Geology of the Prince William Sound Region, Alaska

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ABSTRACT

The geology of Prince William Sound was the subject of some of the earliest geologic investigation carried on in Alaska and from the beginning has presented problems of age and structure that are still only partly solved. The rocks are dominantly sedimentary deposits probably of late Mesozoic age. They include a small proportion of somewhat altered basaltic lava flows and intrusives and a still smaller proportion of light-colored granitic intrusives, dominantly of acidic types, occurring as dikes, sills, and batholithic bodies.

The sedimentary beds are generally described as slates and graywackes. In a few places they include argillite, arkosic sandstone, conglomerate, and a little limestone. The sedimentary beds and interstratified greenstones are strongly folded and locally are considerably altered, even schistose near intrusive bodies or strong faults. These rocks were divided by the early geologists into two groups, the Valdez and the Orca, which were believed to show a slight difference in petrology and metamorphism. The rocks of the older group, the Valdez, are exposed chiefly on the north and west sides of the sound. The younger or less altered rocks of the Orca group make up most of the islands and the mainland of the southeastern part of the sound. They were conceived as overlying the Valdez rocks unconformably.

The basic lava flows and intrusives include basalt and diabase. They are somewhat altered chemically and mineralogically and have taken on a green color, because of which they are commonly called greenstones. A common characteristic of the flows is their ellipsoidal or pillow structure. They are interstratified with thin beds of slate and graywacke and are believed to be restricted to the Orca group of sediments except where they are faulted into rocks of the Valdez group.

The sedimentary rocks of the Valdez and Orca groups have yielded the fossil remains of both plants and animals, which are of some help in correlation. Some of the fossils prove a Late Cretaceous age for at least part of the Valdez and Orca groups.

Heavy snows and accumulations of glacial ice characterize the Prince William Sound region. It owes much of its present form and appearance to erosion caused by the ice. Its remaining glaciers are among the best known glaciers of Alaska.

The modes of occurrence of copper and gold, the principal metalliferous products of the Prince William Sound region, are described briefly.

INTRODUCTION

This paper describes the geology of the Prince William Sound region, a part of south-central Alaska (see fig. 41). It deals with the rocks of a section of the Coast Ranges that has been studied by various geologists over a period of many years and still offers basic problems that are unsolved. Prince William Sound is well known for its mining activities, but the intention here is to describe the areal and stratigraphic geology of the district rather than its mineral resources and to present a statement that will serve as a report of progress and a basis for more detailed field work.

Prince William Sound is an embayment in the most northerly bend of the Pacific coast of Alaska. It penetrates far into the Coast Range mountains and is almost shut off from the ocean by a succession of islands that lie across its south side and form a practically landlocked basin behind their shelter. Its mainland shoreline is intricate, affording many protected harbors for large as well as small vessels. Numerous islands are distributed throughout the sound, constituting dangers to navigation, yet providing additional harbors for fishing

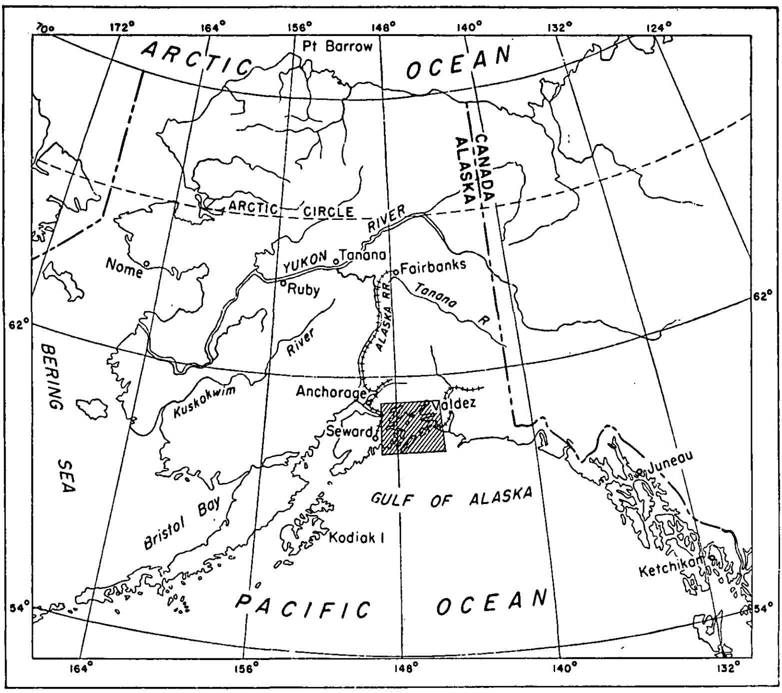

FIGURE 41.—Index map of Alaska showing the location of Prince William Sound.

craft and even for ships. Although its waters are little affected by the heavy seas of the Pacific and usually are relatively quiet, they are subject at times to sudden squalls and gales, especially when fall winds sweep down from the mountains on the north or the winter storms blow in from the Gulf of Alaska. In favorable weather the shining water and the green slopes and snow-covered tops of the surrounding mountains combine to make a scene that delights the eye of every observer.

EARLY EXPLORATION AND MINING

Prince William Sound was explored in 1778 by Capt. James Cook of the British Royal Navy, who called it Prince William's Sound. Cook gave other names that are still in use—among them, Montague Island and Cape Hinchinbrook. English, Russian, and Spanish adventurers followed Cook in voyages of exploration. The Russian Potan Zaikof entered Prince William Sound in a trading vessel in 1783, which is the first time Russian traders are definitely known to have reached the mainland of Alaska. Capt. John Meares, in the trading vessel *Nootka*, wintered in Prince William Sound in 1786–1787. Capt. Nathaniel Portlock and Capt. George Dixon, in two vessels, spent part of the summer of 1787 on the sound. In 1790, Lieut. Fidalgo (Sr. D. Salvador Fidalgo) visited Port Valdez and applied the name Puerto de Valdes, which is now used in the modified form, Valdez, for both the bay and the town. Capt. George Vancouver, an outstanding investigator in command of the sloop of war *Discovery*, carried on extensive explorations in 1794 and named Hawkins Island, Hinchinbrook Island, Port Fidalgo, and Port Wells. Other voyages of exploration and trade were made, but the first efforts to occupy as well as to explore the sound were made by the Russians.

The Russians knew Prince William Sound as Chugach Gulf. They established settlements and organized the fur trade with the Alaska natives. One of their earliest and best known settlements was on Hinchinbrook Island at Nuchek, in Port Etches. Two Russian settlements are reported to have been in existence in 1819. The Russians directed their activities in Prince William Sound chiefly to the fur trade and appear to have made no great effort to find valuable minerals, to promote mining or fishing, or otherwise to develop the numerous resources of the district.

After the purchase of Alaska from Russia by the United States in 1867, the activities of the Russian fur traders were immediately taken up by American companies, which established widely scattered trading posts throughout the Alaska Territory. These companies were interested in developing other sources of income as well as the fur trade, and in some measure they are to be credited with encouraging the first venturesome prospectors to undertake the search for valuable mineral deposits on Prince William Sound and in other parts of Alaska. This interest in mineral deposits was greatly stimulated by the discovery of gold on the Klondike River in 1896. Not all of the hundreds of prospectors who, as a result of that discovery, landed in Valdez in 1897 and 1898, seeking a road to the interior, crossed the passes. Some of them remained to look for gold and copper in the mountains near the sound. Their number grew rapidly and probably reached its maximum about 1907. In consequence of their search, the copper deposits at Ellamar and Latouche and the gold-bearing veins of the Cliff and Granite mines were discovered, and also many smaller, less valuable deposits of these metals. Mining claims were staked at Ellamar and Latouche in 1897, and the properties at both places were soon producing copper ore commercially. The Cliff Mine was staked in 1906 and was in production in 1910. From 1897 to the breaking out of World War II few years passed when production of gold or copper from Prince William Sound was not recorded. Mining was entirely suspended during the second war and had not been resumed in 1952, probably because of the cost of equipment and labor.

HISTORY OF GEOLOGIC INVESTIGATIONS

Study of the geology of Prince William Sound by the U. S. Geological Survey began almost as soon as the search for mineral deposits. Two military expeditions were sent to Alaska by the War Department in 1898 to collect information concerning all features of the country but particularly to search for favorable routes of travel from the coast to the interior. One party, known as Expedition No. 2, under Capt. W. R. Abercrombie, was sent to Prince William Sound and landed in Port Valdez in the early spring. Mr. F. C. Schrader of the U. S. Geological Survey was detailed to this party with instructions to collect information on the geology and the occurrence of valuable minerals in the areas to be visited by him—Prince William Sound and part of the Copper River valley. The investigation brought to light some of the outstanding features of the geology and raised fundamental questions which have not yet been fully answered. The second party, Expedition No. 3, under command of Capt. Edwin F. Glenn, was sent to Cook Inlet and established headquarters near Tyonek. To this party Mr. W. C. Mendenhall of the Geological Survey was attached as geologist. Most of Mendenhall's work related to a reconnaissance from Resurrection Bay to the Tanana River by way of the Matanuska Valley and the Copper River basin, but it began in Prince William Sound with a visit to Portage Bay [Passage Canal].

The following year (1899) the Harriman Alaska Expedition, a private enterprise, visited parts of the sound, paying particular attention to glacial phenomena.

Two years after Schrader's first visit (1900), he and Mr. A. C. Spencer made geological investigations in Prince William Sound in connection with a larger project of studying the mineral deposits and geology of the Chitina Valley.

The growing importance of the mining industry and the increased demand for information about the distribution and occurrence of the ore deposits on Prince William Sound led to a beginning of more thorough and systematic study by the U. S. Geological Survey, which was undertaken by Prof. U. S. Grant, assisted by Messrs. Sidney Paige in 1905 and D. F. Higgins in 1908 and 1909. Mr. A. H. Brooks began a study of the rocks of Port Valdez in 1910 but was prevented by the press of administrative work from continuing it another season. In 1912 Messrs. S. R. Capps and B. L. Johnson made a study of the Ellamar mine and vicinity that added more to a detailed knowledge of the geology of the sound than any investigation previously undertaken. Johnson continued in this work in other parts of the sound, especially the north and west sides, from 1913 to 1917 and was able, with his findings at Ellamar as a basis, to add substantially to an understanding of the stratigraphy and areal geology. The writer spent the 1923 to 1925 field seasons in similar studies. Again in 1943, in association with Mr. R. E. Fellows, he visited nearly all the old copper prospects of Prince William Sound with the purpose of learning their condition and possible usefulness as a source of copper for meeting war requirements. This involved some study of the areal geology.

As a result of these investigations, the U. S. Geological Survey has produced a large number of reports dealing not only with the mineral deposits but also with the general geology, knowledge of which is necessary for an understanding of the distribution and nature of the ores. The publications to which reference is made in this report are those most needed for an understanding of the wider geologic problems and the development of views concerning them.

GEOGRAPHY

Prince William Sound (see fig. 41) is the largest embayment in the coast of Alaska between Cape Spencer and Cook Inlet and gives access from the coast, by highway or railroad, to the Copper River and Susitna River valleys and to the Yukon-Tanana region beyond. It is rudely triangular in form. The west side extends north and south, and the other two sides, conforming to the southeast trend of the mainland and the northeast trend of the large islands across its south side, intersect at the eastern limit of the sound. The triangular form, however, is imperfect, for the shoreline is indented with many deep bays and confused with numerous islands.

The distance from the head of Orca Inlet, the most easterly point on the sound, to the extreme west shore of Port Nellie Juan is approximately 110 miles. The distance from the head of College Fiord south to the entrance of Montague Strait is a few miles less.

The intricacy of the shoreline is best realized from a study of the topographic map (see pl. 8). On all sides of the sound, long narrow waterways or fiords, separated by mountains that rise directly from the shores, extend into the mainland. These inlets afford the only practicable approach to much of the mountain area.

Three long, narrow islands—Hawkins, Hinchinbrook and Montague—extend southwestward from the eastern mainland for almost 100 miles across the south side of the sound. One conspicuous open space between them—Hinchinbrook Entrance—is the principal entrance to the sound. Steamships approaching from the east use this entrance, for the waters between Hawkins and Hinchinbrook islands and the mainland to the east are shallow. The western entrance, commonly used by the regular steamers, is Elrington Passage, although Latouche Passage and Montague Strait are sometimes preferred for the Army transports and other large vessels. Montague Strait lies between Montague Island and a group of closely associated islands, which includes Latouche, Elrington, Evans, and Bainbridge, lying near the mainland on the west. Knight Island lies to the north of these and with Montague Island limits the waterway from the strait to the open sound.

The Chugach Mountains, which surround the waters of Prince William Sound, and the mountains of the islands scattered over it are youthful in form and nearly everywhere show the rugged outlines common to young mountains (see fig. 42), except at lower levels, where the glacial ice that once almost submerged them ground off their projecting ledges (see figs. 43, 44). The mountains of Knight Island

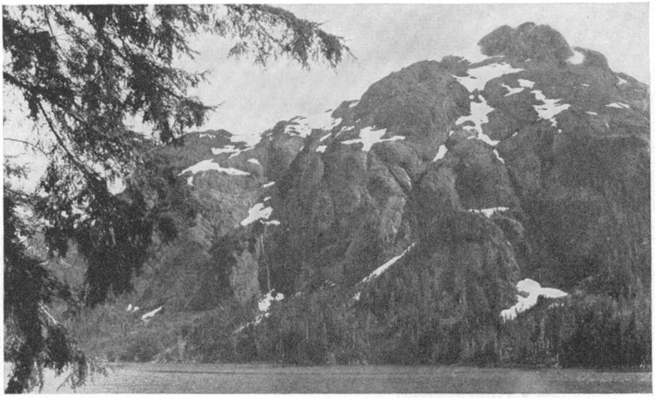

FIGURE 42.—View in Lower Herring Bay, Knight Island. This view is typical of the greenstone areas of Knight Island and indicates a young topography.

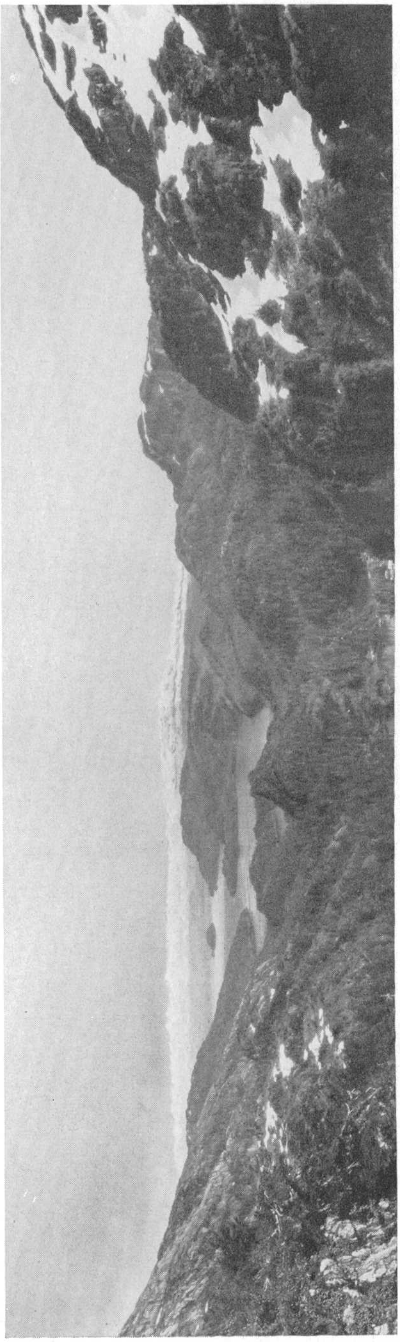

FIGURE 43.—View across Louis Bay showing the north end of Knight Island and the snow-covered Chugach Mountains in the distance. Glacial topography in an area of greenstone. The lower hills are rounded and timber covered; the heights are rugged and bare.

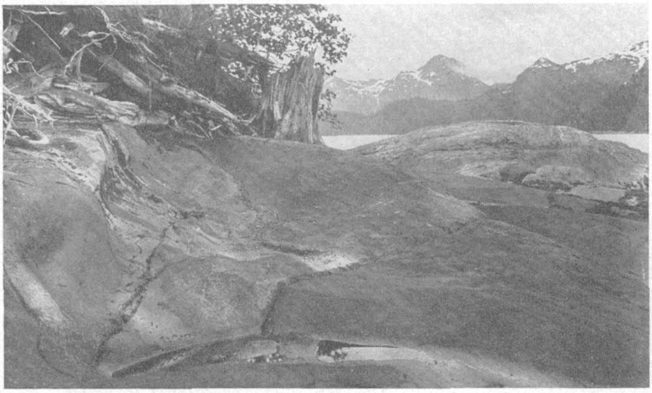

FIGURE 44.—Glaciated surface of the greenstone at the entrance to Marsha Bay, Knight Island.

merit special mention because of the jaggedness of their outlines, although their highest point is only 3,000 feet in altitude. This feature is in part an expression of their geologic character, for they are made up of resistant lava flows.

In most of the middle and southern parts of the area the mountain tops do not exceed a height of 4,000 feet, and the general relief is considerably less. The tallest peaks are in the snowcapped part of the Coast Range north of the sound, where they reach their maximum height of 13,250 feet in Mount Marcus Baker. Much of this higher mountain country is occupied by fields of ice, the source of numerous valley glaciers that slowly make their way to lower levels and even to tidewater, in which they break up and disappear.

Characteristically, the mountains of Prince William Sound rise abruptly from the shores of the fiords and islands. Extensive areas of level or moderately sloping ground are uncommon except in the valleys at the heads of inlets, where shifting streams, encroaching on the shoreline, have spread their load of gravel and silt.

The larger streams entering Prince William Sound are nearly all fed by glaciers, and although much runoff is produced by melting snow and ice and the heavy rainfall of the coast area, none of the streams exceeds 30 miles in length or is of more than local interest. The Valdez glacier stream and the Lowe River are typical of the larger ones. They are swift, sometimes carry large volumes of water, and shift their channels widely over their flood plains (see fig. 45). All the valley glaciers give rise to streams, but many tidewater glaciers discharge their waters under the ice of the sound.

The Prince William Sound region has a large annual precipitation that varies much with the locality. It is greatest near the ocean and less in sheltered valleys such as that of Port Valdez. The summer rains drain from the mountainsides quickly, but winter snow accumu-

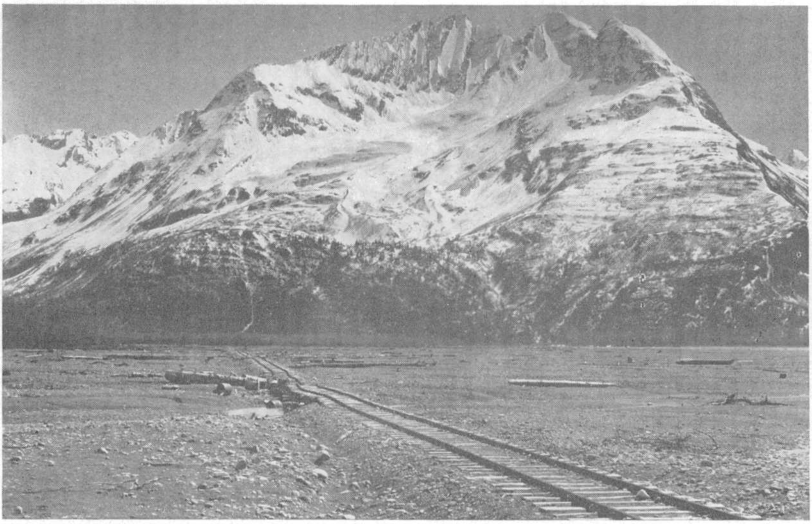

FIGURE 45.—View from the town of Valdez southward across the flood plains of the Valdez Glacier stream and Lowe River. The mountains are rocks of the Valdez group. New snow brings out the glacial benching of the mountainside.

lates at all altitudes, and even below the line of perpetual snow some of it lingers until late in summer. Weather records (Capps and Johnson, 1915, p. 21) covering the period from May 1909 to December 1912 show an average annual precipitation of 140.54 inches at Cordova. In one of these years, 1912, the precipitation of 192.62 inches was unusually high. The annual precipitation at old Fort Liscum on the south shore of Port Valdez is about half that at Cordova.

Among the many bays and arms of Prince William Sound are several of special importance, upon whose shores are sites of settlements, coast terminals of travel routes, mining enterprises, or canneries. Orca Bay, between Hawkins Island and the mainland, is the route for vessels to the town of Cordova, a town that was built as the coast terminal of the Copper River and Northwestern Railway. This railway was constructed to carry copper ore from the Kennecott mines to the steamship lines and was in operation from 1911 until 1938, when mining was discontinued. Cordova is now an important fishing center and the site of several canneries. Port Fidalgo was formerly the site of a number of copper mining enterprises. Port Valdez boasts the oldest permanent white settlement on Prince William Sound. The town of Valdez was established in 1897 and 1898 as the port of entry for the Copper River valley and became the coast terminus of the Richardson highway. Until recently it was the headquarters of the Third Judicial District of Alaska.

Passage Canal gives the most direct access to Anchorage and the Susitna Valley from the south (see pl. 8). Two tunnels have been driven through the mountains between Passage Canal and Turnagain Arm for a short branch railroad, completed in 1943, which connects the Alaska Railroad at Portage and Moraine with the new town of Whittier, port of transfer from ship to rail. Port Nellie Juan is the site of a large cannery.

Other white settlements are at Ellamar, where the old mine buildings have been adapted to the use of a cannery, and at Latouche, where dwelling houses formerly occupied by miners are now occupied by fishermen and their families. Canneries are in operation at Crab and Sawmill Bays on Evans Island, opposite Latouche.

Native villages or schools are maintained at Valdez, Tatitlek, Cordova, and the south end of Chenega Island.

GEOLOGY

INTRODUCTION

The geology of the Prince William Sound region (see pl. 8) is essentially like the geology of a larger province that includes much of the coastal mountains to the east and to the west. So far as is known the consolidated sedimentary rocks probably do not represent more than one era of geologic time—the Mesozoic. No Paleozoic sediments have been identified and none of the Tertiary deposits so extensively exposed along the coast east of the Copper River is known to extend into the area of the sound. The only recognized representatives of the Cenozoic era are the unconsolidated deposits of the beaches and stream valleys and the glacial outwash gravels and moraines.

