be common hornblende. A possible reaction for this retrogression is as follows:

$$\underset{\text{glaucophane}}{25(H_2Na_2Mg_3Al_2Si_8O_{24})} + \underset{\text{epidote}}{6(HCa_2Al_3Si_3O_{13})} + \underset{\text{quartz}}{7(SiO_2)} + \underset{\text{water}}{14H_2O} \rightarrow$$

$$\underset{\text{albite}}{50(NaAlSi_3O_8)} + \underset{\text{chlorite}}{9(H_8Mg_5Al_2Si_3O_{18})} + \underset{\text{actinolite}}{6(H_2Ca_2Mg_5Si_8O_{24})}.$$

Although chlorite and actinolite occur in rocks of the first group, they are intergrown with glaucophane and are not clearly retrograde as in the second group. Retrograde rocks have been identified at other localities on the Seward Peninsula, and apparently an initial period of blueschist metamorphism was followed by at least one period of static heating or loss of high pressure with concomitant change to greenschist or epidote-amphibolite facies. As will be shown in the final part of this report, the dynamic metamorphism that produced the blueschist rocks was probably of Precambrian age; hence, the blueschists have gone through a major thrust cycle, which produced no regional metamorphism, as well as a younger regional metamorphism in Cretaceous time that made marble of limestone. In addition, local hydrothermal alteration has further modified some of the blueschist rocks. The retrograde metamorphism recorded by the rocks of group 2 cannot as yet be definitely correlated with the Cretaceous thermal event, principally because blueschist rocks have not been found outside the zone of regional thermal metamorphism. However, massive garnet-glaucophane rocks of group 1 and retrograde rocks of group 2 occur within a few miles of one another, showing that retrogression was not regional in scope.

Group 3 rocks consist of metapelitic rocks equivalent to the slate of the York region; these rocks are younger than the Nome Group rocks of groups 1 and 2. They were examined principally to see if they contained aragonite, for some contain appreciable carbonate. All are from rocks believed to be younger than the Nome Group, which contain the blueschists here described; and all represent mildly metamorphosed pelitic rocks, which were originally composed principally of silt-size quartz grains, minor clay minerals, carbonaceous matter, and carbonate. The samples studied are glistening black phyllites with veinlets of white quartz. Two distinct S-planes are visible, an S-1 plane which represents the main foliation, and an S-2 plane which consists of a strong crinkling of the S-1 planes. Individual samples and their mineral assemblages are as follows:

Field No.	*Description*
67–ASn–137	Quartz–mica–graphite–chlorite–albite.
67–ASn–326	Quartz–mica–carbonate–chlorite–graphite.
67–ASn–369	Quartz–albite–mica–chlorite–carbonate–graphite.
67–ASn–434	Quartz–albite–chlorite–mica–carbonate–graphite.
62–ASn–652D	Quartz–albite–white mica–carbonate–graphite.

Present textures of these rocks are metamorphic and markedly schistose. The albite (indices less than for Canada balsam) forms irregular porphyroblasts that contain numerous inclusions of graphite; carbonate occurs as irregular porphyroblasts. The mica is mainly white (phengitic?) and is concentrated along folia; locally, chlorite is interleaved with the white mica. Opaque clots are mostly graphite, but some rutile needles were observed.

These graphitic metapelitic rocks probably belong to the greenschist facies—a classification which agrees with the impression given by field mapping. Although in places the rocks are so completely recrystallized that quartz grains are much larger and graphite is completely clotted, temperatures were so low that quartz

did not react with calcite to form calc-silicate rocks. There is no hint of blueschist-facies metamorphism in any of the rocks examined.