Marine sedimentary rocks of probable Mesozoic age are the prevailing rocks of Prince William Sound. Most of them may be described as slates and graywackes, with the understanding that these terms are not always used in their strictest sense and that the rocks, especially those known as graywacke, show considerable variation in composition and texture. In places, by a change in proportion or in size of the constituent particles, the coarser deposits become arkosic sandstones, quartzites, or even conglomerates. The mud rocks may lack cleavage and appear as dense, hard argillites. In general the bedding is distinct. Everywhere these bedded rocks are folded and faulted and show varying degrees of metamorphism. Locally they are schistose, having undergone chemical and physical alteration that appears to be more common in the vicinity of intrusive bodies that invaded the sedimentary beds. Briefly, the usual types of rock are graywacke, slate, arkosic sandstone, and argillite. Conglomerate occurs in many places but it is not one of the prominent rocks. Limestone is still less common and where it occurs is nearly always in dark-colored, inconspicuous thin beds. The sedimentary deposits of Prince

William Sound are notably lacking in limy beds. It is evident from the manner of occurrence of the sedimentary deposits and the condition of their constituents that they were formed from material produced by the rapid erosion of an exposed land mass and that the cycle of processes which they indicate was repeated almost endlessly and with comparatively little variation through a long interval of time. The beds in many places give evidence of deposition in shallow waters.

Igneous rocks, although subordinate to the sedimentary deposits, are widely distributed in the area and are of special economic importance because they are believed to have a genetic relationship to the mineral deposits. The principal igneous rocks are of two general classes: somewhat altered basaltic rocks, which occur as lava flows and tuffaceous material, interbedded with certain of the sedimentary deposits or intruded into them; and granitic igneous rocks, which appear as dikes, sills, and larger bodies of less regular and less easily recognized form.

All the rocks of Prince William Sound were deformed by the mountain-building forces that gave rise to the Coast Ranges, of which they are a part. The folding was intense and was accompanied by alteration, especially by recrystallization, which resulted locally in the development of cleavage or schistosity and the formation of secondary minerals. The rocks, however, are not regionally schistose as are the rocks of the north flank of the Chugach Mountains, although schistosity is well developed in places. The sedimentary rocks have yielded fossils, but the fossils are few in both number and species and for the most part are poorly preserved. A few of them are sufficiently diagnostic to afford definite proof of Late Cretaceous age. The scarcity of fossils that might be useful for making correlations and the absence of easily recognized, conspicuous beds that could serve as horizon markers throughout the district make the separation of different formations and the determination of structure difficult. In view of the weakness of the paleontologic evidence and the lack of easily recognizable formations it is readily seen that differences of interpretation might arise among different observers and that only through much detailed field work will it be possible to solve some of the problems of distribution, stratigraphy, and structure presented by the geology of the district. Yet, the solution of these problems is much to be desired, for it will mark an important advance in knowledge of the geology of the Coast Ranges of Alaska as well as of Prince William Sound.

SUMMARY OF GEOLOGIC INVESTIGATIONS

From the time of almost the earliest geologic investigations in the Prince William Sound region the sedimentary beds exposed there have been described as forming two groups, to which the names Valdez and Orca were given. Both groups consist largely of slate and graywacke. The Orca or younger group was thought to be somewhat less metamorphosed than the Valdez group and to be further distinguished from it by the presence of basaltic lava flows and intrusives, and of some thick beds of conglomerate. The Valdez group was thought to be exposed typically in the mountains north and west of the sound: the Orca group was believed to make up the mountains on the east and most of the islands. The slates and graywackes north and west of the sound are thicker bedded and in general of more uniform composition than those on the east and on the islands. Furthermore, the sedimentary beds assigned to the Orca are more conspicuously bedded and include a larger proportion of light-colored siliceous beds, as well as more beds of conglomerate.

The distinctions just pointed out seem to imply that the Valdez and Orca groups are more certainly established as stratigraphic units than is probably true, for doubt still exists concerning the adequacy of the evidence advanced in support of the use of the two terms. The geologists who have studied the sedimentary deposits of the Prince William Sound region in the field have accepted the rocks around Port Valdez as typical of the group to which the name Valdez should apply and have agreed in assigning the basaltic flows and intrusives, or greenstones as they are commonly called, and the massive conglomerate beds of the Ellamar district to the Orca group. Aside from these points held in common there is no generally accepted definition of what constitutes the Valdez and Orca groups, what are their limits, and what are the stratigraphic and structural relations of the beds included in them. Unfortunately, it does not seem possible with the evidence at hand to define the Valdez and Orca groups closely, or even to show beyond doubt that the two are distinct and of significantly different ages, although the groups include formational units that probably can be separated in detailed mapping.

A brief review and comparison of the published opinions of geologists who have studied the rocks of the Prince William Sound region will be given in order to show the character of the problems to be solved and bring out the various conclusions arrived at. The terms "Valdes series" and "Orca series" were proposed by Schrader (1900, p. 404–410) to designate the sedimentary rocks of eastern Prince William Sound. He based the separation of the two "series" on an apparent slight difference in lithology and metamorphism. Although not fully convinced at the time of the correctness of this distinction, he was inclined to believe that it was valid and that the beds of the "Valdes series" are older than those of the "Orca series" and lie beneath them. Following his first examination of these rocks in 1898, Schrader described the two "series" as follows:

The Orca is a

> sedimentary series consisting of thick-bedded, brown and gray sandstones, black limestones, and arkoses, interlarded with usually thin layers of dark shale and slate, and occasionally some conglomerate.

The rocks of the "Valdes series" are

> more highly metamorphosed and consist of bluish-gray and dark quartzites, arkoses and quartz-schists, interbedded with generally thin beds of dark-blue or black slate, shale and mica-schist (sometimes slightly graphitic), nodular mica-schist, and occasionally some stretched conglomerate. These rocks may be a direct continuation of the Orca rocks, more highly metamorphosed and altered as they pass toward the axis of the mountain range; but for the present, on account of their difference from the Orca rocks in lithologic character, they have been given another name and are here called the Valdes series, from the fact that they are best exposed about Port Valdes.

In the same year (1898) Mendenhall examined the rocks in the vicinity of Passage Canal (Portage Bay of Mendenhall), Prince William Sound, and from Resurrection Bay to Turnagain Arm on the Kenai Peninsula. He described the rocks (Mendenhall, 1900, p. 305) as the "Sunrise series", in these terms:

> These rocks, wherever examined, consist of interbedded, fine blue-black slates and dark-gray arkoses, all having been subjected to varying degrees of alteration * * *.
>
> The slates are generally clean and fine in grain with here and there more sandy layers, approaching the arkoses in coarseness. The latter are fine-grained detrital rocks made up chiefly of fragments of quartz and feldspar crystals, with some bits of shale and a little clayey matrix. The feldspars are more usually orthoclase and acid plagioclase, generally angular, but sometimes slightly rounded. They are all remarkable for their freshness, and indicate a very complete and rapid breaking up without weathering of the igneous rocks from which they were derived.
>
> The coarser beds often contain angular fragments and sometimes well-rounded pebbles of the slates, indicating rapid but brief interruptions in the sedimentation which produced them.

The "Sunrise series" is at least in part the westward or southwestward continuation of rocks exposed along the north side of Prince William Sound, as has been recognized by all later geologists who have studied it, and in some undetermined measure it is to be correlated with the "Valdes series".

In 1900 Schrader and Spencer (1901, p. 34–40) made a further brief study of the rocks of Prince William Sound. They defined the "Valdes series" and "Orca series" in greater detail and amplified their description of the "Valdes series" as follows:

> It is a series which, on the whole, is of rather uniform composition, in which there are no lithologic differences sufficient for making any special divisions. In a large way it is homogeneous, rather than heterogeneous, since throughout its thickness there is a constant repetition of alternating thin bands of arkoses, sandstones, and shales in various stages of metamorphism. The series, in gen-

eral, may be characterized as a schist, although it does not show the extreme metamorphism of many rocks for which this term has been used.

Of the "Orca series" they say (p. 37–38)

> The rocks of the Orca series consist of arkose sandstones, usually very massive, interbedded with occasional black limestones and with a considerable amount of black shale. Locally there are conglomerates and rather massive brown and gray sandstones. The conglomerates are composed very largely of gray quartzites, with quartz grains, which are usually well-rounded. The pebbles sometimes reach a diameter of 3 inches, though they are seldom larger than 1 inch. The sandstones are sometimes siliceous and frequently calcareous or ferruginous, but by far the greater part of the sandstones are feldspathic. On a fresh surface they are usually dark blue or gray in color, but when exposed to the weather they assume a pepper-and-salt appearance, giving a general grayish effect. Dark-blue or black limestones have been observed within the series at Yellow Cedar Bay, on the north side of Hawkins Island, in layers from 1 to 2 feet in thickness.
>
> Occurring with the sediments of the Orca series, and to all appearance interbedded with them, there are some important masses of diabase or basalt. It seems probable that the period during which the Orca series was deposited was one of volcanic activity and that sedimentation went on alternately with the extrusion of lavas * * *.
>
> The rocks of the Orca series have been generally folded and sheared, but the metamorphism which they have suffered is somewhat less than that which has affected the Valdes series.

A more comprehensive view of the rocks of Prince William Sound was gained from the work of Grant and Paige in 1905 and of Grant and Higgins in 1908 and 1909. Grant and Higgins (1910, p. 11) summarize their conclusions concerning the geology as follows:

> The sedimentary rocks of Prince William Sound are separable into two divisions, known as the Valdez group and the Orca group. The Valdez is the older. and outcrops along the northern part of the sound, especially on the shores of Port Valdez. This group is composed of slates and graywackes which have been closely folded and metamorphosed to some extent, so that they are now partly crystallized. No markedly crystalline schists occur, except in the vicinity of granitic intrusions. The Orca group lies unconformably upon the Valdez and has been much folded, though not as closely as the Valdez. The Orca group consists in the main of dark-colored slates and graywackes, with locally much greenstone; conglomerates and inconspicuous limestones occur in some places. The greenstones are to a large extent altered basic lava flows, interstratified with slates and graywackes. The peculiar ellipsoidal structure of these greenstones is a marked characteristic of parts of the Orca group.

As understood by Grant and Higgins (1910, p. 26), the Orca rocks comprise two divisions which they describe thus:

> The Orca rocks can be separated into two divisions, one of which is characterized by the presence of much greenstone with subordinate amounts of slates, usually black in color, graywackes, and conglomerates. The other division has little or no greenstone, and consists of slates and graywackes.

They say of the base of the Orca that it is locally a conglomerate of well-worn pebbles which are in some localities graywacke and slate set in a matrix of graywacke. Bands of graywacke and slate are associated with the conglomerate.

The work of Capps and Johnson (1912) in the Ellamar district was a more detailed study of Prince William Sound rocks than had been undertaken up to that time and was concerned with an area that was favorable for study. Retaining the two groups, Valdez and Orca, and defining the Valdez group as consisting of slates and graywackes, they recognized six formations as making up the Orca group (Capps and Johnson, 1915, p. 27, pl. 2). These formations, named in the order of their deposition, are:

Black, fine-grained slates.
Slates and graywackes.
Greenstones and included sediments, more or less metamorphosed.
Greenstones, consisting chiefly of slightly altered, ellipsoidal, and massive diabase flows with some intrusive diabase and interbedded slate and graywacke.
Conglomerate.
The black slate of Bligh Island.

Capps and Johnson thought that unconformities probably exist at the top of the Valdez group and of the conglomerate formation, but they felt uncertainty as to the stratigraphic position of the black slate of Bligh Island, owing to its isolated position and its relation to the adjacent greenstone, from which it is separated by a probable fault.

Johnson extended the detailed work begun in the Ellamar district to Jack Bay and Port Valdez in 1913–15 and 1917 and carried on a similar study of Latouche and Knight Islands and their vicinity in 1916. In 1919 (p. 158–163) and in an unpublished report (Geology and mineral resources of the Port Valdez and Jack Bay district, Prince William Sound, in the files of the U. S. Geological Survey) he retained the terms Valdez and Orca but redefined them in such a way as to include in the Orca group of Jack Bay and Port Valdez only the greenstones, with their associated sedimentary beds, and the massive conglomerate. In the Valdez group he distinguished (1) a basal formation of black slates with minor amounts of graywacke and dark, impure limestone; (2) an intermediate formation of black slates, possibly of the lower division but also possibly representing thick beds of graywacke; and (3) an upper formation of interbedded graywacke and argillite with some slate. Johnson, in 1917 (p. 197–200) and in another unpublished report (Geology and mineral deposits of Latouche and Knight Islands and vicinity, Prince William Sound, Alaska, in the files of the U. S. Geological Survey) included only the greenstones in the Orca group of Latouche and Knight

Islands and vicinity. All the sedimentary rocks were assigned to the Valdez group, which included, in the order of their deposition:

Dark grayish-black slates.
Fine-grained, thinbedded graywackes.
Alternating slate, graywacke, argillite, chert, and limestone.
Conglomerates.
Graywackes.
Black slates.

The different interpretations and definitions of the Valdez and Orca groups that have just been given are shown more clearly in the table on the following page.

From this table it is evident that several matters are controversial or in doubt, among them, that (1) Schrader's original uncertainty concerning the separation of the Valdez and Orca groups was warranted; (2) the sequence of the sedimentary deposits, especially in the formations of the Orca group, is in question; and (3) the correct group assignment of some formations remains to be worked out.

An analysis of the field studies so far made encourages the belief that division of the sedimentary rocks of Prince William Sound into a number of formations will eventually be possible but suggests that a satisfactory subdivision will require more detailed surveys than have yet been undertaken.

In continuing the field work of previous geologists, the writer examined most of the accessible outcrops of bedrock on the shores of Prince William Sound, except the seaward side of the larger islands, stretches of the north shore between Valdez and Passage Canal, and some of the smaller islands. In places the geologic mapping was extended inland, but a thorough, detailed investigation of the whole area was prevented by its extent and the lack of time. This study served to emphasize a number of matters that will be considered more fully in later pages. The slates and graywackes of the Prince William Sound region are not easily classifiable into formational units. The evidence now at hand seems to indicate that in the absence of diagnostic fossils the separation of the Valdez and Orca groups depends on differences in lithology more than on differences in metamorphism. Difference in degree of metamorphism is not fully reliable as a criterion for distinguishing the groups, as it varies much in rocks of the same group. The fossils so far collected do not suggest a distinct difference in age of the beds assigned to the two groups; they suggest nearness or equivalence in age. However, the evidence is not decisive.

A further statement may be required to explain some lack of consistency that will appear in the development of this report. Geologic investigations have been carried on by various geologists in the Prince William Sound region over a period of nearly 50 years. The longer the work has gone on the less certain appears to be the distinction be-

Formations assigned by early investigators to the Valdez and Orca groups

	Schrader, Prince William Sound (1898).	Grant and Higgins, Prince William Sound (1909).	Capps and Johnson, Ellamar district (1912).	Johnson, Port Valdez and Jack Bay (1917).	Johnson, Latouche and Knight Islands (1916).
Orca group	"* * * sedimentary series consisting of thick-bedded brown and gray sandstone, black limestone, and arkoses, interbedded with thin layers of dark shale and slate, and occasionally some conglomerate.	Slate and graywackes with little or no greenstone. Greenstone with subordinate amounts of slate, graywacke, and conglomerate.	Upper slates and graywackes of Bligh Island. Conglomerates with some arkoses and a little slate. Some interbedded diabase flows near the base. Greenstones, consisting principally of little-metamorphosed ellipsoidal and massive diabase flows, with some intrusive diabase. Contains locally considerable slate and graywacke interbedded with flows. Greenstones and included sediments, more or less metamorphosed. Lower slates and graywackes. Black, fine-grained slates, with a little interbedded graywacke.	Conglomerate. Unconformity? Greenstone intrusives and flows.	Greenstone intrusives, flows, and agglomerate.
		Unconformity	Unconformity	Unconformity	Unconformity
Valdez group	"Bluish-gray and dark quartzites, arkoses, and quartz schists, interbedded with usually thin beds of dark blue or black slate, shale, and mica schist, and occasionally some stretched conglomerate. More metamorphosed than the Orca."	Graywackes and slates.	Interbedded slates and graywackes.	Interbedded graywacke and argillite with some slate beds. Black slates possibly of the lower division but also possibly representing thick beds of graywacke. Black slates with minor amounts of graywacke and dark, impure limestone.	Black slates. Graywackes. Conglomerates. Alternating slate, graywacke, argillite, chert, and limestone. Fine-grained, thinbedded graywackes. Dark, grayish, black slates.

tween the Valdez and Orca groups, in so far as difference in age and unconformable stratigraphic and structural relations are concerned. The desirability of discontinuing use of the names has been considered; they are retained in this report as convenient terms for designating major groups of the undifferentiated Mesozoic beds, which probably will be further subdivided, if not partly reassigned, when more detailed mapping is done.

UNDIFFERENTIATED MESOZOIC BEDDED ROCKS

THE VALDEZ GROUP

CHARACTER AND DISTRIBUTION

By original definition (Schrader, 1900, p. 408, pl. 21) the Valdez group is typified by the sedimentary rocks exposed about Port Valdez (see pl. 8). These rocks are dominantly graywacke, argillite, and slate, derived from muds and feldspathic sands of somewhat variable composition expressed largely by the proportions of quartz and feldspar. Siliceous and carbonaceous slates and feldspathic quartzites are variants of the dominant slates and graywackes. Beds of conglomerate and of dark, impure limestone are interstratified with the slates and graywackes in places but are relatively uncommon. The argillite and slate represent the finest of the original sedimentary materials deposited. They differ from each other in the superior hardness and less well developed cleavage of the argillite, by reason of which it is more resistant to erosion than the slate. Strongly contrasting color is not a feature of these beds. The color of the slate is bluish-gray or black, that of the graywacke is more commonly gray or bluish but is lighter on the weathered surface and may be brownish from the oxidation of pyrite.

The thickness of individual beds ranges from a fraction of a foot to scores of feet. The beds are closely folded and show metamorphism that is not uniform but is so far advanced in places that the slate and graywacke are changed to phyllite and schist. Their general trend is east, parallel with the long direction of Port Valdez. Faulting is extensive. Quartz veins are abundant and range from fine, closely spaced veinlets in a complicated network to separate, individual veins several feet thick (see figs. 46, 47).

Without doubt the original muds and sands were derived from a common source; but the causes that brought about the deposition of alternating fine and coarse material, differing so little in composition, are not apparent. The thickness of many beds of slate and graywacke seems too great to be accounted for as a result of alternating seasonal changes in erosion and deposition. Some beds are plainly lenticular, and all would appear so if seen as a whole. The conditions controlling deposition did not favor the formation of recognizable beds of wide extent.

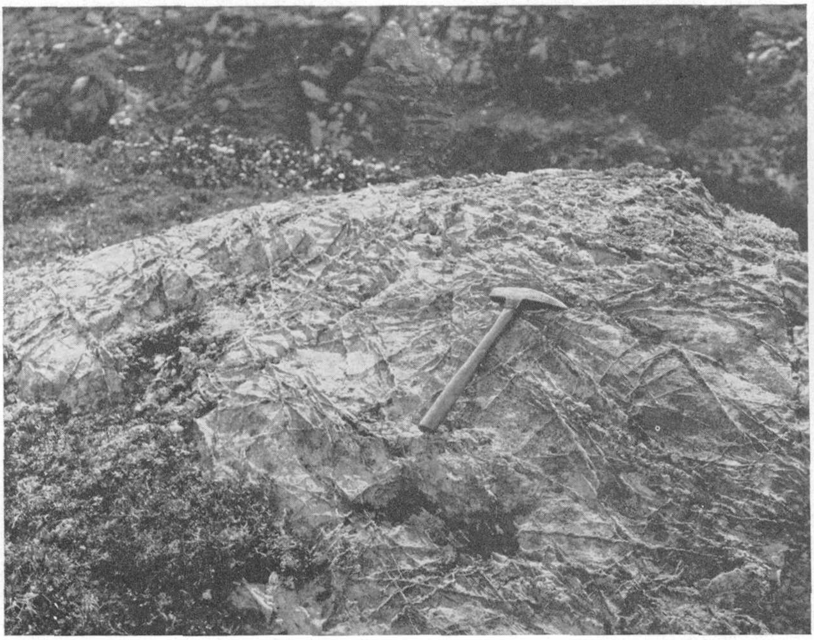

FIGURE 46.—Network of quartz veinlets in fractured graywacke of the Valdez group. The quartz is more resistant than the graywacke and stands out in relief. Photograph by Johnson.

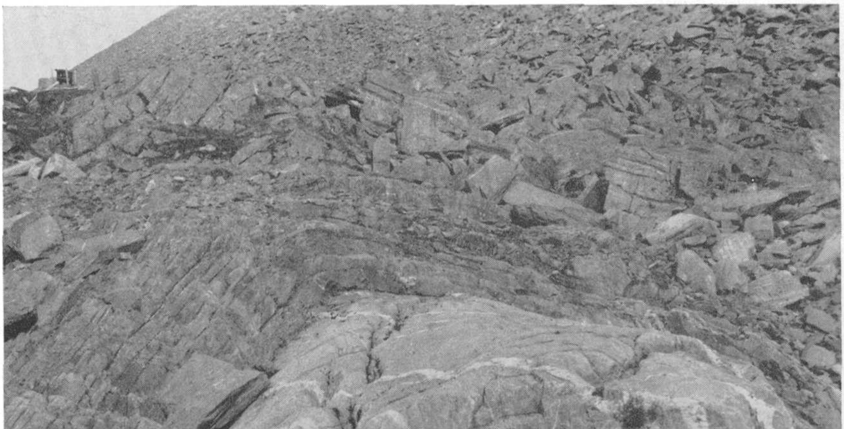

FIGURE 47.—Folded beds of slate and graywacke of the Valdez group near the Valdez Glacier. The fractured, hard beds are commonly seamed with quartz. Photograph by Johnson.

The Valdez group of slates and graywackes on Port Valdez is measured in thousands of feet and, according to Johnson, may be separated into two divisions. The lower division is made up of black slates with minor amounts of graywacke and dark limestone. This division he formerly regarded as part of the Orca group. The upper division consists of interbedded graywacke and argillite with some slate beds. Some of the slate beds of the upper division are thick (see fig. 48) and by themselves are indistinguishable from massive beds of the lower division. This separation of the Valdez group has not been tested outside of the Port Valdez district and is here looked on as tentative. Johnson describes the rocks of Port Valdez as more severely disturbed and altered than the Valdez rocks of other parts of Prince William Sound and states that this difference becomes notable immediately west of Valdez Arm.