Group 4 rocks represent selected specimens of metagabbros and related mafic dikes that intruded rocks as young as the slate of the York region at many places throughout the Seward Peninsula. These mafic dikes are compositionally close to volcanic rocks and might have been expected to become blueschists, if they had gone through the blueschist metamorphic event. All have gone through the thrust cycles. Selected specimens were collected progressively from west to east across the Seward Peninsula (fig. 1, table 1), from outside the zone of blueschist facies into the Kougarok River area where blueschist rocks are common. The following is a list of these rocks and their mineral assemblages:

Field No.	*Description*
61–ASn–477	Augite–titaniferous magnetite–leucoxene–labradorite–serpentine–sideritic carbonate.
67–ASn–65	Actinolite–epidote–chlorite–albite–augite(?)–white mica.
67–ASn–135E	Titaniferous augite–ilmenite–leucoxene–white mica–chlorite–actinolite–epidote.
67–ASn–242	Augite–actinolite–epidote–albite–leucoxene–titaniferous magnetite(?)–chlorite.
68–ASn–136	Augite–actinolite–leucoxene–epidote–chlorite–plagioclase.

These rocks, though containing minerals such as epidote, chlorite, and actinolite, which are often found in the retrograde blueschists, differ markedly from the blueschist rocks in several respects: (1) primary augite remains, (2) zoned high-calcic plagioclase remains, (3) opaque iron ores remain and are altering to leucoxene, (4) the relict igneous texture is clearly visible, and (5) none contain garnets. The textures, shearing, and metamorphic minerals are possibly related to the thrust cycles and to the younger regional static thermal metamorphism; clearly, however, none of these rocks have been completely reconstituted and made schistose as has happened to chemically similar blueschist rocks. Nevertheless, the most altered of these rocks resemble the retrograde blueschists somewhat, although they are readily distinguished in thin section. The rocks of this group intruded the upper Precambrian slates, but not the younger carbonate rocks, and are probably of late or latest Precambrian age.

Group 5 rocks represent mafic dikes that cut limestone schists in the Nome Group of Precambrian age, and altered mafic material occurring as lenticular beds (fig. 2) and isolated clots in limestone schists intercalated in the blueschists of the Nome Group. These rocks and their mineral assemblages are listed below:

Field No.	*Description*
67–ASn–41	Garnet–quartz–epidote–apatite–sphene–albite–chlorite–calcite–blue-green amphibole.
68–ASn–567	Garnet–white mica–epidote–quartz–calcite–sphene–apatite–magnetite–hematite.
68–ASn–444	Garnet–albite–epidote–chlorite–sphene–quartz–calcite.

These rocks are unusual in that they contain garnet, are obviously schistose, and lack glaucophane. The mafic material which occurs in the limestone lacks amphibole entirely, whereas it commonly contains white mica. Garnets are subhedral to anhedral, and most contain numerous inclusions. There is no clear evidence that these rocks ever contained glaucophane. The limestone shown in figure 3, which surrounds the material represented by 68–ASn–567, is schistose and contains rounded quartz grains and white mica. The quartz grains have not reacted with the carbonate. The schistosity, complete mineralogical reconstitution, and lack of relict igneous textures and minerals show that this group of rocks, though in part definitely intrusive, has passed through a regional metamorphism in a high-stress environment which did not affect the metagabbros of group 4. Hence, it is concluded that the blueschist metamorphism occurred between the intrusion of the two different mafic-dike suites that are represented by rocks of groups 4 and 5, and must, therefore, be of late Precambrian age.

Petrography of related variants

A suite of samples (group 6) from a well-exposed outcrop of Nome Group blueschist rocks (fig. 4) was