Sedimentary rocks in the vicinity of Passage Canal (Portage Bay of Mendenhall), in the northwestern part of Prince William Sound, were described by Mendenhall (1900, p. 305) under the name, "Sunrise series", but as the "Sunrise series" of Passage Canal represents, at least in part, the westward continuation of beds that are exposed on the north side of Prince William Sound and are there included in the Valdez group, the term "Sunrise" is not used in this paper as an additional stratigraphic name.

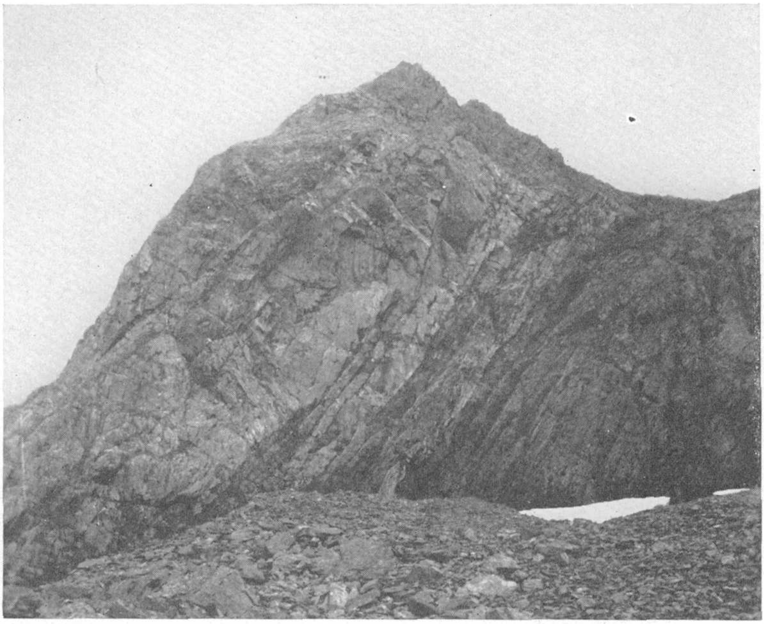

FIGURE 48.—Massive graywacke of the Valdez group overlying black slate in the Jack Bay area. Photograph by Johnson.

This group of rocks consists of fine, blue-black slates and dark gray arkoses, all of which show alteration in varying degree. A feature of the rocks of Passage Canal to which attention is directed is the change in strike, which is more nearly north than the strike of the beds on Port Valdez. This is in accord with the changing trend of the Chugach Mountains.

Mendenhall laid emphasis on the unweathered state of the feldspar fragments, which, together with grains of quartz, make up most of the material of the detrital rocks, and drew from their condition the conclusion that they were derived from igneous rocks that were being rapidly broken down without weathering.

The source locality from which the material was derived is not known, but it included both sedimentary and igneous rocks and probably was not far away. More emphasis on the idea of derivation from igneous rocks than is intended may possibly be conveyed by the statement about the feldspathic constituent of the arkoses and graywackes, for it is also true that argillaceous and other sedimentary rocks contributed a share of the detritus. The coarser graywacke beds and the arkoses with their included fragments of shale give evidence of this.

The sedimentary rocks of the mainland on the west side of Prince William Sound and on some of the adjacent islands consist almost wholly of closely folded graywacke and slate. These beds in general are thick. They appear massive, commonly with obscure structure lines, and show little contrast of color when examined in the outcrop (see fig. 49). The graywacke beds are dominant and are the most con-

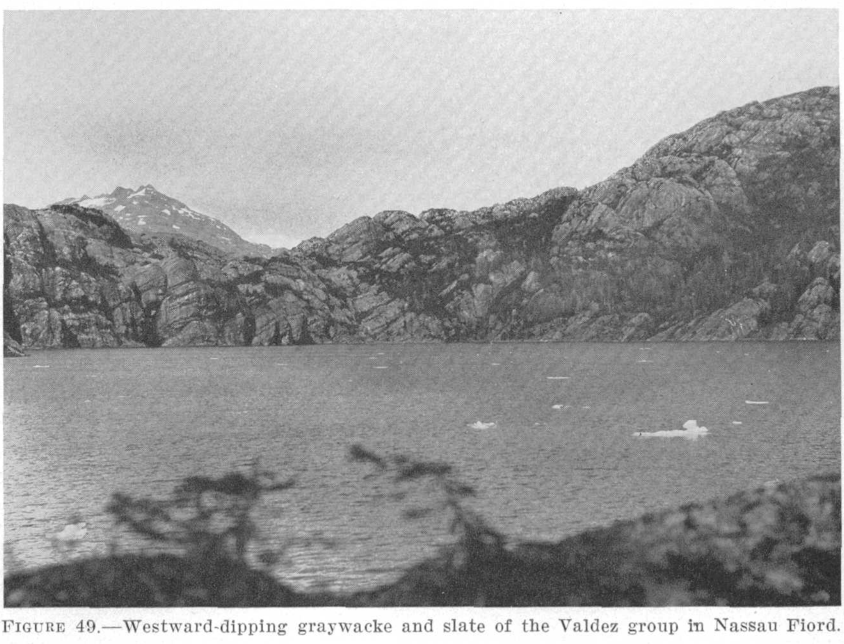

FIGURE 49.—Westward-dipping graywacke and slate of the Valdez group in Nassau Fiord.

spicuous rocks of the whole eastern side of the Kenai Peninsula from Port Wells to Cape Puget. They probably will be one of the stratigraphic units of future classifications and are already described by Grant (1915, p. 210) as the oldest of the divisions that he makes of the rocks of eastern and southern Kenai Peninsula. Their prominence is due in part to the superior resistance of the graywackes to weathering but is also due to their abundance. The graywackes in places are arkosic. They are gray or bluish gray but are lighter on the weathered surface than on the freshly broken surface. The somewhat lighter gray of the graywackes as compared with the gray of the slates appears to be due in part to the presence of more and larger particles of quartz in the graywacke. Near some of the granite intrusives the graywacke is saturated with the granite, and biotite is abundantly developed. Such rocks appear gneissic.

The slates are dark gray or bluish black and fine grained. Cleavage is commonly well developed in them yet is almost as well developed in some of the graywacke. In places the cleavage of the slates is crinkly or wavy like that of some schists. Some of the rocks derived from mud are without cleavage and should be called argillite rather than slate.

The slates and graywackes of the Kenai Peninsula adjacent to the west side of Prince William Sound are closely folded. The general strike of the beds from Port Wells to Port Bainbridge is a little east of north and is plainly reflected in the trend of most of the bays and arms of that side of the sound, as well as in the trend of the intervening mountains. The folds are on a large scale and are overturned to the east. This is shown in the section of beds (see fig. 50) that is exposed along the shore of the ocean west of Puget Bay and was described by Grant (1915, p. 210). Such folds are uncommon in the lava flows and interbedded sediments of Knight and Bainbridge islands although they were seen on Latouche Island. There, however, the folding is not so close as on the mainland.

Faulting accompanied the folding of the slates and graywackes and is more common than appears from the field observations of a reconnaissance survey. A study of the map of the west side of

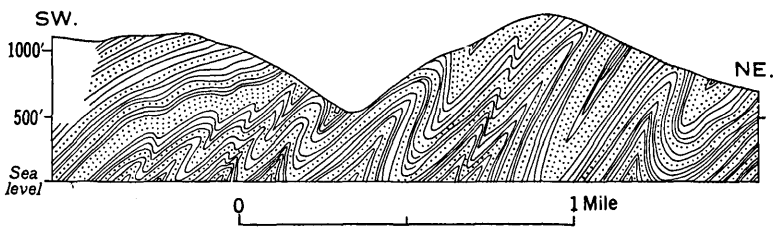

FIGURE 50.—Sketch map showing structure between Puget Bay and Cape Junken. By D. F. Higgins.

Prince William Sound immediately suggests that faulting must have had an important influence in determining the location and form of the many waterways, for they have an arrangement that could hardly have been dependent on folding alone.

The sedimentary beds of the Valdez group are intruded by igneous rocks in the form of large, irregularly shaped bodies or, more commonly, of dikes and sills, the offshoots of the larger bodies. Dikes and sills are widely distributed and appear wherever the Valdez rocks are known but are more numerous in the vicinity of the batholiths. They include acidic and basic intrusives but are dominantly light-colored granitic rocks, ranging from diorite to aplite. Many of the dikes are persistent for long distances and are readily recognized against the dark background of the slates and graywackes. They and the batholiths will be described more fully in the section on igneous rocks.

THE ORCA GROUP

INTRODUCTION

The type locality of the Orca group is the Orca Bay district of southeastern Prince William Sound. The Orca group, like the Valdez group, consists dominantly of slate and graywacke, but it includes altered basic extrusive and intrusive rocks that are known as greenstones and are extensively exposed in parts of the sound. Although subordinate to the slate and graywacke and somewhat irregularly distributed, the greenstones have long been considered to be the most characteristic unit of the Orca group.

Notwithstanding the similarities of the two groups, the Orca, when compared with the Valdez, shows greater diversity in the kinds of rocks composing it. Variations from the typical slate and graywacke appear to be greater in the Orca than in the Valdez group. The sedimentary beds show more variety. Much of the original muddy sediment now appears as argillite rather than slate. Locally, the coarser sands contain a high proportion of quartz, and the rocks derived from them are more exactly described as sandstone and quartzite. The Orca group includes occasional beds of conglomerate and limestone in addition to the sedimentary rocks mentioned. Conglomerate beds are prominent in several widely separated localities, but limestone beds are uncommon and notably inconspicuous.

The beds of the Orca group are closely folded and much faulted but in general are not greatly altered. Locally they are metamorphosed in consequence of igneous intrusion or other local cause. A judgment of the relative degree of alteration of the rocks of the Orca and Valdez groups is difficult to form, for folding and alteration are not uniform throughout either group. The Orca rocks in places have an appearance of much disorder. They were both crushed and folded and show confusion of strikes and dips that make the interpretation of structure uncertain. Possibly they were deformed under a lighter load of overlying sediments than the beds of the Valdez group.

The general distribution of the rocks here described as the Orca group is represented on the geologic map (pl. 8) in much the same way as it was given by Grant and Higgins, although additions and changes have been made that are based on the later work of Capps, Johnson, and the writer. The Orca group, however, cannot yet be clearly differentiated from the Valdez group. Grant and Higgins included in the Orca group, as appears from their geologic map (1910, pl. 2), all the greenstones of Prince William Sound; the sedimentary rocks east of a line drawn northward from Port Bainbridge through Bainbridge Passage and Knight Island Passage to Long Bay; and most of the sedimentary rocks south of an irregular line drawn so as to include Glacier Island, the west side of Valdez Arm, the Ellamar district and Port Fidalgo. They conceived the Orca as having two divisions and believed that the greenstones with their interbedded sedimentary members make up the lower division and overlie the Valdez group unconformably. The upper division consists of slate and graywacke. The only place where Grant and Higgins show Valdez and Orca rocks in contact is in the Ellamar district, the adjacent Valdez Arm, and on Unakwik Inlet.

Capps and Johnson (1915, p. 27–28) accepted the Orca group as a stratigraphic unit but found that the greenstone unit of the group in the Ellamar district is underlain by several thousand feet of fine black slate and interbedded slate and graywacke that they regard as belonging to the Orca group (see fig. 51). The rocks which they assigned to the Valdez group in that area are brought into contact with the greenstone unit of the Orca group by a great overthrust fault, not known to Grant and Higgins, and the normal contact of rocks of the two groups was nowhere recognized by them.

Johnson's later work on Port Valdez and Jack Bay was chiefly among rocks of the Valdez group. The Valdez group, however, was defined by Johnson so as to include certain rocks that formerly were mapped as Orca (see p. 244). Johnson also made changes in the assignment of beds to the Valdez and Orca groups of the Knight Island and Latouche Island districts, transferring from the Orca group to the Valdez group all the sedimentary beds in that part of Prince William Sound that formerly were regarded as Orca. By these changes Johnson would reduce the Orca group so as to include only the greenstones throughout the sound area and the massive conglomerate near Ellamar. The succession of formations proposed by Johnson is shown in the tables on pages 241 and 270. The writer, after spending considerable time in examining the rocks of the Knight Island and Latouche Island

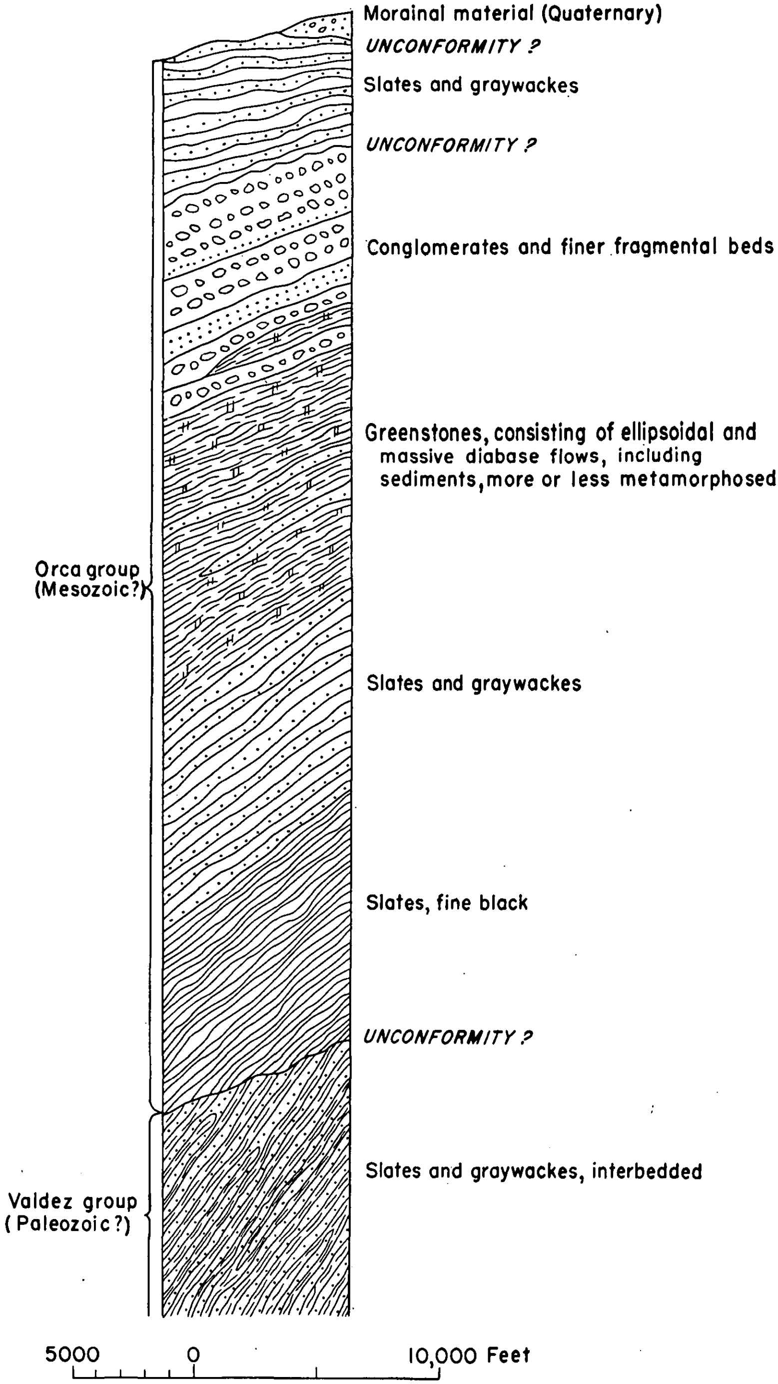

FIGURE 51.—Generalized columnar section of the rocks of the Ellamar district. By S. R. Capps.

districts, has retained the general distribution of the Valdez and Orca groups given by Grant and Higgins, in the belief that better criteria for distinguishing the two groups are needed before changes can be made with assurance.

Some features of the Orca group can be described more fully now than could be done by previous investigators, and with that purpose in view several localities will be considered in some detail.

ORCA BAY

The rocks of the mainland, adjacent to Orca Inlet and Orca Bay, and of Hawkins Island make up the type locality of the Orca group. These rocks, like those of the Valdez group, are commonly described as slate and graywacke, although they include rocks of other kinds. Most of them were probably derived from the same or similar sources and differ because of varying conditions of sedimentation or later alteration. Besides slate and graywacke the group includes argillite, arkose, sandstone, conglomerate, limestone, and greenstone or somewhat altered basaltic lava. All these rocks are severely folded (see figs. 52, 53), and locally are somewhat altered. The type locality, however, is not fully representative of the beds that have been referred to the Orca group in other places.

Comparison of the sedimentary beds in different parts of Prince William Sound seems to show that the proportion of quartzose sediments is relatively high in the southeastern part. Sandstones are more abundant in the Orca Bay district than elsewhere and form a large part of the sedimentary rocks exposed there, although they are

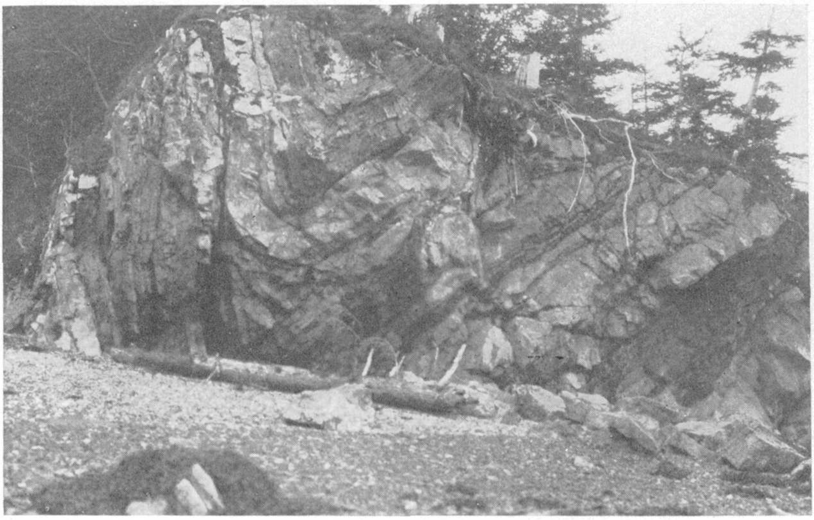

FIGURE 52.—Folded slate and graywacke of the Orca group near the cannery at the head of Orca Bay.

FIGURE 53.—Closely folded vertical beds of the Orca group on the shore at the north end of Montague Island.

subordinate to the argillaceous rocks. The proportion of sandstone to interbedded argillite and arkose at one locality on the south shore of Hawkins Island was estimated to be about one to three. In a section of vertical beds especially favorable for observation, approximately 50 feet of sandstone is followed by 150 feet of the dark beds, and the succession is repeated several times. The beds are not sharply divided but grade into one another, changing gradually from coarse, siliceous material to fine, argillaceous material, or the reverse. This section is believed to be representative of much of the area. West and north from Orca Bay the sandstone beds give way largely to less siliceous deposits.

Beds of conglomerate crop out on the north side of Orca Bay, extending east and east-northeast from Sheep Point to the projecting point of land that forms the east side of Simpson Bay. At Sheep Point the pebbles and cobbles range from a fraction of an inch to 10 inches in diameter and are flattened. Most of the pebbles and cobbles look like the sandstone matrix, but pebbles of light-colored quartzite, granite, and a dense feldspar porphyry of light color are present. Similar conglomerate is the principal rock of the narrow point east of Simpson Bay, where it is associated with an agglomerate containing occasional rounded cobbles. The beds stand vertically and strike N. 60° E. Beds of finer conglomerate with pebbles up to an inch in diameter continue to the head of the bay between Bomb Point and Simpson Bay. The waters of Orca Bay conceal any extension of the coarse conglomerate on the west. The thickness of the coarse conglomerate, including arkosic beds, may be as great as several hundred feet.

Stratification is commonly conspicuous in the outcrops of bedrock in southeastern Prince William Sound. This is because the beds generally are not as massive as beds of the Valdez group and locally show distinct contrast between hard and soft beds or between dark and light beds (see fig. 54). The rocks of the Orca Bay district are much folded. Many folds are closely compressed, and commonly the dip of the bedding is high. Folds with vertical axes indicate the extreme degree of local deformation and disturbance. The rocks, however, are less altered chemically and mineralogically than the rocks of the eastern parts of Port Gravina and Port Fidalgo and around Port Valdez. The rocks of those localities are schistose in places and appear to have been affected by regional causes as well as by local igneous intrusion. On Port Gravina and Sheep Bay the sedimentary beds were altered through the intrusion of a granitic batholith and are locally recrystallized or are stretched and broken (see fig. 55).

Many observations of strike and dip were made in the Orca district. The strikes and dips are highly variable yet serve to show that the general trend of the beds is indicated by the trend of the fiords and intervening mountain masses, which is about north-northeast.

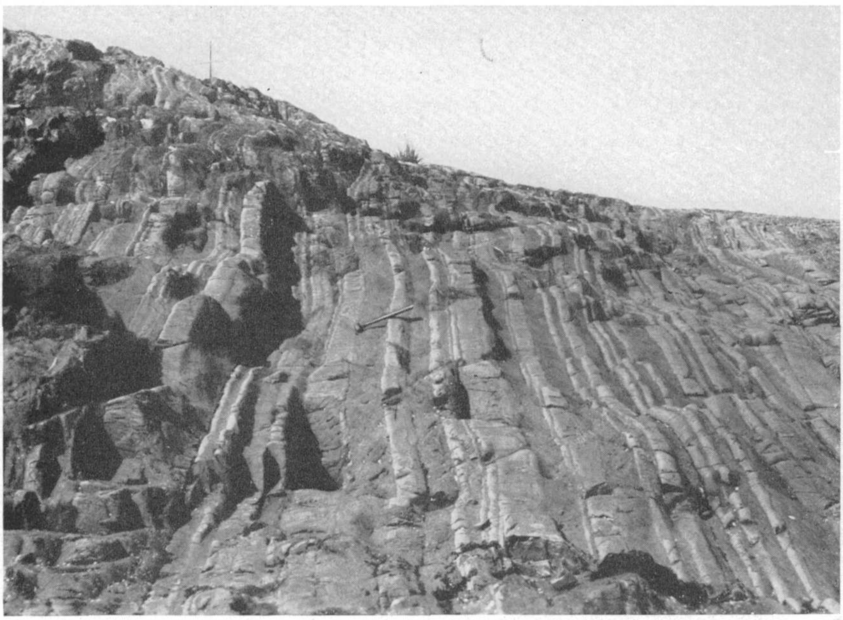

FIGURE 54.—Interbedded slate and graywacke of the Orca group on Gull Island, between Goose Island and the mainland, separating Port Fidalgo from Port Gravina. The exposure shows contrast of color and differential weathering due to the difference in hardness of the beds. Photograph by Paige.

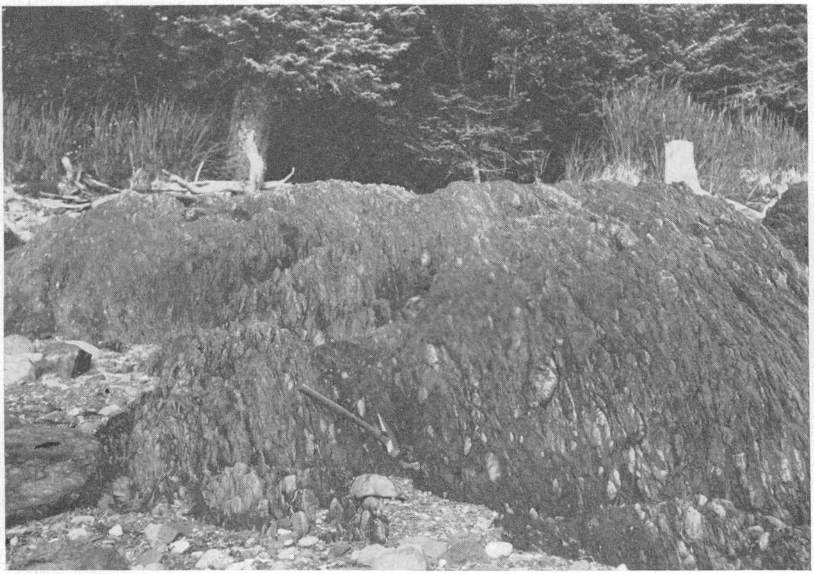

FIGURE 55.—Stretched graywacke and slate beds north of Gravina Point. Photograph by Paige.

This correspondence of strike of beds and trend of physiographic features is not true of Port Fidalgo and the Ellamar districts, where strikes of bedding and formation boundaries are northwesterly.

The type locality of the Orca group includes an area of greenstone which is exposed in a narrow belt near Cordova and extends eastward for an unknown distance. Like all the greenstone areas, it attracted early attention by its showings of copper-bearing minerals.

ELLAMAR DISTRICT

The rocks of the Ellamar district that Capps and Johnson (1915, p. 27) assigned to the Orca group are shown in the generalized columnar section of figure 51, which is reproduced from their report. The rocks are given in still more generalized form on the geologic map (see pl. 8). The section shows that the Orca rocks of the Ellamar district are many thousands of feet thick but makes it evident that the presence or absencce of the greenstone and conglomerate affects the estimated of thickness in great degree, as these two formations comprise approximately one-half of the maximum thickness of Orca rocks in this district.

The columnar section includes four conformable formational units resting unconformably on slates and graywackes of the Valdez group. The oldest formation is made up of fine black slates. This is overlain by interbedded slates and graywackes. Then follow altered diabase flows or greenstones interbedded with sediments, which in turn give way to a thick conglomerate formation. A fifth formation, of slates and graywackes, is thought to rest unconformably on the conglomerate; but the stratigraphic position of this formation is not yet certainly known.

The Ellamar district offers the most favorable opportunity for the study of the stratigraphy of the Orca rocks that is known, and this section therefore merits further consideration. It is not to be expected, however, that the rocks of the section will be constant and similarly exposed throughout the area occupied by the Orca group in Prince William Sound. The restricted local occurrence of both the greenstone and conglomerate demonstrates that changes in the stratigraphic section take place even in short distances.

The black slate formation, regarded by Capps and Johnson as the lowest and therefore the oldest of the divisions of the Orca group differentiated in the Ellamar district, includes very little graywacke. It is made up almost entirely of slate in which the bedding commonly is not plainly seen; and in places it is made evident only by weathering and the resulting differences of color. The principal exposures of the slate are along the east side of Tatitlek Narrows and in the peninsula between Boulder and Landlocked Bays. In much of this area the beds dip steeply toward the northeast and show no recognized repetition. The northeasterly dip of the beds and the area occupied by them appear to indicate a great thickness of the slate, probably amounting to several thousand feet, but faulting and possible repetition of folded beds make estimates of thickness questionable. Uncertainty also arises concerning the stratigraphic relation of the black slate to the slate-graywacke beds bordering them on the east. The contact of the two was not seen but the dip of the beds should carry them beneath the slates and graywackes.

The formation overlying the black slate is made up of thin beds of slate and graywacke, none of which exceeds a few feet in thickness. These beds dip under the greenstone in the vicinity of Ellamar and upper Galena Bay. They are absent on the peninsula between Boulder Bay and Landlocked Bay, probably being faulted out there, but appear again east of Landlocked Bay. They include locally a small amount of black limestone and conglomerate. The slate-graywacke formation and the underlying black slate were less resistant to pressure and distortion than the greenstone above them and are more severely folded. The thickness of the slate-graywacke beds may be as great as that of the black slate but here also folding and faulting make estimates of thickness extremely unreliable. Although the structural and stratigraphic relation of the slate-graywacke beds to the black slate is not convincingly indicated, the relation of the slate-graywacke beds to the greenstone is not in doubt: Both the structure and the areal distribution show that the greenstone overlies the slates and graywackes.

The greenstones record an episode or episodes in the course of deposition of the sedimentary beds. They are composed of somewhat altered basaltic lavas that were poured out on the bottom of a shallow sea, thus acquiring their characteristic pillow structure. The evidence of underwater extrusion is confirmed by the beds of slate and graywacke that are interstratified with the flows. The greenstones are the principal rocks of an elongated area that extends from Port Fidalgo to Valdez Arm, a distance of about 13 miles, but are not continuous across the valley that leads from Boulder Bay to Galena Bay. Greenstone also occupies the northeast part of Bligh Island, all of Busby Island, and a part of the west shore of Valdez Arm. These separate areas are probably parts of one originally continuous area that was divided through the incidences of faulting and erosion. Other isolated greenstone areas near Ellamar are that of Glacier Island, a long narrow area on the north side of the valley of Jack Bay, and another near the head of that valley on upper Solomon Gulch. These areas have no evident connection with the greenstone area of the Ellamar district. The greenstone areas in the valley of Jack Bay and on Solomon Gulch are surrounded by rocks of the Valdez group and appear to be faulted into their present position. If not infaulted blocks they are intrusions in rocks of the Valdez group or in rocks wrongly assigned to the Valdez group. A small area of altered igneous rocks associated with black slate and crystalline limestone at the head of Port Fidalgo apparently belongs to the greenstone group and indicates the extension of the Orca rocks into the mountains on the east.

The maximum thickness of the greenstones and interbedded sediments near Ellamar is several thousand feet, which is unequaled in any locality in Prince William Sound with the possible exception of Knight Island.

The massive conglomerate of the Ellamar district has had a prominent place in all the discussion of the Orca group for it is one of the two formations accepted by all as belonging to the group. It was described by Capps and Johnson (1915, p. 42–44) as follows:

> As the top of the greenstones is approached, near the narrow low gap 1½ miles southeast of Rocky Point, the shale beds alternating with the greenstone flows become more numerous, small quantities of limestone occur, and thin conglomerate beds appear between the thin lava beds. Above the last greenstone flow a very thick conglomerate occupies all the end of the peninsula between Galena Bay and Tatitlek Narrows. It lies conformably on the underlying greenstones * * *. The texture of the rocks varies from gritty beds, which approach coarse sandstone in appearance, to coarse massive conglomerates containing boulders and blocks of rock several feet in diameter. Between the pebbly beds in places occurs a little slate and graywacke. The pebbles in the conglomerate are composed mainly of graywacke or slate, though some crystalline pebbles of granitic texture were seen and also a few pebbles or boulders which might have been derived from the greenstones of the Orca group. The matrix is commonly a black argillaceous material, and most of the conglomerate was probably de-

rived by erosion from the slates and graywacke of the Valdez group. The bedding of the finer gritty beds of the conglomerate can in general be easily determined, but the coarser conglomerates are massive and at many places show no distinguishable bedding planes.

A second, smaller area of the massive conglomerate lies along the east shore of a small cove about one mile north of Galena Bay (see fig. 56). The area is nearly 1 mile long. The conglomerate rests in part on greenstone and is well exposed on the shores of the cove, especially in a high bluff at the south end of the area. Johnson (1919, p. 162) gave this description of the beds:

> The conglomerate near the southern end of the bluff is a massive, coarse-grained heterogeneous mixture with no sign of bedding. There are abundant angular to subangular boulders of all sizes, the largest of which are several feet in diameter. Most of the boulders, however, are small and less than a foot in diameter. They consist chiefly of greenstone, graywacke, slate, and argillite. A few small, exceptionally well rounded pebbles of siliceous argillite are found. The greenstone boulders appear most abundantly in the lower part of the southern end of the bluff. To the northward the conglomerate is finer grained, and a few thin lenticular beds of graywacke 1 to 4 inches thick, which strike N. 30°–45° E. and dip 12°–25° W., appear in the conglomerate. The pebbles in the conglomerate at the north end of the bluff are mostly 1 to 2 inches in diameter, although in places larger boulders occur.

The occurrence of greenstone in the conglomerate suggests a number of possibilities concerning the age of the greenstone as well as the conglomerate. As the conglomerate rests on a mass of greenstone and contains boulders of greenstone, a reasonable assumption would be

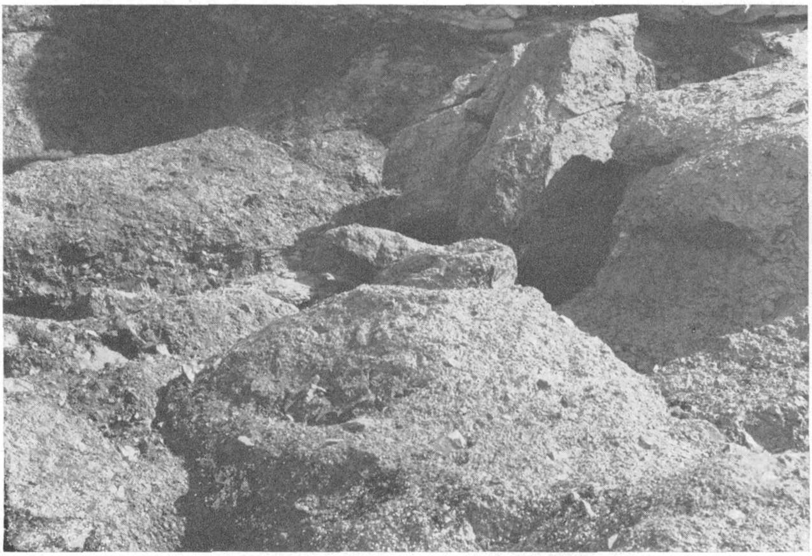

FIGURE 56.—Conglomerate of the Orca group on the beach of a small bay north of the entrance to Galena Bay. Photo by Paige.

that the conglomerate is younger than Orca rocks and is not to be included with them. This assumption raises the question of whether the conglomerate on the north side of Galena Bay is correctly correlated with that on the south side. Most of the geologists have not questioned this correlation.

Estimates of the thickness of the bedded rocks of the Orca group in the Ellamar district show only the order of thickness. They are not based on field measurements of sections but rather on the relief of the surface and a general knowledge of the attitude of the beds. They apply to an area where the greenstone is of exceptional thickness and the conglomerate may be unique, for it has not yet been correlated with any other conglomerate of the sound. Capps and Johnson (1915, p. 145) state that the greenstones are several thousand feet thick at Ellamar and that the conglomerate at Rocky Point appears to be at least 3,000 feet thick. Since the other formations of the group seem to be comparable with the greenstone and the conglomerate the total thickness of the group probably is many thousands of feet.

The structure of the bedded rocks of the Orca group in the Ellamar district is not fully understood. Several assumed relationships are open to doubt. The relation of the greenstone to the conglomerate that overlies it and to the slate-graywacke formation beneath it is fairly well established as structural conformity. The relation of the black slate to the slate-graywacke formation of Bligh Island with reference to the other formations is still less known, although because of their simpler structure the slates and graywackes are assumed to be younger than the massive conglomerate.

For the most part these formations trend in a northwest direction and are bordered on the northeast by rocks of the Valdez group which are overthrust on the greenstone formation in most of the area. The base of the Orca group has not been recognized. The greenstone of Ellamar Mountain appears to occupy a central place in a synclinal fold in the lower slate-graywacke formation, and the greenstone of Bligh and Busby Islands appears to be separated from adjacent sedimentary beds on both the northeast and the southwest by northwestward-trending faults.

The slate, argillite, and graywacke fragments in the conglomerate of the Orca group were thought to be derived in part at least from rocks of the Valdez group, which supposedly is lacking in greenstone, but fragments of greenstone in a conglomerate of Orca age would indicate the probable presence of greenstone in the Valdez group or the exposure and erosion of older Orca rocks.

The conglomerate bed on the shore north of the entrance to Galena Bay appears to be made up in part of material from the greenstone on which it rests. This relationship may arise from either of the possibilities just suggested—that the underlying greenstone is older than the rocks of the Orca group, or that it is an older unit of the Orca group that was exposed to erosion.

The resemblance of the massive conglomerate to indurated till or tillite was noted by Capps and Johnson (1915, p. 43), although they were unable to find evidence of the glacial origin of the conglomerate and suggested such an origin only as a possibility.

The uppermost division of the Orca group in the Ellamar district consists of slates and graywackes occupying the southwestern, larger part of Bligh Island. These beds are similar to beds of the Valdez group and to the lower slates and graywackes of the Orca group. They differ from them in being much less closely folded and less altered. They occupy an isolated position and are probably separated from the greenstone flows of northeastern Bligh Island by a fault. Their stratigraphic position is therefore in doubt, but their simpler structure and less altered state seemed to justify their assignment to a place above the greenstone and conglomerate.

Faulting took place on a notable scale during the deformation of the rocks of the Ellamar district. Several prominent faults have been mentioned. Other faults in the Jack Bay valley, between Galena Bay and Port Valdez (see pl. 8), were mapped by Johnson (1919, p. 158, pl. III). Their arrangement and extent suggest that they may have been important factors in locating Jack Bay and point to some unusual stresses affecting that area.

HAWKINS, HINCHINBROOK, AND MONTAGUE ISLANDS

The rocks of the Orca group extend southwestward from Orca Bay and are exposed on Hawkins, Hinchinbrook, and Montague Islands, and on most of the larger islands between Montague Island and the mainland of Kenai Peninsula. The seaward coasts of Hinchinbrook and Montague Islands are almost unknown, as they are exposed to the full sweep of the ocean waves and have no harbors offering shelter for boats. Landings on the beach are thus practical only at times when the surf is favorable. The seaward beach of Montague Island, however, has long been known locally as a place where lost boats or other valuable flotage may be stranded and sometimes yields articles that are worth the cost of salvage. Montague Island beach has been visited occasionally by hunters of stranded property but rarely by prospectors or geologists. The north shore of the island is low and, compared with most of the other islands, has fewer outcrops near the water. Spruce timber covers the lowland back to the mountains and extends up the lower slopes to an altitude of 500 to 600 feet.

The rocks of these sheltering islands are dominantly slates, graywackes, argillites, and arkosic sandstone. A few thin beds of dark, impure limestone crop out on Hawkins Island. On the south shore of Hawkins Island beds of grit and conglomerate, with pebbles and cobbles of quartz as large as 6 inches in diameter and pebbles of fine-grained acidic igneous rock and granite(?), are exposed at one locality.

An 18-inch dike of dark basaltic rock cutting the sedimentary beds and a small area of greenstone that may be Orca greenstone are exposed on the east side of Canoe Passage, Hawkins Island, but no similar rocks were seen on Hinchinbrook and Montague Islands.

The western shore of Hinchinbrook Island from Johnson Point to Cape Hinchinbrook shows nearly continuous exposures of the Orca rocks, which consist almost entirely of thin-bedded graywacke, slate, and argillite. The beds, the thickest of which are only a few feet thick, are closely compressed and stand vertically or nearly so. Much deviation from this position is so uncommon as to attract attention. The rocks exposed on the shores of Port Etches include much black slate and argillite with many beds showing indistinct or fragmentary organic remains on the bedding surfaces. They are much crushed as well as closely folded, and in places the crushed rocks are healed with a network of white veinlets. The strikes of the beds are highly variable. Some of them conform to the trend of the island, but many were measured that are directly across it and trend from north to northwest. The dips are commonly high to the east.

A section 3,100 feet long was measured by pacing along the north shore of Port Etches, beginning at the end of the sandbar connecting Nuchek "Island" with Hinchinbrook Island and extending to the west. The rocks of the section make up alternating stretches of massive graywacke, much fractured and seamed with white veinlets and for the most part showing indistinct structure, and highly contorted, thin-bedded argillite and graywacke with shaly partings. The massive graywacke and the thin-bedded rocks are in the proportion of about 3 to 2. The graywacke unit is not over 460 feet thick, and the section of thin-bedded units is not over 280 feet thick. Scattered through one massive 200-foot unit are pebbles and cobbles, from 2 to 8 inches in diameter, of material like the graywacke itself.

The shores of Zaikof and Rocky Bays at the north end of Montague Island offer exposures favorable for examination. In these exposures the rocks do not differ in kind from the rocks of Hinchinbrook Island but are more thinly bedded, more regular in strike, and more openly folded. They show many carbonized remains of plants and the borings and trails of marine animals. Well-preserved ripple marks indicate that the waters of the sea in this vicinity were shallow when the muds and sands were being deposited.

The trend of the folded beds is commonly east-northeast. Most of the measured strikes fall into two groups that range from east to about N. 60° W. It is evident that the folds on the north shore of Zaikof Bay make up a series of anticlines and synclines pitching moderately eastward. The folding, however, is close enough so that the dips of the beds commonly range from 60° to 90°, and the usual impression is that the beds are vertical (see fig. 57).

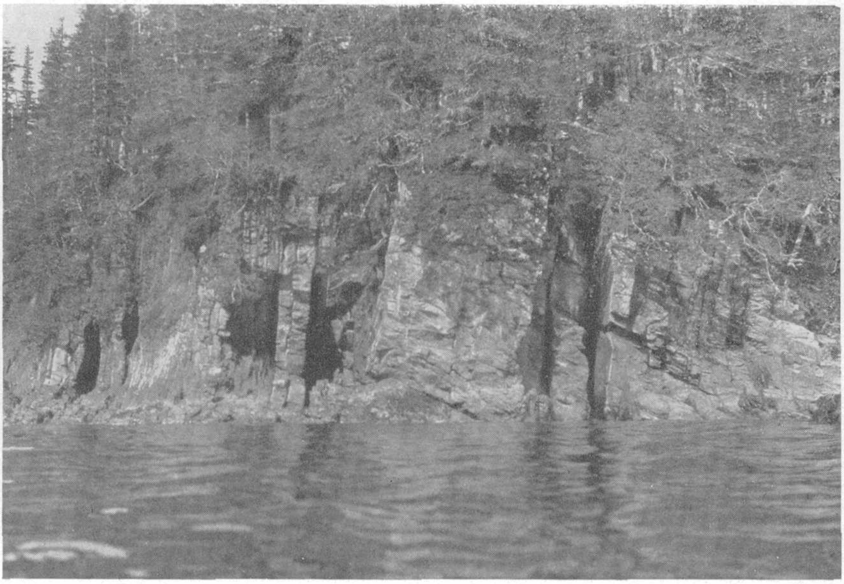

FIGURE 57.—Thin-bedded graywacke and slate of the Orca group on the shore of Zaikof Bay. The steep dip is almost universal and is evidence of close folding. The top of the ledge is an old erosion surface.

A section of the beds on the north shore of Zaikof Bay, about halfway from Middle Point to the head of the bay, indicates the character of the sedimentation. The measurements given are approximate, and the top and bottom of the section were not distinguished. This section represents only a small part of the Orca group.

Section of Orca rocks on the north shore of Zaikof Bay, Alaska

	Feet
Slate, in beds averaging 2 in. in thickness, banded with fine-grained graywacke in beds from ½ to 1½ in. thick; slate or argillaceous rock dominates; strike east, dip 90°	175
Graywacke, in beds 1 to 3 feet thick	15
Argillite, thin-bedded, with graywacke, a few inches thick	20
Graywacke, in beds 1 to 12 feet thick	75
Graywacke, in beds 6 inches to 1 foot thick	20
Argillite, thin-bedded, with ribbons of graywacke	30
Blank	30
Graywacke	15
Argillite, thin-bedded	15
Graywacke, in beds 6 inches to 1 foot thick	150
Argillite, thin-bedded	100

	Feet
Graywacke, in beds up to 7 feet thick	20
Argillite, thin-bedded	40
Graywacke, in beds 1 to 12 feet thick	40
Argillite, thin-bedded	30
Graywacke, in beds 6 inches to 20 feet thick	70
	845

Most of the inside shore of Montague Island is made up of sandy beaches back of which are lowland areas that extend to the lower slopes of the mountain. The projecting points with few exceptions are bedrock consisting of graywacke beds, banded argillites, and some arkosic sandstone. At one locality on the south side of Stockdale Harbor the sandy beds include calcareous concretions ranging up to 2 feet in diameter. At Point Gilmore a bed of sandy shale contains scattered, well-rounded pebbles and cobbles from 2 to 3 inches, occasionally as large as 5 inches, in diameter. These pebbles resemble some of the local bedrock. At the next point of land, 4 miles to the southwest of Point Gilmore, a sandstone bed has scattered through it an abundance of small, well-rounded pebbles ranging up to 1½ inches in diameter. Many of the pebbles are quartz but some are gray granite or diorite of medium grain. Near Point Woodcock, Macleod Harbor, massive graywacke beds and thin-bedded graywacke and argillite beds that strike N. 30° E. and dip 90° are exposed. This more northerly strike conforms to the changed trend of the folded beds on the west side of Prince William Sound. One thin bed of graywacke at this locality has about 5 inches of conglomerate on one side. Conglomerate beds such as those that have been mentioned do not appear to indicate important unconformities. The Orca group of sedimentary beds seems to be largely shallow-water deposits and probably derived much material from nearby, local sources.

The backbone of Montague Island is a rugged mountain chain without low passes to the seaward side of the island. It shows many small cirque basins that were occupied by ice after the disappearance of the great ice mass that filled Prince William Sound. So far as is known this mountain ridge consists entirely of rocks such as are exposed on the shores.