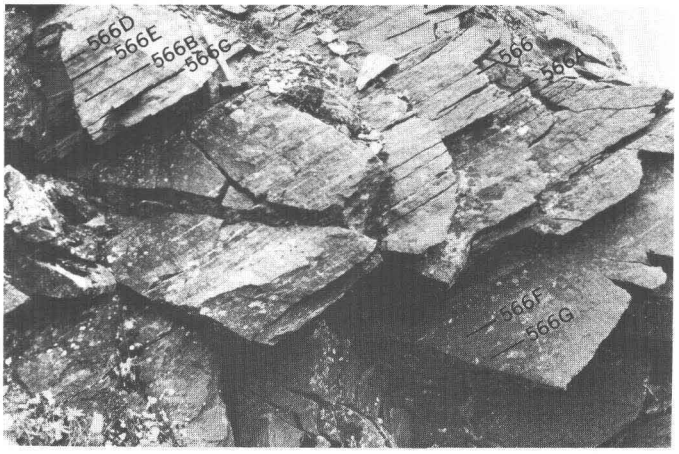

FIGURE 4.—Photograph of outcrop of retrograde bluechist rocks, showing location of closely spaced samples. All sample numbers are preceded by 68–ASn.

studied to determine the mineralogical variations within a restricted area. Individual samples and mineral assemblages as determined by Sainsbury are listed below:

Field No.	*Description*
68–ASn–566	Garnet–white mica–chlorite–sphene–calcite–quartz–blue-green amphibole–epidote–pyrite.
68–ASn–566B	Quartz–white mica–garnet–epidote–sphene–minor blue-green amphibole–apatite.
68–ASn–566C	Quartz–albite–white mica–garnet–calcite–sphene–epidote–apatite.
68–ASn–566D	Quartz–albite–white mica–chlorite–garnet.
68–ASn–566E	Calcite–white mica–quartz–epidote–sphene–garnet in calcite-rich layer; and quartz–calcite–white mica–sphene–chlorite–apatite–pyrrhotite in quartz-rich part.
68–ASn–566F	Quartz–albite–white mica–chlorite–garnet–magnetite–biotite–apatite–biotite.
68–ASn–566G	Quartz–albite–white mica–garnet–chlorite–magnetite–biotite–apatite.
68–ASn–566H	Quartz–albite–white mica–chlorite–epidote–magnetite–calcite.

These rocks are clearly retrograde garnet-bearing rocks, but the mineral assemblages are controlled by the bulk composition of the rock. Where quartz, albite, or calcite predominates, blue amphibole and sphene are virtually absent. In quartz-albite-rich rocks, garnet is poorly developed, forming a net that surrounds quartz and albite grains; in the rock that contains amphibole, garnet is subhedral. Chlorite is retrograde from white mica. The development of bits of biotite in 68–ASn–566F suggests that a thermal event has been impressed upon the retrograde rocks. This event is probably correlative with the intrusion of granite stocks in the Kigluaik Mountains.

Other areas of blueschist rocks

Blueschist-facies rocks were reported by Moffit (1913, p. 32–33) east of Nome at Osborn and Buster Creeks (area 22, fig. 1), where they are in part intrusive into schistose limestone of the Nome Group. The mineral assemblage reported by Moffit (1913) is garnet–glaucophane–chlorite–epidote–titanite–albite; locally, iron ores, pyrite, rutile, quartz, and calcite occur. Moffit noted that the rocks intrusive into limestone are less schistose than the surrounded blueschists. Smith (1910, p. 76–83) discussed glaucophane-bearing rocks in the Solomon area (area 23, fig. 1); he stated that some are unquestionably intrusive into limestone (see photograph on p. 76 of Smith, 1910), and that two ages of mafic intrusives are represented:

> It should be stated, however, that although some of the feldspathic schists were undoubtedly formed from rocks similar in composition to the greenstones, a part of the greenstones are later than these schists, for they show but slight evidences of having been subjected to the same amount of metamorphism.

Smith did not describe individual mineral assemblages of single rock specimens. He noted, however, that most contain garnet, green to blue soda amphibole, chlorite, sphene, quartz, and albite; this mineralogy relates them to the blueschist facies. The rocks described by Smith belong to the Nome Group.