GREEN ISLAND

The rocks of Green Island are black, banded slate and shale with occasional thick beds of graywacke or sandstone. The graywacke is more siliceous, softer, and more brownish on a weathered surface than most of the graywacke of Montague Island. Evidences of former life are common and include the carbonized fragments of plants and the borings and trails of worms or other animals, but none of the organic material found was sufficiently well preserved to be collected or to have diagnostic value.

LATOUCHE ISLAND

The geology of Latouche Island has particular economic interest because of the copper and iron sulfide deposits at Latouche, Horseshoe Bay, and other less abundantly mineralized localities. The areal geology and mineral deposits of the island were studied by Grant and Higgins in 1910, by Johnson in 1918 (p. 193–220; unpublished report on Latouche and Knight Islands), and by the writer. In addition, the geology of the mines at Latouche was studied and described by geologists associated with the mining companies. The most comprehensive descriptions of the mines at Latouche are by Lincoln and Bateman (1924, p. 338–368), who were chiefly concerned with the occurrence and structure of the ore deposits at that place, though their study involved some consideration of the general areal and structural problems of the district. The geology of Latouche Island has thus been investigated more fully than that of the other islands of the sound.

Latouche Island affords abundant exposures of the country rock, although it offers less favorable opportunities for the study of stratigraphic problems than the Ellamar district. This is because the beds are more lacking in distinctive features by which they may be recognized or differentiated and are difficult to correlate from place to place. They consist almost exclusively of slate and graywacke, which, however, show some variety, due to slightly changing conditions of erosion and deposition that took place while the muds and sands were accumulating and thus gave a little variety to an otherwise monotonous succession of alternating beds. The original mud deposits became argillite in places. Some of the sands were more richly feldspathic and yielded arkosic sandstones. A few more distinctive rocks were formed. Occasional beds of conglomerate are interstratified with the slates and graywackes. Limestone occurs in a few places. Igneous rocks were intruded as dikes cutting the sedimentary beds in several widely separated localities and probably are more numerous than is now known.

The slates and argillites are black or dark gray and much of the slate has a well-developed cleavage. The color of the graywacke differs little from that of the slate but tends to be somewhat lighter. Many beds of graywacke are almost as fine grained as the slate. From such textures the graywackes range to sandstones of medium and coarse grain. In most of the area the slates and graywackes are thin bedded and show their bedding distinctly (see fig. 58). They differ in hardness and resistance to weathering, which has expression in the land forms, for many prominent points of the ridges and the shoreline are due to the superior resistance of the graywacke.

FIGURE 58.—Interbedded slate and graywacke of the Orca group near Latouche. The beds are prevailingly graywacke. Photograph by Johnson.

The east slope of Latouche Island appears to be dominated by graywacke in which a relatively small amount of slate is interbedded. The northwest slope is thin-bedded slate, argillite, and graywacke, except for a narrow belt of black slate that occupies the west shore of the island from Horseshoe Bay southward to Pleasant Bay.

Most of the slate and graywacke of Latouche Island is thinly stratified and occurs in alternating beds of the two rocks (see fig. 58). Beds of graywacke measuring tens of feet in thickness are uncommon. In most places individual beds of the interstratified slate and graywacke are measured in inches or a few feet.

The beds are folded and have a prevailing westerly dip. In general the folding was severe but does not appear to be close enough to bring the limbs of folds into strict parallelism in much of the area. The more closely compressed folds are in the slates, which were less resistant to pressure than the graywacke beds. Strikes of about N. 20° E. and dips ranging from 55° to 70° W. are numerous in the northern part of the island. In the southern part the general strike is somewhat more easterly, but the prevailing dip is about the same. This prevailing high westerly dip is not without variation, for secondary folds (see fig. 59) of the dragfold type are superposed upon the larger structure, so that low westerly dips or reversed dips to the east appear. The axial planes of some folds dip high to the east but more of them dip to the west. Folds of open form were seen at several places (see fig. 60). The slates of the west side of Gibbon Peak show a moderately compressed synclinal fold, 300 feet across, separated from the nearly horizontal beds of the peak itself by a vertical fault. Such folds are probably numerous.

FIGURE 59.—Dragfolds in the thin bedded slate and graywacke of the Orca group on Elrington Island near Point Elrington light. Photograph by Johnson.

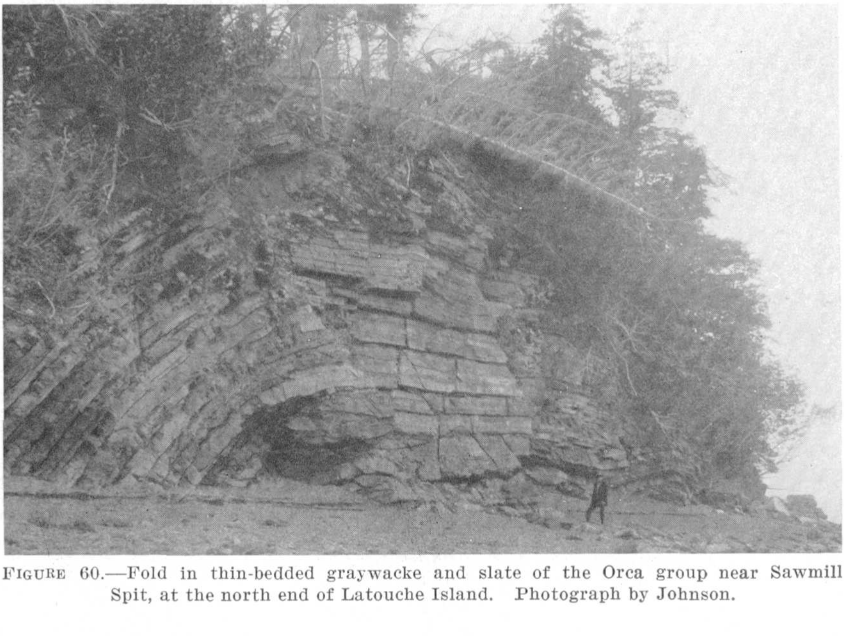

FIGURE 60.—Fold in thin-bedded graywacke and slate of the Orca group near Sawmill Spit, at the north end of Latouche Island. Photograph by Johnson.

Beds of conglomerate crop out at Latouche, and on Wilson Bay, Horseshoe Bay, and Pleasant Bay. This alinement of the outcrops suggests that the conglomerate is probably continuous through this distance although it may be lenticular or faulted out locally. It lies east of the black slate belt but is covered in most places and can not be traced on the surface. At Latouche the conglomerate appears to be not less than 75 feet thick. It includes pebbles and cobbles up to 1 foot in diameter, set in a matrix of coarse graywacke containing sandy lenses. The well-rounded pebbles and cobbles are quartzose rocks of various kinds, slate, and dark, fine-grained porphyritic rocks. Grant and Higgins (1910, p. 29) describes them as "Vein quartz and slate, black and gray in color and in places flinty, * * * fine-grained gray granites of at least four types: white and gray quartzites, hard silicified quartz, porphyries and trachytes, and more basic, porphyritic rocks that are probably andesites."

This assemblage of pebbles and cobbles is not one that could be derived from the rocks exposed in this district at present. The conglomerate resembles that of Evans Island, which is described on page 276. The shore exposures at Latouche suggest the probability of an anticlinal structure in a conglomerate bed that has been eroded through the crest and thus was left as two parallel outcrops of the same bed.

Only one bed of conglomerate is in view at Pleasant Bay. This bed ranges from 12 to 15 feet in thickness and lies between thick beds of graywacke, into which it grades above and below. The beds dip 60° W.

Another bed of conglomerate, 6 feet thick and interstratified with graywacke, crops out on a spur of the mountain ridge one mile south-southeast of Mount Beatson. It appears to be of lenticular form and has no evident connection with the conglomerate at Latouche.

Cleavage, more or less perfect, developed in most of the rocks but is best in the slates. The strike of the cleavage corresponds generally with that of the bedding, although the dip is greater, 70°–80° W., and is notably constant. In consequence of the difference in dips of cleavage and bedding, the two structures commonly intersect.

The structure of the beds is complicated by faults, which undoubtedly are more numerous than appears from the outcrops or the geologic map. Many faults have the same strike as the bedding and cleavage and approximately the same dip. The longest of the known faults is one on which the largest of the known mineral deposits is situated. This fault or fault zone extends south from Latouche to Pleasant Bay (see pl. 8), dipping steeply to the west. It is not a simple fault but includes minor fractures that may differ in both strike and dip from the trend and dip of the fault zone. The amount of displacement has not been determined. One of the members of this fault zone was known at Latouche as the Bonanza Fault and had an important influence on ore deposition and mining operations. At Pleasant Bay a strong fault striking N. 40° E. and dipping 60° W. is parallel to the bedding and separates graywacke on the west from sheared slate on the east. The fault lies from 60 to 80 feet stratigraphically below or on the east side of the conglomerate that is interbedded with the graywacke. This fault has not been traced northward so as to prove its relationship to the faults at Latouche, but it is believed to belong to the same fault system.

The thickness of the slate and graywacke of Latouche Island is not known but is doubtless of the order of thousands of feet. Until more is learned of the stratigraphy and structure it will be impossible to make even an approximate estimate. The apparent monoclinal dip to the west would indicate an enormous thickness if the beds are not duplicated through folding and the measurements are not seriously affected by faulting.

Johnson (1917, p. 197, 198) divided the sedimentary rocks of Latouche and Knight Islands into 6 formations, at least one of which he regarded as subject to possible further subdivision. Arranged in their natural order with the oldest at the bottom, the formations are:

Slate, black.
Graywacke, upper.
Conglomerate.
Slates, argillites, and graywackes, with a little chert and limestone on Latouche Island.
Graywacke, with a little slate.
Slates, dark, grayish-black.

These formations, except the oldest, the dark, grayish-black slates, were believed to be exposed on Latouche Island, dipping west and following one another in their natural order with the lower graywacke occupying the east side of the island. The lower graywacke formation and the overlying slate, argillite, and graywacke formation are in belts extending the full length of the island. The conglomerate, upper graywacke, and black slate occur only south of Latouche, and the upper graywacke would appear to be either locally absent or to be partly cut out by faulting. Johnson, however, referred all these rocks to the Valdez group, not the Orca, and stated that he considered the greenstone to be the only representative of the Orca group in this district. He was not able, with the information he had, to extend the subdivisions to the islands west of Latouche Island.

The writer examined (see p. 248) the north part of Latouche Island and the south end of Knight Island, seeking to verify Johnson's stratigraphic section, and reached the conclusion that the section should be regarded as tentative until more detailed field investigation establishes its correctness and shows that it has general application. The problems connected with it involve distinctions between intrusive and extrusive greenstones and the determination of relationships between greenstones and sedimentary beds that are not yet fully understood. Solution of these problems is essential to a correct interpretation of the stratigraphy.

KNIGHT ISLAND

Most of Knight Island, except a small area at the south end that extends from Snug Harbor to Point Helen, is made up of greenstone that is in part intrusive and in part extrusive. The greenstone, however, includes a small proportion of interbedded slate and graywacke, which is so inconspicuous in places as to be easily overlooked.

Much the greater part of the greenstone of Knight Island shows ellipsoidal or pillow structure (see figs. 61, 62) and is therefore believed to be congealed lava that was poured out on the sea bottom. Pillow structure appears to be the most reliable and widely available criterion for field use in distinguishing the extrusive from the intrusive lavas, for the contact effects of intrusions are less frequently seen. In the absence of both pillow structure and contact effects, the two forms of lava may be difficult to distinguish in the outcrop. It seems beyond question that the extrusion of lavas in the sea did not interrupt the deposition of sediments more than temporarily, for fine mud and coarser material filled the space between pillows and built up the beds of shale and sand that separate some of the successive flows of lava.

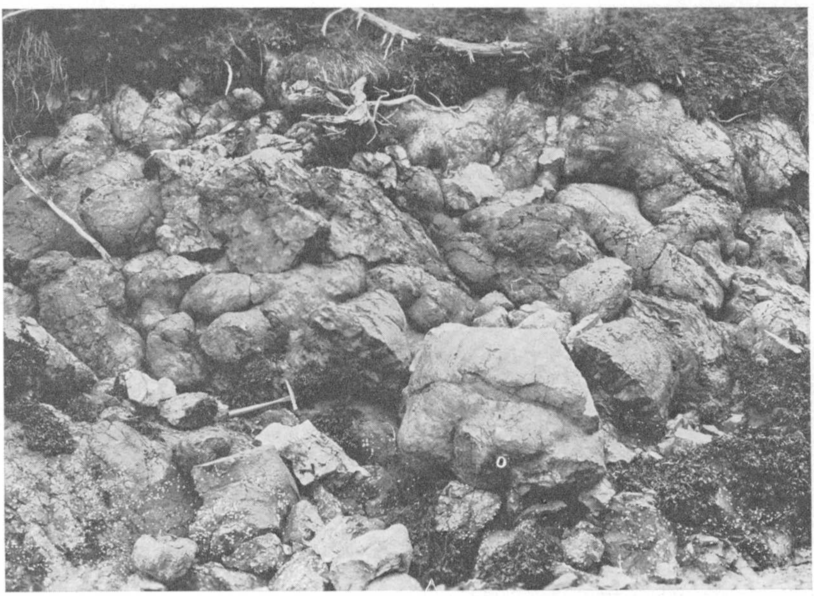

FIGURE 61.—Pillow lavas in Lower Herring Bay, Knight Island. This view shows the appearance of the upper surface of the lava flow and the loaflike form of the pillows.

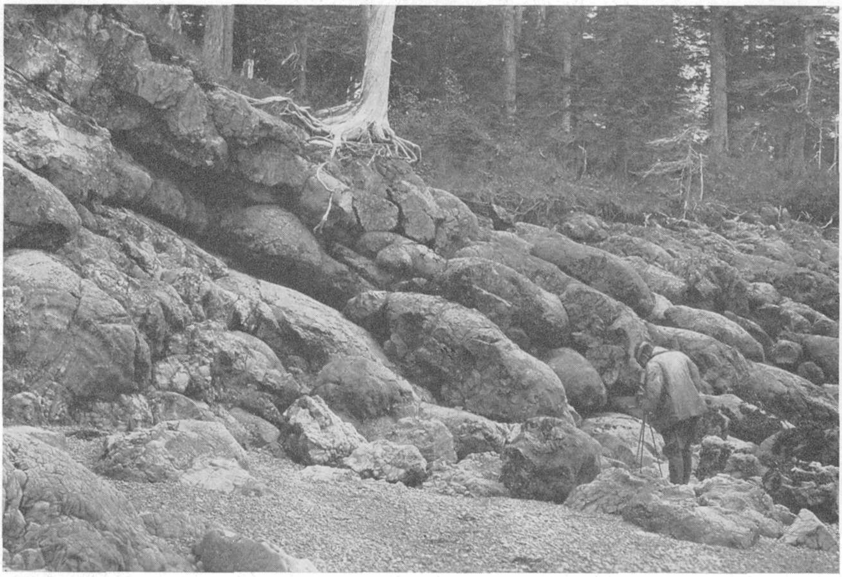

FIGURE 62.—Pillow lavas on the northwest shore of Ingot Island. This view shows the bedded nature of the flows and the form of the pillows as seen along the strike.

Part of the greenstone was melted rock that broke through previously solidified flows and reached the surface. Another part was intruded into the older flows and the sedimentary beds. Intrusive greenstones are believed to be more abundant in the southern part of the island than in the northern part and more widely distributed in the sedimentary rocks of neighboring islands than in the surface flows of Knight Island.

The sedimentary rocks of the south end of Knight Island include slate and graywacke chiefly. Black slate occupies a small area of less than one and one-half square miles south of the entrance to Snug Harbor. West of the black slate, extending from Snug Harbor to Point Helen and including Hogan Bay, is a belt of rocks that is dominantly graywacke but includes a little greenstone. Still farther west, between Point Helen and Mummy Bay, is an area of rocks that includes slate, argillite, graywacke, and a few small outcrops of conglomerate. These three units belong to the three lowest formations of the section of Valdez rocks proposed by Johnson (see p. 66).

The black slate is not known to have any equivalent on Latouche Island or elsewhere. The graywacke unit differs from that of Latouche Island in that it includes small isolated bodies of greenstone. The structure of the beds is more complicated than that of Latouche Island, and any correlation of beds that is made at present is based on lithologic similarities.

EVANS AND NEIGHBORING ISLANDS

The larger islands between Latouche Passage and the mainland of Kenai Peninsula, including Evans, Elrington, and Bainbridge, are geologically much alike. The rocks exposed there include greenstone, black slate, graywacke, and conglomerate, which are named in the order of their abundance, with greenstone heading the group and probably covering more area than all the sedimentary beds combined. Greenstone occupies approximately half the area of Evans Island and probably makes up four-fifths or more of Elrington Island. The western side of Bainbridge Island is massive graywacke interbedded with slate and is without greenstone. The exposures of conglomerate are relatively small but are widely distributed.

The greenstone appears in both extrusive and intrusive form (see fig. 63). Pillow lavas are abundant on the shores of Farm Bay and Shelter Bay at the north end of Evans Island. They are also well exposed at the north end of Bainbridge Island and with little doubt will be found in other places. Lavas having flow structure and including fragments of slate crop out at the south end of Elrington Island but are without pillow structure. Notwithstanding the common occurrence of surface flows, many small bodies of greenstone show by their form and distribution in the black slate that they were intruded into the slate rather than poured out on it or faulted into it. Further evidence of the intrusive nature of part of the greenstone is

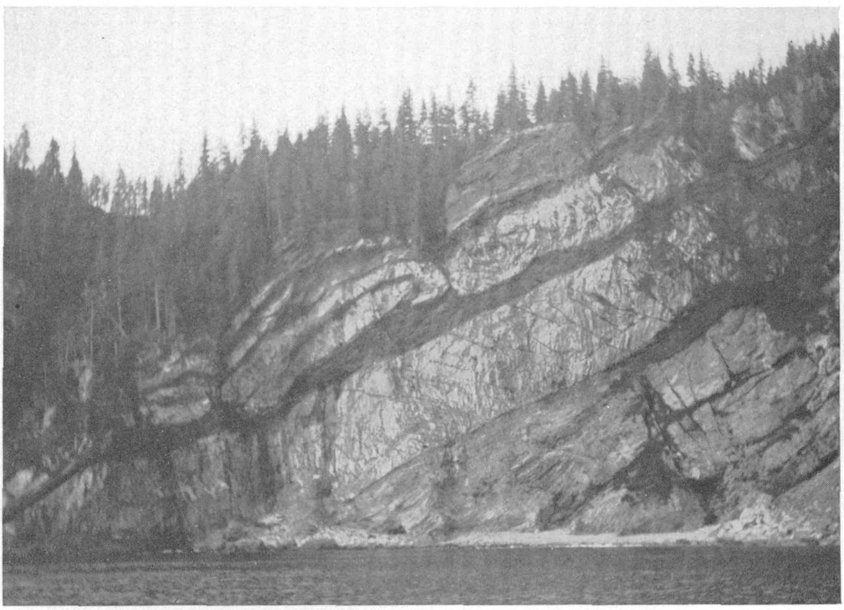

FIGURE 63.—Slate and graywacke, intruded by dikes and sills of diabase (greenstone), on the south side of Elrington Island. Photograph by Paige.

furnished by outcrops on the west side of Farm Bay where apophyses of the igneous rock extend into the slate and graywacke.

Black slate is the dominant type of sedimentary rock in the north half of Evans Island but is accompanied by graywacke, conglomerate, and chert. Three small areas of rocks containing an exceptional proportion of graywacke were regarded by Johnson as belonging to the upper graywacke formation of his section. They lie east of the entrance to Farm Bay, at the head of Shelter Bay, and east of Crab Bay.

Conglomerate resembling that of Latouche Island is exposed near Bishop Rock in the extreme eastern part of the island and at intervals along the shore to the southwest. Similar beds crop out north of the summit of the mountain between Bishop Rock and the head of Shelter Bay.

The conglomerate consists of pebbles ranging upward to 1½ inches in diameter in a groundmass of gray sandstone, but it includes 4- to 6-inch cobbles and even a 1-foot boulder. The pebbles are largely igneous rocks—both coarse- and fine-grained—associated with much quartz, quartzite, and some slate and chert. One of the sandstone beds includes fragments of slate as much as 10 inches long. Near Observation Island a conglomerate bed crops out in a northerly-pitching anticline. A parallel anticline near Bishop Rock gave the following section:

	Feet
Slate and graywacke, interbedded, dipping 65° to 70° N.	
Conglomerate and sand beds	100?
Slate and graywacke	200
Conglomerate (3 beds), interstratified with graywacke	35
Slate and graywacke	250
Axis of anticline.	

Conglomerate occurs at several localities along the shore to the southwest. At least 50 feet of conglomerate including some graywacke and black slate crops out on the south side of a little bay 2 miles from Bishop Rock. The beds strike N. 15° E., dip 45° W., and are overlain by sandstone or hard graywacke, on which rests 10 feet more of conglomerate. Then follow small beds of conglomerate interstratified with slate and graywacke.

The conglomerate on the mountain top 1½ miles west-northwest of Bishop Rock is not so well exposed. It resembles that at the beach and contains pebbles of quartz, dark banded quartzose rocks, granite, and fine-grained light-colored igneous rocks. Cobbles as large as 6 inches in diameter were seen. The bed strikes north and stands vertically.

A bed of conglomerate approximately 75 feet thick is exposed on the shore of Elrington Island near the southwest end of Elrington Passage. It strikes east and dips from 35° to 60° N., forming a belt 100 feet wide and one-half mile long. It overlies black slate and is overlain by slate and graywacke. The conglomerate consists of rounded pebbles that average less than 2 inches in diameter but reach 5 inches. They include a variety of igneous rocks, quartz, quartzite, and a little slate. At one place the graywacke overlying the conglomerate includes a bed of slate conglomerate or breccia 10 to 15 feet thick that contains angular fragments of slate up to 10 inches long.

Johnson (1917, p. 199) reported the finding of greenstone pebbles in a conglomerate bed on Hogg Bay and inferred from them that the conglomerate and associated sedimentary beds of the west side of Bainbridge Island are younger than the sedimentary beds and associated greenstones of the east side and overlie them. He did not, however, consider the evidence as conclusive.

These scattered conglomerate beds, not including that of Hogg Bay, have points of resemblance that suggest correlations among themselves and with the conglomerate of Latouche Island. Some units of the group may be stratigraphically equivalent, yet there is no evidence at hand by which to correlate them with certainty. Conglomerates have interest beyond that of most of the sedimentary beds associated with them because, in the absence of more distinctive and reliable horizon markers, they may aid in solving structural and related problems and especially because they supplied the principal reason for assuming an unconformity between the Valdez and Orca groups. The early geologists looked on the conglomerates of Ellamar as basal units of the Orca group which were deposited on the truncated beds of the Valdez group when they were submerged.

Among the less common rocks of Evans Island are cherts, which have been found in only a few places but may be more widely distributed. The black slate near the southwest corner of the head of Shelter Bay includes a bed of chert from 15 to 20 feet thick. The chert conforms with the bedding of the slates, which strike N. 15° W. and dip 50° W., and shows an indistinct banding parallel to the bedding. It weathers white and has a conchoidal fracture, which is more noticeable in the lower part of the bed. The contact with the underlying slate is a fault contact that strikes N. 30° W. and dips 50° W.

At two places on the shore of Shelter Bay northeast of the locality just described and less than one-half mile from it, a bed of chert overlies masses of greenstone included in black slate. The contact of the chert and greenstone at one outcrop strikes N. 30° W. and dips 60° W. Other outcrops of chert appear in the valley of the little creek coming down from the southeast. The association of chert with the greenstone suggests the possible silicification of slate beds by the intrusion of igneous rocks. The underlying beds, however, were not seen to be affected in this manner.

BAINBRIDGE ISLAND

Bainbridge Island is adjacent to the eastern shore of Kenai Peninsula and shares in the geologic character of the mainland on the west and the islands on the east. A line from Hogg Bay to the head of the long narrow bay of the north part of the island divides the rocks into two groups. On the east are slates, graywackes, and greenstones like those of Evans and Elrington Islands. On the west are thick beds of graywacke with interstratified slate in subordinate amount. The rocks of western Bainbridge Island are assigned to the Valdez group, although a definite boundary delimiting them has not been established.

The long, club-shaped peninsula forming the north end of the island is made up of slate, some graywacke, and interbedded greenstone. These rocks extend southwest along Prince of Wales Passage, and appear also on Flemming Island. The sedimentary beds are dominantly slate that locally cleaves into paper-thin leaves. Weathering emphasizes the prominence of the graywacke, for the beds commonly stand out in relief owing to their superior resistance. Pillow structure is distinctly shown by the greenstone at many localities but is absent in others. Alternating beds of slate and greenstone from 10 to 20 feet thick are exposed on the west side of nearby Flemming Island. The greenstone shows indistinct traces of pillow structure too poor to be identified with certainty, yet it appears to be extrusive rather than intrusive.

The trend of the folded sedimentary beds and the interstratified greenstones of northern Bainbridge Island is east-northeast, but many strikes to the north and north-northwest were noted. Westerly dips are prevalent, for the bedded rocks are closely compressed and overturned to the east. The strike of the cleavage, likewise, is variable, ranging from N. 40° W. to N. 10° E. at localities where observations were made. The dip of the cleavage is less changeable and commonly is about 60° W. Folding of the beds was accompanied by faulting, which brought about many abnormal positions of the sedimentary rocks and the greenstone bodies. Faulting probably controlled the courses followed by the invading lavas and was itself influenced by the intruded bodies and the surface flows.

CHENEGA ISLAND

Slate and graywacke are the dominant rocks of Chenega Island. The slate is bluish-black or gray and in places is banded. The graywacke is notably more thick bedded than the graywacke of Latouche and Knight Islands. In some places the slate is almost schistose, and the thinner beds of graywacke are drawn out into lenticular bodies. In the eastern part of the island the slate and graywacke are interbedded with greenstone and coarse tuff or breccia. The greenstone crops out on the east shore in flows that are separated by beds of slate, and also appear less extensively on the shores of the bay at the north end. In some of the greenstone the pillow structure is indistinct or absent, but in many exposures it is well developed. At one of the localities visited, fragments of slate are included in the greenstone.

The slate and graywacke are closely folded and overturned to the east. Although the greenstone interbedded with the slate and graywacke is folded with them and in places dips as much as 60°, no exposures were found where the greenstone and sedimentary beds had been compressed into close parallel folds.

Chenega Island is adjacent to an area of intrusive granitic rocks and shows the effects of intrusion in local metamorphic changes and in structure. Strikes ranging from northeast to west were seen, but the prevailing strike ranges from north-northwest to north-northeast, and the dips are commonly high to the west. This island, like Bainbridge Island, seems to consist of rocks of the Valdez and Orca groups.

AGE OF THE SEDIMENTARY ROCKS

The age of the sedimentary rocks of Prince William Sound—the Valdez and Orca groups—has long been a subject of speculation. The early geologists, in the absence of diagnostic fossils and in view of the degree of metamorphism of certain of the rocks, were inclined to assign to them Paleozoic rather than Mesozoic age (Mendenhall, 1900, p. 307), although Schrader (1900, p. 407, 409; Schrader and Spencer, 1901, p. 36, 39) first suggested that the Orca group is Late Cretaceous or early Tertiary.

Grant and Higgins (1910, p. 24, 33) concluded that the evidence available to them indicated Paleozoic age for the Valdez group and Mesozoic age (probably Early Jurassic) for at least part of the Orca group.

Later investigators with a few more fossils and somewhat wider knowledge of the rocks to support their belief, look on both groups as younger than Paleozoic and assign to them probable late Mesozoic age with a remote possibility that they include older rocks.

Carbonized remains of plants and other evidences of life, such as worm borings, the trails of sea animals, and a few imperfect shells have been found in widely separated parts of the area and encourage the hope that full proof for the age of the rocks will eventually be discovered. A common and widely distributed evidence of former animal life is the worm boring known as *Terebellina palachei* Ulrich. This worm tube is not diagnostic of age but is believed to have value for correlating beds. The presence of *Terebellina* in all parts of the sound—in rocks that have been assigned to the Orca group as well as in rocks of the Valdez group—seems to indicate that the two groups differ little in age. This supposition is also supported in some degree by the distribution of the plant remains, although usually these are distorted and poorly preserved and rarely are worthy of collection and identification.

The slates and graywackes of the Valdez and Orca groups are similar in their general character to certain rocks of the Controller Bay and Yakutat Bay districts east of Prince William Sound and of the Kenai and Kodiak districts to the southwest. Ulrich (1904, p. 132) grouped together the rocks of all these districts, in which he found *Terebellina* and a few other fossils, naming them the "Yakutat series", and regarded them as probably of early Jurassic age. Reeside and Imlay in a communication concerning fossils collected by the author in Prince William Sound in 1923, write of them:

> The fossils in the nine lots contained in this collection are all, so far as they can be determined, identical with species described by Ulrich from the Yakutat formation. Ulrich regarded the age as Liassic, but the species described by Ulrich as *Inoceramya concentrica* is a Late Cretaceous type of *Inoceramus* characterized by bearing radial markings. The occurrences, also, in the beds of a rather modernized type of crinoid (Johnson, 1917, p. 198) and an echinoid of late type (collected by R. S. Tarr in 1906) suggested a similar age.

Geologists who have studied the rocks of the Valdez group in the north part of Prince William Sound and the "Sunrise series" of Portage Bay and Turnagain Arm agree that the two units are to be correlated, at least in part. Evidence bearing on the age of the rocks of Turnagain Arm therefore may throw some light on the age of the Valdez rocks.

In 1911, B. L. Johnson collected fossils from beds of the "Sunrise series" near the head of Crow and Raven Creeks north of Turnagain Arm. They consisted entirely of imprints of a small *Inoceramus* which T. W. Stanton suggested to be possibly identical with the Yakutat fossil described by Ulrich as *Inoceramya concentrica.* Again in 1915, Johnson collected an *Inoceramus* sp. from float in a moraine on the east side of Valdez Glacier, which he believed to have come from the mountains of the middle and upper reaches of the glacier. Several years later, in 1931, Park (1933, p. 393–394) collected fragments and imprints of *Inoceramus* from the "Sunrise group" in six localities scattered throughout the Girdwood district, which includes the Crow Creek locality of Johnson. These fossils were reported by Reeside and Imlay to be identical with species in the lower part of the Cody shale of the western interior region and to represent, therefore, the middle of the Late Cretaceous.

Park's conclusion from the paleontologic and field evidence was that the rocks are of Late Cretaceous age, but their nature and stratigraphic relations indicate that they are not the youngest of the Upper Cretaceous sedimentary beds of the Girdwood district.

Fossils were found at only 49 localities in the Prince William Sound area. This scarcity strongly suggests a poverty of invertebrate life. Not only was the number comparatively small but the paucity of species is even more notable. Most of the fossils collected consist of fragmentary remains of plants or of the wormlike organism, *Terebellina.* Similar remains were observed in many other localities where it is not possible to collect. None of the fossils is indicative of a Paleozoic age.

The rocks of the Valdez and Orca groups were originally separated on the basis of degree of metamorphism (see p. 237): the Valdez rocks—more altered than those of the Orca group—were held to be the older. This difference, nowhere strongly marked, is not clear in some exposures and is locally exceeded by differences within the Orca group itself. Yet the Orca group as a whole appears to be less metamorphosed than the Valdez group. Differences in composition and structure also exist between the groups (see p. 248), and greenstones are held to be characteristic of the Orca group. These conditions in the aggregate appeared to justify the separation of the two groups. Other conditions suggest a different conclusion and should be considered.

The fossil evidence regarding the age of the sedimentary rocks of the Prince William Sound region, although scanty and applied to an extensive area, suggests correlation rather than separation of the groups and casts doubt on the adequacy of the reasons offered for suggesting that they are two distinct groups. Furthermore, it brings in question the assumed structural relation of the groups, for the Orca was originally thought to be not only younger than the Valdez group but to lie unconformably on it.

The only definite boundary lines that can be drawn between the sedimentary rocks of the two groups are fault contacts rather than surfaces of deposition. Except the greenstone lava flows and related intrusives, and the conglomerates of the Ellamar district, there is no agreement about the rocks included in the Orca group. It may be said that the stratigraphic order of the two groups and their relative age is questionable. The fossils, although inadequate to offer assistance in solving the stratigraphic problem, indicate with some certainty that part of the rocks assigned to the Valdez group, in the mountains north of Prince William Sound, are not older than Late Cretaceous. Further, it may be said that if the fossil *Terebellina palachei* Ulrich has value for correlation, and if the original determination of the plant remains collected by Schrader (1900, p. 406) on Hawkins Island was correct, then many or all of the sedimentary rocks exposed in the islands and on the mainland of the southeastern part of the Prince William Sound area, including the type locality of the Orca group, are also probably of Late Cretaceous age.

IGNEOUS ROCKS

The igneous rocks of Prince William Sound can be more clearly understood if their classification as intrusive and extrusive rocks is modified with reference to other characteristics, particularly association and composition. The intrusives include coarse-grained granitic rocks of a dominantly acidic nature, and dark basaltic and diabasic intrusives so interrelated to associated extrusive rocks that they will be described with them. The basaltic intrusives and extrusives are metamorphosed in varying degree and have taken on a green color, which led early writers and prospectors to describe them as greenstones. This name is commonly used in the Prince William Sound region and is used in this report.

GREENSTONE

CHARACTER AND DISTRIBUTION

The rocks that are here designated greenstone consist principally of altered lava flows ranging from dense basalt to rather massive diabase of distinctly coarser texture than the basalt. They also include intrusive rocks of the same petrographic nature as the surface flows, beds of agglomerate consisting of angular fragments of lava in a matrix of lava, and beds of tuffaceous material (see fig. 64). A

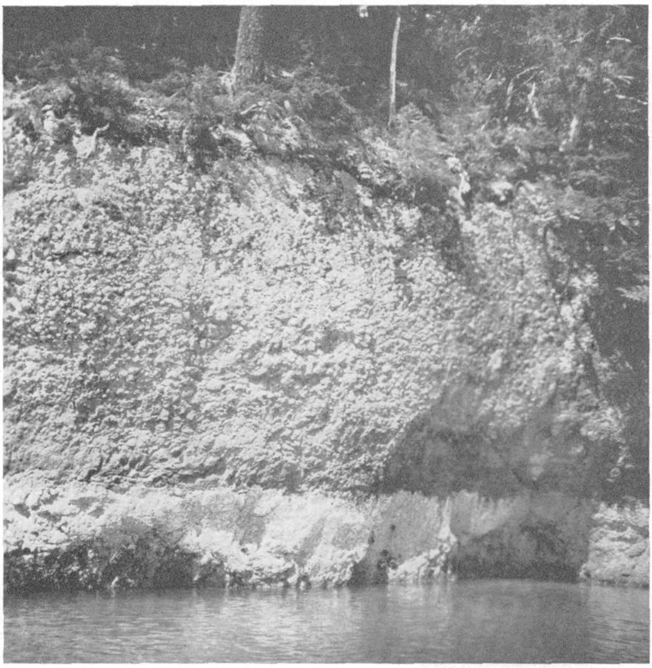

FIGURE 64.—Volcanic tuff near the entrance to the small bay north of Galena Bay. The lower band of white does not indicate bedding. Photograph by Paige.

characteristic feature of the surface flows is their ellipsoidal or "pillow" structure (see figs. 61, 62) which appears in nearly all localities in the Prince William Sound region where the greenstones are exposed, in many places developed to an extraordinary degree.

The lava flows were poured out on the sea bottom, where deposition of sediments was in progress, and are commonly interstratified with beds of shale, graywacke, and less often of conglomerate. Eruption of the lavas was intermittent and must have gone on for an extended time as is shown by the interbedded sediments, which are numerous and in places include individual beds that reach a thickness of 300 feet or more. Although the greenstone is somewhat irregular and widely distributed, it makes up only a small proportion of the rocks of Prince William Sound.

The largest area of greenstone (see pl. 8) appears in a group of islands that includes Knight, Elrington, Evans, and Bainbridge. This area, not excluding its numerous bays and waterways, has a length of 52 miles between Point Elinor and Point Elrington, and a maximum width of 12 miles between Latouche Passage and the Bainbridge Passage. The islands are not made up exclusively of greenstone, for all, the southern islands in particular, include a large proportion of sedimentary deposits.

The largest area of greenstone, next to that of the Knight Island district, is in the vicinity of Ellamar. It is smaller than the area of Knight Island alone but may be continuous on the sea bottom with an area of greenstone on the west side of Valdez Arm and thus be larger than appears on the geologic map.

Other areas of greenstone are Glacier Island, an area in the valley of Jack Bay, one at the head of Solomon Gulch, and an area near Cordova. All of them are considerably smaller than that of the Ellamar district and seem to have no immediate connection with it.

When considered by themselves these different areas of greenstone appear to be independent of one another, but their arrangement as seen on the geologic map suggests an alinement of the Knight Island-Glacier Island-Valdez Arm areas that probably arises from some structural cause. What part the greenstone of Ellamar and Cordova may have in this arrangement is not apparent. Grant and Higgins thought of the greenstones as occurring in the lower part of the Orca group and overlying the rocks of the Valdez group. Under this interpretation they held that the greenstones roughly outline the area assigned to rocks of the Orca group.

According to Grant and Higgins (1910, p. 51) the coarser greenstones show plagioclase feldspars and traces of augite. Commonly they have ophitic structure and so are classed as diabase although coarser types approach the gabbros. Some of the greenstones are finely porphyritic and some are amygdaloidal. A spherulitic structure was noted at Mummy Bay on Knight Island. In the more altered forms the original augite is changed to hornblende, and in places chlorite has developed. Capps and Johnson (1915, p. 28) described serpentines and amphibole schist as resulting from the alteration of the lava flows in the Ellamar district. At Ellamar and on Knight Island the greenstones are associated in a few places with irregularly shaped bodies of chert.

The greenstones owe their color to chemical and mineralogical changes that probably took place when they were deeply buried and subjected to heat and pressure during the folding of the rocks of the Chugach Mountains. Alteration of the original flows and intrusives went so far in places that they became schistose or subschistose.

By far the greater portion of the greenstones appears to be surface flows locally interstratified with sedimentary beds that for the most part are slate but not uncommonly are graywacke or even coarser clastic materials. The earlier flows and the included sediments are cut by dikes and sills of basalt and diabase, feeders for the surface lavas and probably for intrusive masses also. In the outcrop it is locally difficult or impossible to distinguish between the flows and intrusives without seeing the contacts or identifying the pillow structure.

The pillow structure is commonly considered by geologists to indicate the extrusion of surface lavas into the sea. In many places the pillow structure is exceptionally well developed and may be seen either on the upper surfaces of the flows or in cross sections of them (see figs. 61, 62). Pillow structure is particularly well shown on beaches where the lavas are exposed between high and low tides, for in such places the soil and vegetation are absent and the material between the pillows is eroded out, leaving the pillows standing in strong relief. The eroded material was slate or graywacke formed from the mud and sand that were deposited on the surface of the lava during the interval of time between the eruptions of successive flows.

The pillows commonly have the form of large somewhat flattened rounded masses and range in diameter from less than a foot to 10 feet. They also occur as elongated or branching bodies of irregular form (see fig. 61). Some of the pillows have a dense outer zone one inch or more thick which represents the quickly cooled surface. Many of them also show a radial structure in the outer zones that is due to stretched gas cavities arranged perpendicularly to the outer crust. The pillow structure is so commonly present in the greenstones of Knight Island that there are relatively few places where it can not be seen, although it may be indistinct. In many places it is the most striking feature of the lavas.

The thickness of the flows assigned to the greenstone and shown as a formation on the map varies from place to place and depends not only on the quantity of lava that was erupted or intruded but also on the number and thickness of the interstratified sedimentary beds, for the two have not been generally separated. Capps and Johnson (1915, p. 46) estimated the thickness of the greenstone and interbedded sediments near Ellamar as several thousand feet. It is safe to say that the same estimate applies to the greenstones of Knight Island where these rocks probably have their greatest thickness within the Prince William Sound area.

The surface lava flows, which are believed to include the greater part of the greenstones, are contemporaneous with the interbedded sediments and therefore (see p. 275) are considered to be of Late Cretaceous age. As the intrusive greenstones are probably part of the same magma as the surface flows they are looked on as of corresponding age.

GRANITIC INTRUSIVE ROCKS

CHARACTER AND DISTRIBUTION

The granitic intrusive rocks occur as batholiths or large, irregularly shaped bodies of coarsely granular light-colored granite (see fig. 65), and as dikes and sills that are variants of the granite or are closely related to it. The dikes and sills presumably are apophyses of large deep-seated intrusive masses, some of which have been exposed by erosion and some of which are still buried. For the most part the material of the dikes and sills, like that of the batholiths, is light-colored and of medium- to coarse-grained texture, but in places it is basic and dark.

The batholithic bodies occur in several isolated areas, all but one of which are in the western part of the sound. They are distributed as follows: between Port Gravina and Sheep Bay, at Cedar Bay, Esther Island, Passage Canal, Culross Island, Port Nellie Juan, and Eshamy Bay.

The dikes and sills are more common in the north and west parts of the sound than in the southern part and are especially notable in some areas of slate and graywacke belonging to the Valdez group. Dikes cut the larger granitic intrusive bodies as well as the sedimentary beds but in such places may represent only a late phase of the general intrusion.

Grant and Higgins (1910, p. 33–52) described the petrographic character of the igneous rocks of Prince William Sound in considerable detail. Their descriptions will not be repeated as the granitic rocks are not unusual and for the most part may be sufficiently identified as biotite granite. The most common minerals of the granite are quartz, orthoclase feldspar, plagioclase feldspar, biotite, and variable but usually small amounts of hornblende. The usual accessory min-

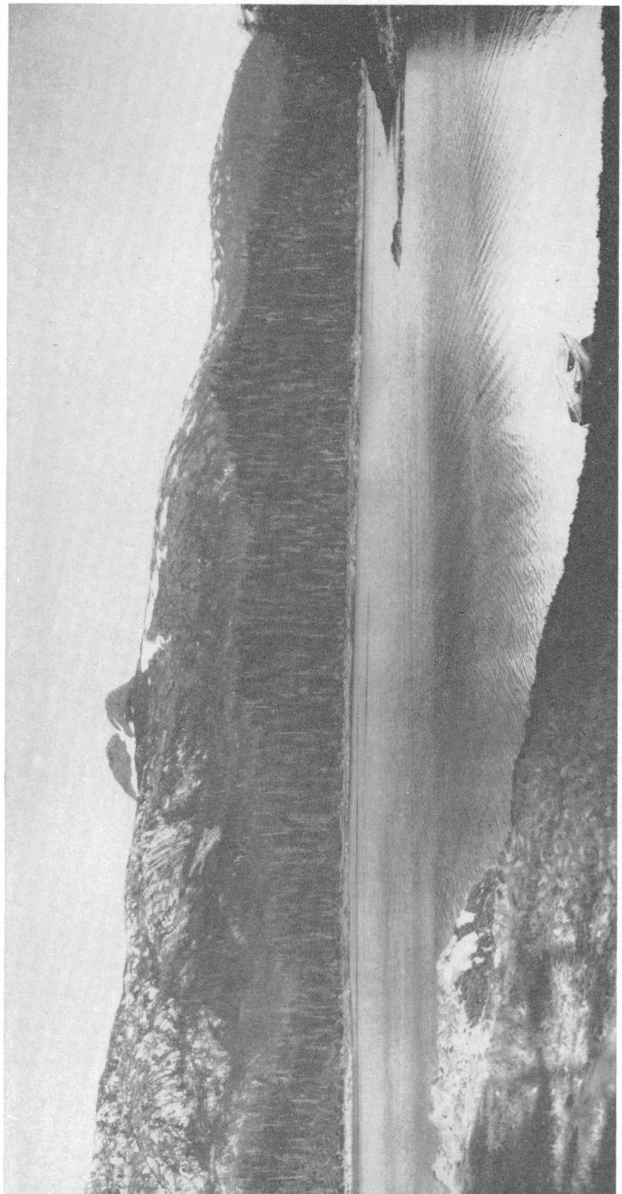

FIGURE 65.—Severe low-altitude glaciation in the granite ridge between Paddy and Ewan Bays. Overripe spruce timber in the foreground.

erals are magnetite, apatite, zircon, and sphene. Some of the granite is slightly porphyritic, showing phenocrysts of feldspar.