Mendenhall (1901) collected chloritic rocks in the Darby Mountains of the southeastern Seward Peninsula (area 24, fig. 1). Two thin sections representing two of these rocks were reexamined in 1969 by T. P. Miller (written commun., 1969), who reported that one rock is a glaucophane schist. The mineral assemblage reported by Miller is chlorite–albite–epidote–sphene–glaucophane; the rock is foliated. The second sample, collected 500 feet away, has relict clinopyroxene associated with colorless amphibole. The mineral assemblages in these two rocks are similar to those of groups 1 and 4 of this report and are the basis for inference by the senior author that the rock containing clinopyroxene is a later intrusive into blueschist-facies rocks of the Nome Group; such a relationship is common far to the west.

CONCLUSIONS

All the blueschist rocks herein described are believed to belong to a metamorphosed sequence of Precambrian age—the Nome Group. The original rocks probably contained varying amounts of mafic volcanic material that included lavas, tuffs, and dikes related to the volcanism. Numerous interbedded limestones suggest that the depositional environment was marine. After deposition of the Nome Group rocks, an intense regional dynamic metamorphism was impressed upon Nome Group rocks over thousands of square miles of the Seaward Peninsula, creating blueschist-facies rocks. After the dynamic metamorphism, a carbonaceous siltite was deposited over much of the Seward Peninsula; the siltite was then intruded by numerous dikes, sills, and bosses of gabbro. All these rocks are believed to be of late Precambrian age. In latest Precambrian time, impure thin-bedded limestones were deposited over much of the Seward Peninsula and are completely unmetamorphosed in the area from Teller west. During Cambrian time, the Seward Peninsula probably was a positive area, for no rocks of this age are known. From Early Ordovician through Mississippian time, carbonate rocks were deposited over the Seward Peninsula. After deposition of the Mississippian limestone and prior to the injection of granitic rocks in the mid-

Cretaceous, rocks of the entire Seward Peninsula were involved in intensive thrust faulting, which juxtaposed Precambrian schists and clastic rocks against Paleozoic carbonate rocks. This juxtaposition led to the puzzling age relations that baffled early workers and led them to conclude that the Nome Group rocks were of Precambrian and Paleozoic age. After the thrusting, granitic rocks were emplaced and formed isolated stocks on the western Seward Peninsula and large batholiths on the eastern Seward Peninsula. The heating associated with the intrusion of granitic rocks probably accounts for the great increase in the metamorphosis of the Paleozoic carbonate of the thrust sheets from west to east. The west-to-east increase in the size of the intrusives—and, concomitantly, in the amount of heat introduced—probably caused the corresponding great increase in the metamorphism of the Paleozoic carbonates of the thrust sheets.

The blueschist rocks are confined to units older than gabbros of latest Precambrian age. Glaucophane-bearing rocks occur near retrograde blueschist rocks because of tectonic transport by thrusting and by local factors, such as hydrothermal alteration, nearness to younger granites, and proximity to thrust faults. The metamorphic fabric of the blueschist rocks clearly shows two periods of deformation, the second of which probably corresponds to the thrust cycle. Blueschist facies rocks often occur in polymetamorphic terranes (Zwart, 1967) or are juxtaposed against lower grade rocks (Coleman, 1967) in a way that leads to enigmatic geologic situations, and the blueschists of the Seward Peninsula conform to that general pattern. However, it should be emphasized that the Seward Peninsula is not part of the circum-Pacific tectonic belt which contains the well-studied blueschist rocks of late Mesozoic age, but rather represents a well-preserved area of Precambrian blueschist rocks.

This preliminary report records the results of studies made as a very minor part of a regional mapping program, and important relations may be glossed over. The blueschist-facies terrane here discussed offers geologic conditions, such as intense thrusting and later progressive metamorphism, which are not everywhere found. It is hoped that this report will lead to detailed studies by geologists and mineralogists interested in the formation and destruction of blueschist-facies rocks.

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THE RELATIONSHIP BETWEEN SURFACE WATER AND GROUND WATER IN SHIP CREEK NEAR ANCHORAGE, ALASKA

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Work done in cooperation with the city of Anchorage and the Greater Anchorage Area Borough

Abstract.—Ship Creek drainage basin is an important recharge area for the Anchorage artesian aquifer. Discharge records show Ship Creek loses an average of 25 cfs in the recharging area and gains about 22 cfs in the reach below the recharge area. A water-budget analysis demonstrates that of this gain at least 11 cfs is ground-water return flow from the recharge area.

Ship Creek has its headwaters in the Chugach Mountains and discharges into Cook Inlet near downtown Anchorage, Alaska. Its stream course traverses 10 miles of alluvial gravel and glacial outwash deposits in the lowlands and foothills. Since the last glaciation, Ship Creek has built an extensive alluvial fan at the foot of the Chugach Mountains (fig. 1). This fan provides about one-fourth of the total recharge to the artesian aquifer system which underlies the city of Anchorage.

The geology of the Anchorage area has been described by Trainer (*in* Cederstrom and others, 1964) and Miller and Dobrovolny (1959). As schematically shown in figure 2, the surficial gravels in the reach of Ship Creek basin below the gaging station at Elmendorf Air Force Base are underlain by a clay bed which is exposed at the mouth of Ship Creek. This clay stratum forms the confining layer of the underlying artesian aquifer and the lower boundary of the unconfined aquifer in Ship Creek basin downstream from the Elmendorf gage.

Two gaging stations are operated on Ship Creek. Continuous discharge records have been obtained since 1946 at the Fort Richardson diversion dam, and are published as Ship Creek near Anchorage. This station is located on exposures of metamorphic rock upstream from the alluvial fan. Six miles downstream, the second gaging station has been operated since 1963. This station, Ship Creek at Elmendorf AFB, is located downstream from the alluvial fan and about 4 miles above the mouth of the stream.

Discharge records show that for the period of record the mean annual flow over the diversion dam is 150 cubic feet per second and that 6 miles downstream at Elmendorf the discharge is 125 cfs. Previous investigators (Cederstrom and others, 1964; Waller, 1964; Sommers and Marcher, 1965) recognized that this reach of Ship Creek was a losing reach. A recent investigation by the author has shown that part of this loss returns to the stream below the Elmendorf gaging station.

A series of seepage measurements was made to determine the relationship between surface water and ground water in Ship Creek basin. Concurrent discharge measurements were made at the Elmendorf gaging station and at Post Road near the mouth of Ship Creek (fig. 1). The measurements were made during periods of steady stage and no local surface runoff. The discharge measurements near the mouth were made above the tide-affected reach so that drainage from bank storage did not contribute to the measured discharge. Under these conditions, any increase in discharge downstream must be due to ground-water inflow. Table 1 tabulates the measurement data as well as all previously available seepage data.

Two of the previously existing seepage runs were disregarded because they were made under conditions which did not conform to the above measuring criteria. Climatologic records show that the seepage run on April 27, 1959, was made while surface runoff from snowmelt was contributing to streamflow. The seepage run on May 16, 1967, was made during a period of rising stage so that the measured gain was affected by