Although the biotite granite of the batholiths and the related rock of the dikes and sills are believed to represent the same or similar original magmas they show differences of composition and appearance. The granite of the batholiths differs in coarseness of grain but has a fairly uniform composition. The dikes and sills, however, show more variation and range from aplite to diorite, probably in consequence of changing proportions of the constituents of the parent magma as the intrusion progressed. Dikes of quartz porphyry are known in two places one in Unakwik Inlet and one in the nunatak of Columbia Glacier. A few occurrences of still more basic granitic-textured rocks are known. Grant and Higgins (1910, p. 20) noted gabbro in two localities, one at the north end of Latouche Island and one on Esther Island. A basic dike, lamphrophyre, was discovered in the underground workings of the copper mines at Latouche (Bateman, 1924, p. 346). Doubtless other basic dikes have escaped notice.

The granite of Sheep Bay is coarser than that of other parts of the sound and plainly shows feldspar, quartz, and biotite to the unaided eye. Its intrusion had a marked effect on the invaded slates and graywackes, which are crushed and silicified. In places a multitude of fine, parallel veinlets of quartz was introduced. The host rocks here are in the type locality of the original Orca group.

In the western part of the sound two types of coarse-grained granitic rock are common—a dark-gray rock with much biotite mica, and a light-gray rock that weathers white and shows much quartz and little mica. The lighter rock, or aplite, cuts the dark granite and therefore is younger, although the difference of age is probably only the difference in time between phases of one general intrusion.

In the vicinity of Eshamy Bay and Granite Bay the instrusives invaded the slates and graywackes and mingled with them in a most intricate way. The graywacke in places seems saturated with the granite rock and resembles gneiss. Elsewhere blocks of the sedimentary beds were caught up and inclosed in the granite. The contrasting colors or shades of the weathered rocks produce an interesting and complicated pattern on exposed surfaces.

In places, as at Sheep Bay, the batholithic intrusives had a notable effect on the rocks they invaded. This effect appears as recrystallization of material of the host rock, crushing, silicification, and veining with quartz. Schistosity is developed in the host rocks near the intrusive bodies but is not confined to those places. It occurs also where the sedimentary beds have been much disturbed, as in the vicinity of strong faults.

AGE OF THE GRANITIC INTRUSIVE ROCKS

Two groups of instrusive rocks have been described, the greenstone basaltic and diabasic intrusives and the granitic intrusives. The basalt and diabase are believed to be products of the volcanism that yielded the ellipsoidal lava flows. These lava flows are interbedded with sedimentary slates and graywackes, the age of which is not definitely known but appears from the evidence available to be not older than Cretaceous, as Jurassic and older rocks have not been recognized in the Prince William Sound region.

The batholithic bodies and the dikes and sills of granitic rock cut some beds belonging to the Valdez group and others that are classed with the Orca group. Although there is a suggestion that the granitic rocks are of two ages it seems equally possible that the different types of rock relate to separate stages of one period of intrusion. Whether they are of one age or two, the granitic intrusives are younger than the sedimentary host rocks. Thus, they would appear to be Cretaceous or Tertiary and younger than the greenstones.

Locally the granite of Eshamy Bay has an imperfect cleavage, which signifies that after its intrusion it was acted on by some of the same forces that folded and otherwise altered the sedimentary host rocks. It is not known exactly when these changes took place but they were not sudden and doubtless required much time. The imperfect cleavage of the granite is evidence that the building of the Chugach Mountains was a process which continued long after the granite invaded the sedimentary beds.

The intrusion of the granitic rocks is believed to have accompanied the earth disturbances that deformed and altered the bedded rocks of the Chugach Mountains and of the Coast Range generally. Igneous rocks like the granites of Prince William Sound are deep-seated in origin and solidified far below the surface of the land. Their exposure to view is due to the removal of the overlying rocks, which in this region probably was brought about by erosion in Tertiary time, followed by glacial abrasion during the Pleistocene epoch.

Events that are suggestive and may give additional weight to the evidence for the age of the granitic rocks in the Prince William Sound region are known from other parts of Alaska where rocks of possibly equivalent age have been studied. The most outstanding invasion of granitic rocks known in Alaska is that of the great Coast Range batholith, which is believed to have begun in Jurassic or Early Cretaceous time. There were, however, later intrusions such as that which took place in southeastern Alaska (Smith, 1939, p. 13) in Tertiary time and in the Alaska Range (Capps, 1940, p. 130) probably at the end of the Mesozoic era and in the early Tertiary. These widely separated occurrences have no established relationship with the intrusion of granitic rocks on Prince William Sound but their timing suggests the possibility that they represent one protracted period of mountain building and volcanism, which began in Mesozoic time and continued into the Cenozoic. The available evidence seems to place the intrusion of the Prince William Sound granitic rocks in the late rather than the early part of this period of mountain building.

UNCONSOLIDATED DEPOSITS

CHARACTER AND DISTRIBUTION

The unconsolidated deposits of Prince William Sound include gravel, sand, and silt laid down in streams and lakes, beach deposits, and glacial deposits. These deposits are not wholly distinct. They merge into one another to a considerable extent. Glacial deposits that are reworked by streams become stream deposits, and the beach deposits consist in part of material contributed by streams and glaciers. None of the three classes of deposits presents unusual features within this area.

STREAM DEPOSITS

Probably most, if not all of the preglacial stream deposits were swept from the valleys by the advancing glacial ice, so that the present stream and lake deposits were formed during and after glaciation. Most of the more extensive stream deposits are outwash gravels laid down by streams flowing from the existing glaciers. They owe their present position and form to running water more than to glacial ice. All the streams, whether of glacial origin or not, transport some unconsolidated material and deposit it, at least temporarily, in or along their channels, where it appears in the flood-plain gravels or in the low terraces. The largest areas of stream deposits are in valleys at the heads of fiords where present glaciers no longer meet tidewater. Such deposits were formed at the head of Port Valdez and in Lowe River valley (see fig. 45), and at the heads of Port Fidalgo, Orca Bay, and Port Nellie Juan. The streams of all these valleys carry much waste rock, both fine and coarse, and still are building up deposits on the land or in the salt water where they discharge their loads at the heads of the fiords. In places they have built extensive mudflats that are bare at low tide, such as that which lies between the deep water of the bay and the flood-plain gravels of the Valdez Glacier stream and the Lowe River, or in front of Shoup Glacier (see fig. 66).

The stream and lake gravels are less extensive than would be expected if the region were less severely and less recently glaciated. Many valleys were vacated by the ice so recently that large bodies of stream gravel have not yet been formed. In a few places, like Mineral Creek near Valdez, the stream gravel is gold bearing, but the gravel is shallow and the concentration of gold in the gravel has nowhere proved to be enough for extensive mining.

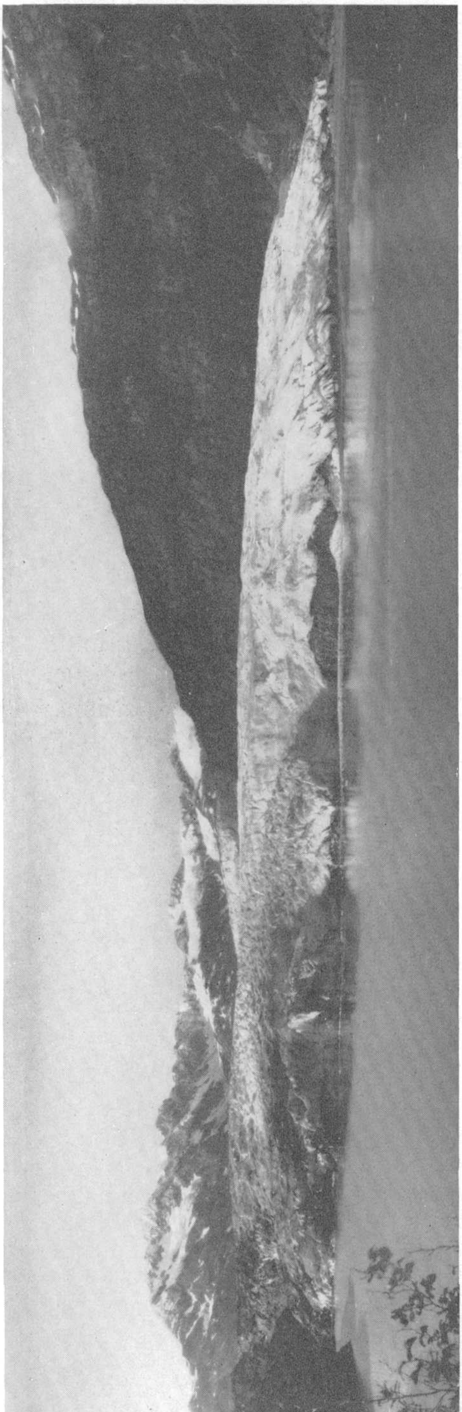

FIGURE 66.—Shoup Glacier from the point on the west shore of Shoup Bay, one-quarter mile north of the mouth of McAllister Creek and slightly more than one-half mile from the front of the ice. Rocks are of the Valdez group; bedrock is exposed at the ice front to the right of center; mudflats show on the right. Photographs by Johnson.

Many of the streams have low gravel terraces bordering their present flood plains, which were formed in the same way that the present flood plains are formed and differ from them in no essential respect except their position. The terraces indicate former flood-plain levels that now appear as terraces because the older deposits are being trenched by the present streams.

High-level bench deposits of gravel appear to be uncommon although high benches cut in the bedrock are frequently seen and are especially noticeable in the mountains about Port Valdez (see fig. 45). These benches are due to erosion by ice and indicate different temporary levels maintained by the glacier that formerly occupied the Port Valdez valley.

Aside from the deposits of sand and gravel on the shores of the existing lakes and ponds, lake deposits are not recognized and evidence of former, more extensive lakes is not known.

BEACH DEPOSITS

The beach deposits consist of sand, gravel, and other rock fragments formed by the action of the waves on the ledges and cliffs of the seashore, or of material brought under the influence of the waves by streams and glaciers. Such material is moved by the currents due to tides and wind just as the material of the fluvial deposits is carried by the currents of the streams. Some of it is transported far from its source and all undergoes rapid abrasion when subjected to the pounding of the waves.

Most of the deposits referred to as beach deposits lie within the present range of the tides. They are not restricted to that range, however, for the work of the ocean currents extends below the level of low tide and some of the old beach deposits are now above high tide.

The beach deposits are not continuous along the coast. They are absent where alongshore currents are strong or deep water comes close to the land. No extensive beach deposits have been formed on the shores of the islands facing the sea. The seaward sides of Hinchinbrook and Montague Islands are exposed to the full force of the winds and waves of the Pacific. The mountains rise steeply from the water's edge and afford no bays or lowland areas. Their south slopes are unexplored, although the outside beach of Montague Island has been traveled on foot between tides.

Inside the sheltering islands that face the ocean, where the force of the waves is less than on the exposed front, deposits of sand and gravel have been built up in protected coves, off points of land, between islands, and in many other places where the waves have heaped them up or the tidal currents have lost their carrying power and deposited their loads in quiet water.

The deposits formed in this way may obstruct navigation or may facilitate it by furnishing shelter. Several of the anchorages used by small boats are protected by natural embankments of sand and gravel built up by the waves. One such anchorage is Constantine Harbor in Port Etches, north of Cape Hinchinbrook. Constantine Harbor is protected from the direct force of the southwest wind and waves of the Pacific Ocean by a bar more than a mile long that rises 20 feet above high tide and connects the southwest end of the onetime island of Nuchek with the shore on the north side of the harbor, thus forming an enclosed area with only one narrow entrance at the east end.

A less-used and little-known anchorage is on the southwest side of Stockdale Harbor on the west side of Montague Island where sand bars connect several islands so as to form an enclosed space and snug harbor for small boats.

MORAINE DEPOSITS

Moraine deposits were left by the retreating ice on the land and in the sea, although they are less noticeable than the unconsolidated waterlaid deposits. A great quantity of rock waste was carried out of Prince William Sound and spread over the continental shelf by the streams of ice that flowed southward during the time of maximum glaciation. The present absence of glacial moraines and other unconsolidated glacial deposits, of sufficient size to account for the mass of material eroded by the ice from the highland and from the submarine floor of the sound, seems to have no other explanation than that the material was carried beyond the sound and deposited on the ocean floor. This manner of disposal is the only one that could have been sufficient if Tarr and Martin (1914, p. 478) are correct in their belief that the sound was formed entirely by glacial erosion (see p. 289).

Typical accumulations of glacial debris of the kind often seen in glaciated areas—terminal and lateral moraines, and bodies of the kame-and-kettle type—are uncommon in the Prince William Sound area. Shallow deposits of till without distinguishing topographic form were left by the ice as it melted. Some till was undoubtedly deposited in the water. Most of the deposits on the land were laid down in valleys at low levels where they are now overgrown by vegetation and are largely hidden from view. They contain a variety of material, some of which is plainly from distant sources, as is easily seen if it came from areas of light-colored crystalline rocks. Thus the granite boulders included in the till exposed on the shores of Hinchinbrook Island were probably derived from the granite batholith of Port Gravina and Sheep Bay. Rocks from all parts of the sound may doubtless be found in the till deposits of the southern islands.

Submarine terminal moraines were built up at various places. An excellent example is the submarine barrier across Unakwik Inlet just above Jonah Bay. This narrow moraine is nearly 2 miles long and has a maximum depth of only 13½ feet of water over it, but it is bordered by 414 feet of water on the south side and over 600 feet of water on the north side. The barrier across the entrance to Shoup Bay in the northwest corner of Port Valdez is another example of the same kind of glacial structure. Extensive areas of shallow water in several parts of the sound may be due to deposits of till, although some shallows probably indicate places where the bedrock is near the surface.

GEOLOGIC HISTORY

The early geologic history of the Prince William Sound region cannot be determined from evidence that has been found locally. Neither sedimentary nor igneous rocks of pre-Paleozoic, Paleozoic, or early Mesozoic age have been identified. Paleozoic and early Mesozoic sedimentary beds exposed in adjacent areas contribute little toward knowledge of the Prince William Sound area. The local record of geologic events thus goes back no further than the deposition of the oldest slate and graywacke beds, presumably the oldest beds of the Valdez group.

Some facts relating to the origin of the slates and graywacke are learned from the composition of the rocks themselves. The nature and the unweathered state of the particles that compose much of the arkose, graywacke, and other clastic deposits indicate that these beds originated from the rapid erosion of a landmass which included a considerable proportion of granular igneous rocks as well as sedimentary beds. The location and extent of this landmass is unknown. Sedimentary deposits older than those of the Prince William Sound region occupy large areas in adjoining regions but their stratigraphic relation to the sedimentary deposits of the sound has not been worked out. Rocks of early Carboniferous age (Moffit, 1933, p. 10–15) make up the north flank of the Chugach Mountains in the Copper River basin. Their structural relation to the rocks of the Valdez group appears to be that of unconformity and implies a great difference in age, possibly representing all the time from the Mississippian epoch to the Cretaceous period.

The waters in which accumulated the muds and sands that later were changed to the present slates and graywackes seem to have been singularly lacking in invertebrate animal life. Plant life was locally abundant and left traces of itself in many places, but the invertebrate animals have been more helpful in suggesting the age of the rocks containing them. Although the collections are small, fossils from widely distributed sedimentary beds in Prince William Sound appear to indicate that all the consolidated sedimentary deposits were laid down in Mesozoic time. Also, it appears from some of the fossils that age limits may be drawn more closely and that a considerable part of the sedimentary beds exposed in the mountains north of the sound are of Late Cretaceous age.

If the assignment is correct it follows that the mountain-making processes that created the Chugach Mountains were active in late Mesozoic or early Tertiary time. They may possibly indicate a place of weakness and disturbance in the earth's crust that existed before the slates and graywackes were deposited, and probably began to act upon these sediments soon after if not during the time of their accumulation. The extrusion of the pillow lavas and tuffs locally interbedded with the slates and graywackes clearly was concurrent with the deposition of the sediments themselves. Injection of the closely related basaltic intrusive rocks appears to be a phase of the same volcanic activity as that to which the surface flows belong, for the rocks of the two classes are lithologically alike and are closely associated in occurrence. Intrusion of the granitic types of rock probably accompanied some of the orogenic movements that produced the mountains and therefore took place in late Mesozoic or Tertiary time. Like the extrusion of the basaltic lavas, the intrusion of the granitic rocks may have been an intermittent process that continued through an extended period of time, as is suggested by an apparent difference in the age of some of the intrusive bodies. The granitic rocks intrude sedimentary beds of both the Valdez and the Orca groups and thus seem to be younger than any of the consolidated sedimentary deposits of the region.

Sedimentary beds of Tertiary age, comparable to the marine sediments associated with the coal-bearing formations of the Katalla district, do not occur in the Prince William Sound area. Their absence may indicate that rocks of this age were not deposited or that they have been removed. In the former case the land probably stood above sea level while the marine Tertiary beds were being deposited nearby, although it is difficult to understand how this section of the Chugach Mountains could have escaped the submergence that took place in the adjacent coastal areas.

Most of Alaska was continuously above the sea during the Tertiary period and underwent prolonged erosion, in consequence of which the highlands were reduced, terrestrial deposits including coal beds were formed in the lowlands, and the landscape generally took on the aspect of maturity. Only on the Pacific shore is there evidence of submergence of the land and the deposition of marine sediments in considerable amount during this period.

Little is known of the Tertiary history of the Prince William Sound region, although it is probable that the mountain-building processes which were in operation during the late Mesozoic continued into the Tertiary and that some intrusion of granitic rocks took place. In common with most of Alaska, this region was subjected to extensive and deep erosion. The great outpouring of the Wrangell lava that took place in the Copper River region during Tertiary and Pleistocene time has no counterpart in the Prince William Sound area.

So far as is known the transition from the Tertiary period to the Quaternary was not signified by any conspicuous event other than the gradual change of climatic conditions that preceded the advent of the glacial ice. During the Pleistocene epoch, however, the established drainage system was temporarily deranged and notable changes were made in the land forms. Abundant evidence of these recent changes appears on every side and some of the processes involved are still active.

The appearance of the Prince William Sound area at the beginning of Pleistocene time, before the advance of the glacial ice began, can only be surmised. Probably streams had dissected the mountain mass and had established an appropriate drainage system, but the general elevation and relief of the land were not as they are today. Tarr and Martin (1914, p. 478) have stated their belief that "* * * there was no preglacial arm of the sea on the present site of Prince William Sound, * * *" but that "* * * glacial erosion has excavated the whole sound on the site of a preglacial lowland, whose rock floor was slightly above the present sea level." It would seem, however, that some earlier causes must have had a part in producing such a distinct physiographic feature and that the sound owes its present form and depth to various factors, including structural characteristics and differential vertical movements of the land as well as glacial sculpture. There can be no doubt, however, that glacial erosion had a profound influence in shaping the land. This is evident from the form of the present valleys and of the submarine floor of the sound. Prince William Sound is unique among the indentations of the Pacific coast of Alaska. Murray (1945, p. 775) says of it: "This sound, having a maximum depth of 479 fathoms or about half a mile, is the deepest depression on the [continental] shelf." It seems evident that some exceptional cause must have been required to produce it.

At the onset of glaciation, snow and ice accumulated in high local snowfields. From its sources in these snowfields, the ice moved to lower levels as mountain valley glaciers that, enlarging and uniting, covered ever larger areas until they filled the intermontane space to a depth of thousands of feet. The areas of accumulation may not have been restricted to the present drainage area of Prince William

Sound. Some glacial ice possibly came from the region on the north, although most of it must have formed from snows that fell within the drainage area of the sound itself.

The glacial ice was not static. It moved from the higher, marginal areas on the east, north, and west toward the central and south part of the sound, and there found passageway to the sea. Streams of ice flowed out between the islands and with little doubt were the cause of channellike depressions in the continental shelf, such as soundings show to extend southwest and south from Hinchinbrook Entrance.

The thickness of the ice varied widely in different localities, depending on the uneven form of the submarine floor and on location within the area. The upper limits of glaciation are indicated by the height of glacial scouring and of deposits laid down by the ice, but these criteria are sometimes hard to find and to interpret. Whatever may have been its upper limits, the ice was deep enough to bury the lower mountains of the islands and most of the area adjacent to the sound. According to Capps (Capps and Johnson, 1915, p. 46) the surface of the ice in the Ellamar district was about 3,000 feet above present sea level. Grant and Higgins (1910, p. 19) found that the ice on Knight Island had extended to about 2,400 feet above the sea. Tarr and Martin (1914, p. 469) give the following figures for the height of recognized glaciation in different parts of the area:

	Feet		*Feet*
Harriman Fiord	4,000	Latouche Island	2,000
Columbia Bay	4,000	Hinchinbrook Entrance	400
Port Valdez	3,200	Orca Inlet	2,300

It appears from these figures that in the Prince William Sound region the maximum height of glacial ice above sea level was lowest near Hinchinbrook Entrance. If the estimate given is correct and 400 feet is added to the deepest sounding east of Zaikof Point, it would appear that the thickness of the ice moving out of Hinchinbrook Entrance was at least 1,690 feet. As Tarr and Martin (1914, p. 476), in a special search for evidence of the thickness of ice at Port Etches, had discovered no glacial deposits above the 400-foot level, they concluded that the surface of the ice sheet was only 400 feet above the present sea level. The topography is such, however, that the present writer believes their estimate to be too low. In either case, Hinchinbrook Entrance was probably the principal outlet for the ice of Prince William Sound. Montague Strait is somewhat shallower than Hinchinbrook Entrance, but the ice stream there was thicker, possibly reaching 2,900 feet.

The present depths of water shown on the Coast Charts of Prince William Sound also indicate that there were two principal channels of escape for the ice—Hinchinbrook Entrance and Montague Strait. In addition, Orca Inlet, and Latouche, Elrington, Prince of Wales, and Bainbridge Passages provided supplementary channels to the sea. Within the area of the sound the largest and deepest channels were those leading from the vicinity of Port Valdez and Columbia Glacier to Hinchinbrook Entrance, and channels on each side of Knight Island, which united off the north end of Latouche Island and discharged their ice principally through Montague Strait. The streams of ice occupying the trunk channels were fed by ice from the surrounding tributary fiords and valleys such as Orca Bay, Port Fidalgo, Valdez Arm, Port Wells, Port Nellie Juan, Icy Bay, and others, some of which are still occupied by glaciers. The channels of most of these tributary streams have the relation of hanging valleys with respect to the channels of the trunk ice streams.

The Coast Survey charts bring out the additional fact that the trunk channels within the sound are much deeper than the outlets to the ocean. Their depths range commonly from 600 to 1,800 feet. The deepest portion of the sound is north of Knight Island where the depth in places is more than 2,400 feet. Yet, not all the deeps are in the trunk channels, for soundings of over 2,400 feet were made in Port Nellie Juan.