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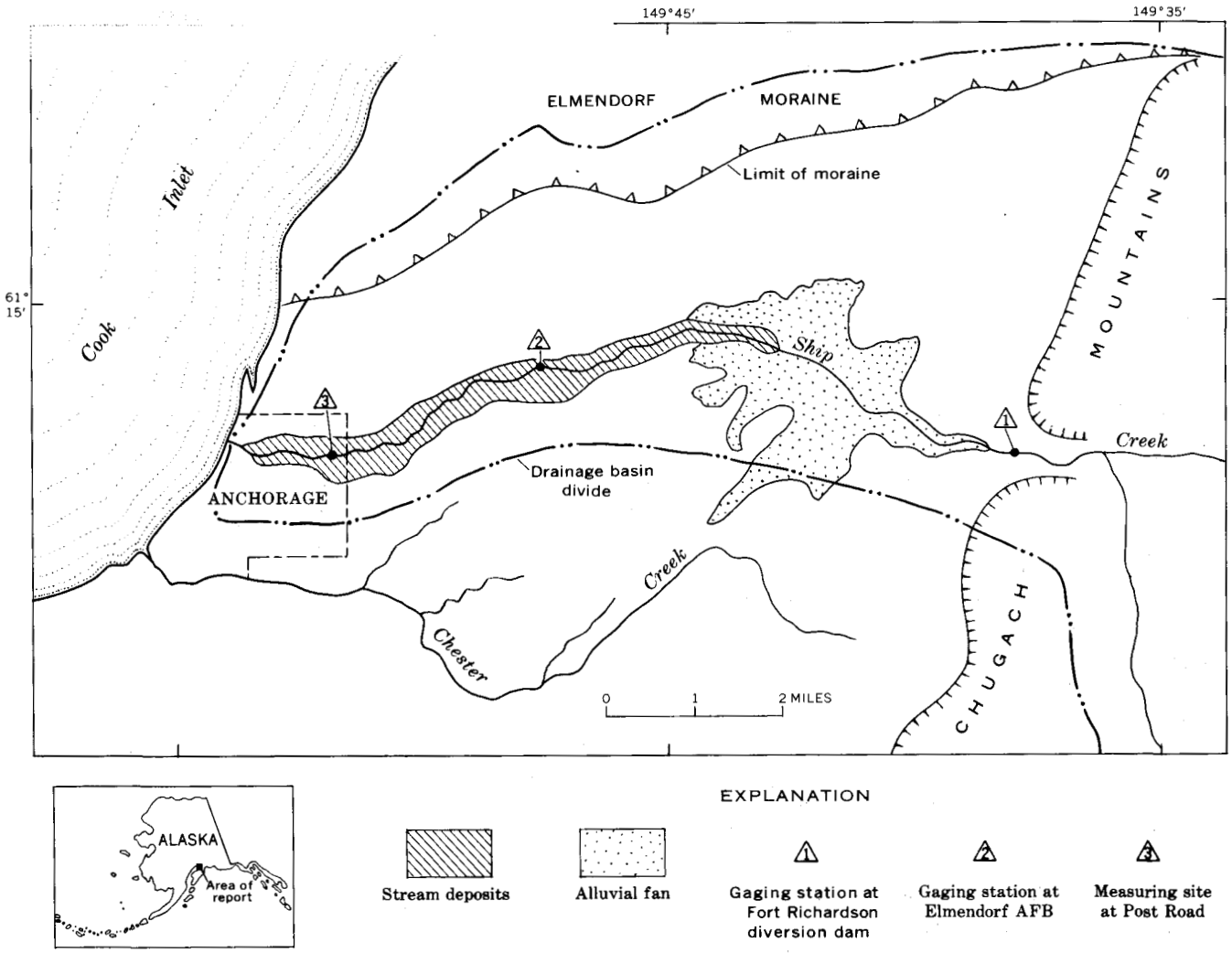

FIGURE 1.—Sketch of the Anchorage area, showing gaging stations and selected features in Ship Creek basin.

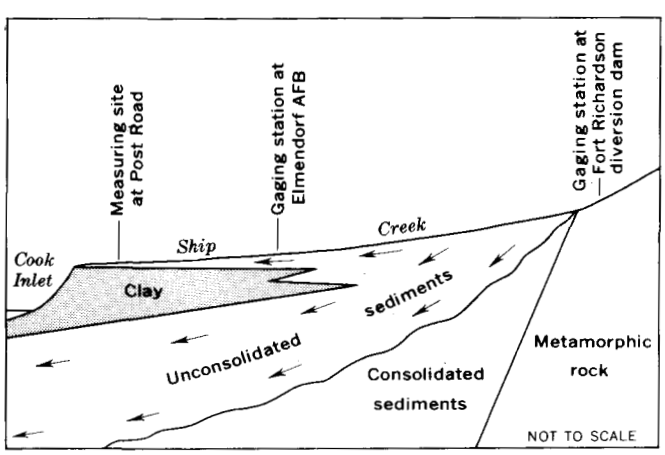

FIGURE 2.—Idealized geologic cross section along Ship Creek, showing the general direction (arrows) of ground-water movement.

channel storage in the reach. If these two seepage runs are disregarded, the average gain in the reach for the remaining nine runs is 21.5 cfs and the standard deviation is 1.9 cfs.

Seepage measurements were not made during the summer months, although the major part of the annual runoff occurs during this period. The mean daily discharge during the high-flow period generally ranges from 200 to 600 cfs, and the discharge measurements are only accurate to about 10 percent. For a discharge of 200 cfs, the possible error in the difference between two measurements is ±40 cfs, and for 600 cfs, ±120 cfs. Therefore, ground-water inflow cannot be reliably determined during high flows because the measurement errors will be nearly as large as, if not larger than, the ground-water contribution to streamflow.

The seepage data show that Ship Creek gains about 22 cfs in the reach below the Elmendorf gaging sta-

TABLE 1.—*Ship Creek seepage measurements made at the Elmendorf Air Force Base gage and near Post Road, in cubic feet per second.*

Date	Discharge measurements		Seepage gain
	Elmendorf gage	Post Road	
Apr. 27, 1959 [1]	28. 3	80. 8	52. 5
Apr. 26, 1960 [1]	20. 4	44. 6	24. 2
Oct. 26, 1960 [1]	172	193	21. 0
Mar. 13, 1961 [1]	19. 2	40. 8	21. 6
May 16, 1967 [1]	182	191	9. 0
Sept. 12, 1968	75. 0	97. 0	22. 0
Nov. 8, 1968	17. 6	41. 6	24. 0
Nov. 15, 1968	2. 8	24. 0	21. 2
Jan. 3, 1969	2. 3	21. 3	19. 0
Jan. 30, 1969	1. 4	23. 3	21. 9
Mar. 26, 1969	1. 3	19. 9	18. 6

[1] Data collected prior to this study.

tion during the low-flow period. Because the ground-water levels are higher in the summer than in the winter, the ground-water contribution to streamflow is likely to be greater during the high-flow period than during the low-flow period. Thus, it can be concluded that the mean annual gain is at least 22 cfs and possibly more. This discharge is supplied in part by ground-water inflow from the recharge area above the Elmendorf gage. This can be shown by the following analysis of the unconfined aquifer in the reach of Ship Creek basin below Elmendorf.

The clay bed underlying Anchorage is exposed along the coastline and forms a ground-water dam which prevents discharge from the unconfined aquifer to Cook Inlet except through Ship Creek. Field observations have located only minor seeps from the bluffs along the coast. The glacial deposits of the Elmendorf moraine (fig. 1) form a barrier to ground-water movement to the north, and a topographic high forms an unconfined ground-water divide to the south. Thus, except for vertical leakage through the clay, the only sources of recharge to the unconfined aquifer are infiltration of precipitation and ground-water inflow from the recharge area above the Elmendorf gage.

The average annual precipitation at Anchorage is 15.14 inches for the 25 years of record, and the area tributary to Ship Creek in the reach below Elmendorf is about 10 square miles. This average precipitation on the tributary area is equivalent to only about 11 cfs per year. Because direct runoff and evapotranspiration losses reduce the amount of precipitation available for recharge, the recharge to the unconfined aquifer must be less than 11 cfs. Therefore, if changes in storage are neglected, at least 11 cfs must be ground-water inflow to account for the 22-cfs gain in Ship Creek.

Potentiometric levels in the reach of Ship Creek basin below Elmendorf have dropped approximately 25 feet in the last 10 years. The seepage data indicate that no significant change in the gain has occurred during this period (standard deviation of 1.9 cfs), and field observations have disclosed that most of the gain occurs in the first half mile below the Elmendorf gage. Because the present potentiometric surface is below stream level in this reach (fig. 3), vertical leakage through the clay cannot contribute to streamflow. The 11-cfs gain must come from the recharge area above the Elmendorf gaging station. Consequently, any estimate of recharge to the aquifer system from the area of Ship Creek basin between the diversion dam and the gage at Elmendorf must account for this return flow.

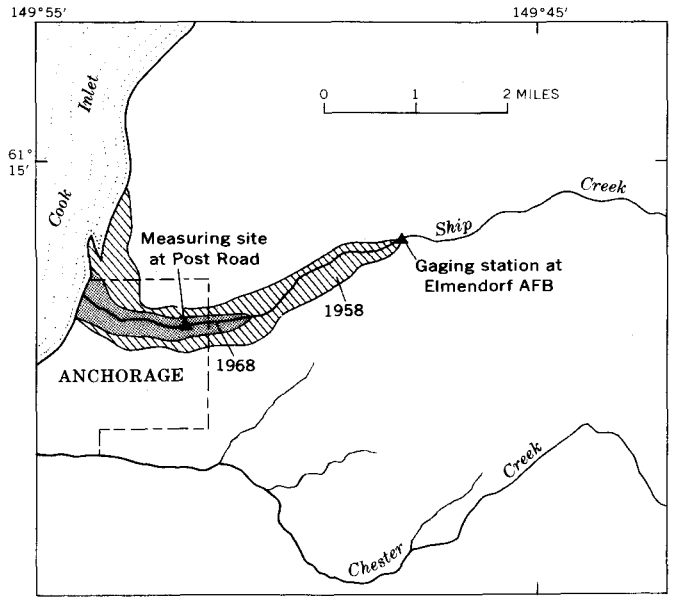

FIGURE 3.—Sketch showing change in area of Ship Creek basin where artesian potentiometric levels were above land surface in 1958 and 1968, as indicated by patterns.

The presence of recent stream deposits along Ship Creek (fig. 1) suggests that the 11-cfs return flow may be largely in the form of underflow. That is, about half of the 25 cfs that is lost in the upper reach of Ship Creek actually recharges the aquifer system, and the remaining half moves through the highly permeable gravels under and adjacent to the stream downgradient.

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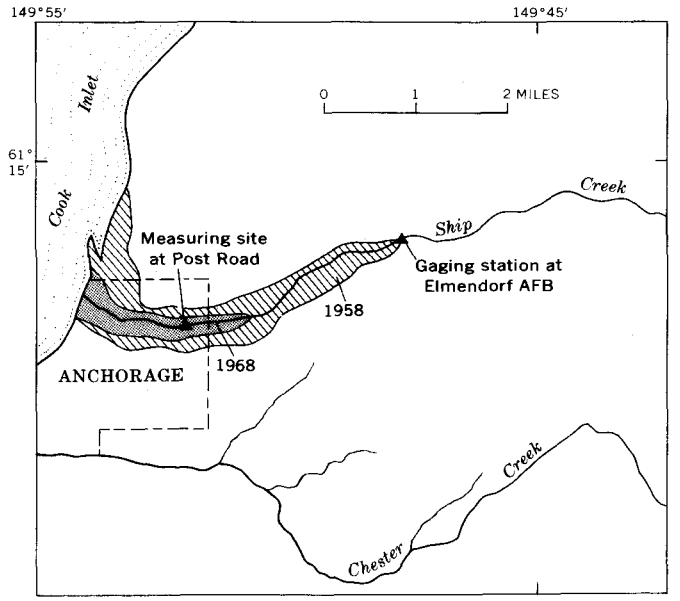

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