Little evidence is at hand to indicate how far the icefront advanced beyond the entrances to the sound and to show its position on the continental shelf outside the sound. Whatever morainal material was carried by the ice was deposited in the sea, but terminal moraines are not visible at the surface and have not been revealed by soundings. It is reported, however, that glacial deposits are exposed on Middleton Island, about 55 miles south-southeast of Cape Hinchinbrook.

Middleton Island is about 7 miles long, 2 miles wide, and rises to a height of 120 feet above sea level. The bedrock consists of steeply dipping sedimentary beds truncated by a nearly horizontal plane of erosion (see Capps, 1933, p. 728–734). On this surface lie unconsolidated deposits which include many large boulders. The nature of these deposits has not been clearly established. The tilted beds are Tertiary deposits. The thick gravel deposits may be of glacial origin, but it will be necessary to determine whether the boulders were deposited as erratics by a moving glacier or whether they were rafted to their present location by floating ice, before they can be accepted as proof that the front of the glacier once extended this far out on the continental shelf.

A notable effect of glacial erosion on the mountains surrounding Prince William Sound and the islands scattered over it is the smoothing and rounding of surfaces that were overridden by the glacial ice (see figs. 43, 44). High peaks that rose above the ice escaped such planation but were exposed to subaerial erosion, especially to the prying of frost and to changes of temperature. During the waning of the ice sheet another form of glacial erosion was active at high altitudes and is still in progress in many places. This is the sapping of the walls of cirque basins by local bodies of ice and is of wide occurrence. High-altitude erosion is a kind of sculpturing that is characterized by angular form, and thus, in the high mountains, rugged tops are commonly associated with smoothly contoured lower slopes. Even more noticeable than the contrast of surface form is the straightening of valley walls that came from the truncation of projecting spurs and the widening of valley floors and gives to the larger valleys their present U-shaped cross sections and smooth lower slopes.

Little consideration has been given in the published accounts of glaciation in Prince William Sound to the possibility of an earlier, pre-Wisconsin period of glaciation. Evidence of such glaciation has not been recognized in the area although it has been found in certain of the mountains of interior Alaska (Capps, 1916, p. 63–67). It seems probable that some of the physiographic problems of Prince William Sound may involve glaciation that is older than that usually recognized. In considering this possibility it is important to remember that some effects of even the more recent glaciation may have been destroyed or in a measure obscured.

Extensive ice fields and numerous valley glaciers still remain in the Prince William Sound area, especially in the mountains of the north and west sides, including some of the best known glaciers of Alaska. Columbia Glacier and many glaciers of the Port Wells district are outstanding in scenic interest. A considerable number discharge bergs directly into the salt water and are a special attraction to tourists because steamers can approach closely, providing excellent near views of the icefront and the floating bergs. Valdez Glacier does not reach the salt water and is less spectacular than Columbia Glacier and the large glaciers of Port Wells, but it was distinguished in earlier days as the only known route from Port Valdez to the Copper River basin. Shoup Glacier (see fig. 66), which is another glacial tributary of Port Valdez, once bore the name Canyon Creek Glacier. It furnished a highway to various lode gold prospects within its drainage area as well as ice for the town of Valdez.

The existing glaciers of Prince William Sound have been described by Grant and Higgins (1913, p. 526) and by Tarr and Martin (1914) who made a special study of them, not only to learn their condition and describe them as they were at the time of visit but to establish reference points and obtain data that will be needed in the future study of their structure and movement.

Many of the valley glaciers give clear evidence of having lately been thicker or longer than they are at present. An excellent example is Chenega Glacier (see fig. 67) which filled Nassau Fiord at so recent

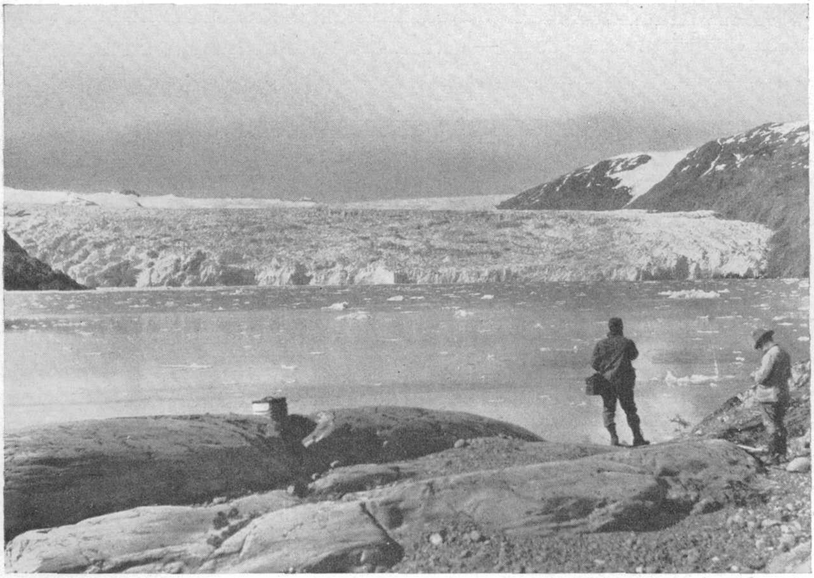

FIGURE 67.—Chenega Glacier from the east side of Nassau Fiord. The view shows westward-dipping beds and glaciated surfaces of the graywacke and slate of the Valdez group; the glacier discharging into the fiord; and the lack of timber, which has not had time to become established since the ice retreated from the bay.

a time that the forest has not yet been established on the glaciated ledges that separate Nassau Fiord from Icy Bay. The present appears to be a time of recession of the ice throughout the sound, but as fluctuation is characteristic of glacier fronts, the recession gives no certain indication of whether the general, longtime movement is an advance or a retreat.

Changes in position of the fronts of existing glaciers or in the thickness of glacial ice are usually gradual and require a number of years to become noticeable. Changes in the relative position of land and sea are still more gradual.

Evidences of a change of level have been seen in Zaikof Bay. Low tide reveals an area about 100 feet square near the shore at the head of the bay where a dozen or more stumps and the spreading roots of trees are standing on the bare sea bottom. The stumps have been riddled by teredos and are almost destroyed, but the roots are interwoven in such a way as to make it improbable that they grew in any other position or locality. It is believed that the submerged stumps indicate a recent change in sea level. This belief is strengthened by the occurrence of dead spruce trees standing with their roots in salt water along the shore of Montague Island about 9 miles northeast of Hanning Bay. The roots are submerged only at high tide, but it does not appear likely that they would have lived and that the trees would have grown to their present size under such conditions. At both of these localities the facts point to a slight subsidence of the land or rise in sea level in recent years—within the lifetime of the standing trees with submerged roots.

MINERAL RESOURCES

INTRODUCTION

As the areal geology and stratigraphic problems of Prince William Sound are the principal subjects of this paper, the mineral resources of the area will not be discussed at length, although a brief statement of the nature of the resources and the manner of their occurrence may be desirable. Practically all the known metallic mineral deposits of proved or prospective commercial value have been visited and described by geologists of the U. S. Geological Survey. Other important contributions to a knowledge of some of the deposits have been made by mining geologists engaged in private work. The references cited have been selected as the more representative of those describing the form and geologic occurrence of the ore bodies. Most of these descriptions were written when mining was most active and do not record later developments, although they give a fair account of the ores themselves and should be helpful in connection with future prospecting and mining operations.

At the outbreak of World War II mining in the Prince William Sound area had already been reduced to the operations of a small number of gold mines and prospects in the north part of the sound. The war put an end to all mining and practically all prospecting, and postwar conditions have so far given little encouragement to their resumption.

The term mineral resources is used here in a restricted way to denote the metals that have been produced commercially and does not include those that are of unproved or doubtful value. The minerals that have been produced commercially up to this time are copper, gold, and silver. Silver has not been mined for itself but is a byproduct of the refining of both gold and copper. It may be conveniently classed with the gold, and thus the lode deposits of Prince William Sound may be described as copper deposits and gold deposits. The separation is not exclusive for the copper ores contain a significant amount of gold and silver in addition to the copper, and the gold ores contain a slight amount of copper as well as gold and silver. Other metals are associated with the copper, gold, and silver but have little or no present commercial importance.

The copper deposits occur in or near areas of greenstone, and although there is a definite association of copper mineralization with the altered lava flows and intrusives, the largest and most productive copper deposits so far discovered were in the slate and graywacke adjacent to areas of the greenstone and not in the greenstone.

The gold lodes occur chiefly in the sedimentary beds of the Valdez group on the north side of the sound. They were introduced by gold- and quartz-bearing solutions that with rare exceptions appear not to have met conditions favorable for the deposition of gold quartz lodes within the areas of greenstone.

The deposition of both copper and gold ores is believed to have taken place in a period of metallization that followed or possibly marked the end of the intrusion of the granitic rocks and therefore was probably in late Mesozoic or Tertiary time. It is not known whether the two types of deposit were formed contemporaneously or whether they were introduced in two stages of mineralization. Some field relations suggest that the gold lodes may be younger.

Johnson (Capps and Johnson, 1915, p. 73–74) has pointed out a similarity of mineral associations in the copper and gold lodes. The lodes, however, differ greatly in the relative abundance of the sulfide minerals. Metallic sulfides make up most of the copper ores but form a small proportion of the valuable minerals of the gold ores, which in general are free-milling gold quartz bodies. Notwithstanding the similarity of mineral associations, the great differences in the proportions of the minerals, especially the much greater proportion of quartz and the smaller proportion of the sulfides in the gold lodes, indicate that differences in composition of the host rocks, depth of cover, character of the solutions, or other influences affected the deposition of the minerals and caused the differences that distinguish the two types of lodes.

Johnson lists the minerals of the following table as primary minerals occurring in the copper and gold ores of the Valdez gold quartz and the Ellamar copper districts. All but the chalmersite (cubanite) and epidote were recognized also among the minerals of the Seward-Sunrise gold-quartz district, which are included in the table.

Primary mineral associations in the Seward-Sunrise gold quartz, Valdez gold quartz, and Ellamar copper districts, Alaska

	Seward-Sunrise gold quartz district	Valdez gold quartz district	Ellamar copper district
Gold	*	*	*
Silver	*	*	*
Arsenopyrite	*	*	*
Chalcopyrite	*	*	*
Galena	*	*	*
Molybdenite	*	----	----
Pyrite	*	*	*
Pyrrhotite	*	*	*
Sphalerite	*	*	*
Stibnite	*	*	----
Chalmersite (Cubanite)	----	----	*
Albite	*	*	---
Calcite	*	*	*
Chlorite	*	*	*
Epidote	----	----	*
Quartz	*	*	*
Sericite	*	*	*

The metalliferous deposits of Prince William Sound do not include such minerals as magnetite, garnet, pyroxene, or tourmaline and others that are classed among the high-temperature minerals. The deposits probably were formed under the influence of igneous intrusive rocks at moderately high temperatures and pressures and at considerable depth. They have been exposed to view or brought near the surface through the erosion of many feet of overlying rock.

COPPER

THE DEPOSITS

The copper deposits of Prince William Sound are sulfide bodies of one general type and are fairly simple in structure, although some of the ore bodies have been disturbed by later faulting. The movement of the mineral-bearing solutions was controlled by the channels available to them, and the ore bodies were formed in or near these channels, especially in places where fracturing of the country rock was pronounced and thus gave freer access to the solutions. Many of the fault zones and some of the mineral deposits are now indicated on the surface by depressions resulting from weathering of material less resistant than the adjoining country rock.

The most abundant sulfide minerals are pyrite, pyrrhotite, and chalcopyrite. These minerals together with other sulfide minerals were deposited along fracture planes or were disseminated through the wall rock, often replacing it completely. The ore bodies are either lenticular or of irregular shape depending on the extent and degree of fracturing, and on whether the solutions followed the fracture planes closely or penetrated irregularly into the wall rock. The disseminated sulfides decrease in quantity with increasing distance from the main channels, so that the size of the ore bodies and the boundaries between ore and waste, limiting mining operations, were often determined by the assay returns in places where a sharp distinction between ore and waste did not exist.

The copper deposits of Prince William Sound show only surficial oxidation. Whatever oxidized zone may have existed at the beginning of Pleistocene time was removed by glacial erosion and has been replaced only in slight degree through oxidation since the ice disappeared.

Johnson (1915, p. 71) defined the primary ore minerals of the Ellamar district as those that were introduced by the ore-bearing solutions or that were developed by the interaction of these solutions with the country rock. His classification, making no distinction between copper and gold ores, may be presented as follows:

Chemical and genetic relationship of minerals in the Ellamar district, Prince William Sound

[After B. L. Johnson]

	Native metals	Oxides	Sulfides	Carbonates	Silicates
Primary	Gold Silver	Quartz	Arsenopyrite Chalcopyrite Galena Pyrite Pyrrhotite Sphalerite Chalmersite (Cubanite)	Calcite	Chlorite Epidote
Secondary [1]	Copper	Limonite	Chalcocite?	Malachite Azurite	

[1] Derived from the primary minerals by oxidation.

Other copper minerals that have been reported as occurring in the Ellamar district or elsewhere in the Prince William Sound region are bornite, chalcocite, cuprite, and gray copper ore, but the identification of several of these is in question. Some of the minerals listed above, particularly quartz, galena, and arsenopyrite, are more commonly present in the gold-quartz lodes than in the copper lodes.

Some evidence of copper has been found throughout the area where greenstone is exposed, either in the greenstone itself or in the adjacent sedimentary rocks. The two principal centers of copper mineralization, however, are in the northeastern and the southwestern parts of the region. The northeastern area includes copper deposits at Ellamar, Landlocked Bay, Port Fidalgo, Galena Bay, and Solomon Gulch. The southwestern area includes Latouche and Knight Islands.

NORTHEASTERN AREA

The copper mine at Ellamar was by far the most productive mine in the northeastern area. It yielded not only copper but important amounts of gold and silver and was a source of pyrite for smelter use. The ore body (Capps and Johnson, 1915, p. 91) was a large lenticular mass of iron and copper sulfides enclosed in the lower slate and graywacke unit of the Orca group. It consisted chiefly of chalcopyrite, pyrrhotite, pyrite, and sphalerite and was made up of two parts—a lens of solid pyrite, forming the hanging wall, and an underlying body made up of parallel lenses of the other sulfides. The two parts were separated by a continuous band of black slate averaging about 2 feet thick.

The steeply pitching sulfide body was exposed on the surface at the beach and was reported to have pinched out at a depth of 530 feet below sea level. It had a maximum horizontal section of ellipsoidal form, 90 feet wide by 240 feet long, at the 200-foot level.

Chalcopyrite was the main source of the copper in the ore. Sphalerite yielded most of the gold and silver, for the other three sulfides contained only a small proportion of gold and silver. Pyrite was the first of the four principal sulfides to form. Sphalerite was the last, which suggests that the gold-bearing lodes of the sound may have been formed slightly later than the copper deposits.

The Ellamar ore body is representative of the copper deposits on northeastern Prince William Sound, although it was much larger than any other known deposit and yielded a greater proportion of gold and silver than the other copper lodes of the district. This body, like that of most of the larger mines and prospects, was deposited in faulted sedimentary beds and had no evident connection with nearby greenstone lavas.

Many other smaller mines and prospects in this part of the sound yielded copper ore that was shipped to the smelter in the course of production or as test samples. Chief among them were the Midas Mine on Solomon Gulch, and operations of the Threeman Mining Company on Landlocked Bay and at the Fidalgo-Alaska Copper Co., the property on Port Fidalgo. The ore from Solomon Gulch and Port Fidalgo was from deposits in faulted sedimentary beds; that from Landlocked Bay was from an area of much faulting where greenstone and sedimentary rocks occur in intimate association. The principal copper mineral in these places was chalcopyrite, though chalcopyrite was supplemented in the Landlocked Bay area by a considerable quantity of chalmersite (cubanite).

SOUTHWESTERN AREA

The ore bodies at Latouche have been the most important of the copper deposits in southwestern Prince William Sound and, though now worked out, were at one time the second largest producers of copper in Alaska. Although separated by many miles from the copper deposits of the northeastern part of the sound, they do not differ from them in essential character. Bateman (1924, p. 338–368) described the deposits at the time when mining was most active. The writer is indebted to him for part of the following facts:

The rocks of Latouche Island are dominantly interbedded graywacke, slate, and argillite, but include conglomerate and a few thin beds of limestone. Several basic dikes cutting the sedimentary beds have been found, but no greenstone is known. The beds are closely folded and overturned to the east. Their prevailing strike is about north-northeast, and their dips commonly range from 60° to 70° W. They were displaced an unknown amount along a fault zone that appears to have practically the same dip and strike as the sedimentary beds and is believed to extend along the west side of the island for nearly its full length. This fault zone is made up of minor faults of varied dip and strike, which furnished channels for the movement of mineral-bearing solutions.

Large bodies of metallic sulfides were deposited in the fractured rocks of this zone at Latouche and at Horseshoe Bay, 2 miles south of Latouche. The ore deposits of Latouche extend along the fault zone for about one-half mile. They have yielded nearly all of the copper that has been mined on the island. The south part of this deposit was originally one of three independently owned mining properties and came to be known as the Beatson mine. It was the principal source of copper at Latouche.

The rocks of the Beatson mine are dominantly graywacke and slate. Two other kinds of rock, however, were of great importance in mining because they were indicators of the high-grade copper ore. They are a greenish schist, and a hard, cherty rock with conchoidal fracture, neither of which conforms to the bedding of the slate and graywacke. Their origin is in doubt, but they apparently resulted from the alteration of an original rock of undetermined character. One of the factors that controlled the location of the ore bodies is the Beatson fault, which separates rocks of the footwall on the east from a mass of black slate on the west. The fault has the same strike as the bedding of the sedimentary rocks and dips westward at almost the same angle. It was the guiding structure that directed the upward movement of the mineral-bearing solutions and turned them away from the overhanging black slate.

The primary ore minerals of the Beatson ore body, as determined by Bateman, are "chalcopyrite, pyrite, pyrrhotite, zincblende, chalmersite (cubanite), galena, quartz, siderite, ankerite, and possibly chlorite. Silver and gold are present in small quantities, but the (mineralogical) forms in which they occur have not been recognized." A few secondary minerals due to a slight surface oxidation are present and include limonite, native copper, covellite, sooty chalcocite, melaconite, and carbonates.

The dominating sulfides are pyrrhotite, pyrite, and chalcopyrite. The pyrite was deposited first but is subordinate in quantity to the pyrrhotite. Chalcopyrite is the important copper-bearing mineral, for the pyrite and pyrrhotite contain little copper. Solid lenses of sulfides were formed along the east side of the Beatson fault and yielded the copper ore of highest grade, but the disseminated sulfides in the sedimentary beds to the east made up the greater part of the ore body. All the rocks, but especially the green schist and the cherty or "flinty" rock, contained disseminated copper. According to Bateman the Beatson ore body had the form of a thick lens with plane surface on the west side next to the fault and irregular knobby surface on the east. It had a maximum length of about 1,000 feet from north to south and a maximum width perpendicular to the

Beatson fault of about 400 feet. Mining operations extended through a vertical distance of about 500 feet.

The sulfide deposits of the Blackbird or Girdwood mine, which is about 2,000 feet north of the Beatson, and that of the Chenega mine, halfway between the Beatson and Girdwood, are practically continuous with the Beatson ore body and are of the same type. All were eventually included in one ownership.

Two large deposits of metallic sulfides containing a little copper were prospected at Horseshoe Bay but were not developed into producing mines. They appear to be in the same fault zone as the Beatson ore body and, although they are about 1,500 feet apart, both have the same strike as the fault zone and are probably closely related in origin and structure. The bedrock is slate and graywacke but includes a thin bed of limestone that was cut in the shaft of the southern or Duke claim. On the surface of this claim the width of the mineralized zone appears to be between 200 and 250 feet. The sulfide lens cut by the underground workings of the Duke claim is 27 feet thick and was exposed for 140 feet along the strike.

The northern or Duchess claim was prospected by cross cuts and drifts at two levels, 100 feet apart. The solid sulfide body was traced along the strike for about 500 feet. It ranges in thickness (Johnson, 1917, p. 208) from less than 1 foot to 122 feet but probably averages between 25 and 30 feet.

The minerals of the deposit are chiefly pyrite and pyrrhotite. Chalcopyrite is present, also a little sphalerite and galena(?). A little quartz accompanies the sulfide minerals.

The copper prospects of Knight Island differ in at least one respect from those of Ellamar and Latouche, for almost all of them are in greenstone rather than in the slate and graywacke. A large number of widely distributed prospects were found on the island. Much money and time were spent in explorations that did not disclose an ore body large enough to sustain a productive mine.

The prospect that has given most promise of yielding copper in practical quantity, and is here used as an example of sulfide deposits in greenstone, is the sulfide body at Rua Cove, on the east side of Knight Island between Marsha Bay and the Bay of Isles. The deposit is on the south slope of a steep mountain that forms the north wall of a small valley opening out into the cove. It has been explored by extensive opencuts and underground openings. The country rock of the valley is greenstone with some interbedded sediments, but the rocks containing the sulfide deposits are igneous. The Rua Cove prospect was recently examined and described by Stefansson and Moxham (1946, p. 85–92). They distinguished and mapped three types of greenstone in the tunnels: (1) a fine-grained greenish rock that is almost black and commonly contains stringers of quartz, (2) a blocky dark-gray porphyritic rock with indistinct pillow structure, and (3) a medium-grained gray-green rock having the composition of quartz diorite. Thin sections of these rocks examined with the microscope showed that all of them are altered igneous rocks.

The greenstones at Rua Cove are broken and displaced along a shear zone that strikes about N. 15° E. The dip of the zone is varied but commonly is between 80° W. and vertical. The shear zone apparently has a maximum width of about 200 feet. The underground workings expose a lens of solid or nearly solid sulfides, ranging from 35 to 50 feet in thickness in most places but pinching out or expanding to 100 feet locally. This lens is on the west side of the shear zone and has been traced for 400 feet horizontally. It strikes N. 25° E. and dips 60° W. East of the sulfide lens the crosscuts and drillholes in the shear zone show mineralized sheared greenstone and barren horses of massive greenstone. Next to the east wall, which like the west wall is a place of strong faulting, is a system of narrow sulfide lenses or a large lens that includes a zone of barren greenstone.

The surface exposures, beginning in an opencut on the mountain side 180 feet higher than the principal tunnnel, indicate a lens of solid sulfides ranging in width from a few feet to 50 feet and having the same strike and dip as the lens exposed on the west side of the shear zone in the tunnel. It appears to be part of the same north-pitching lens of sulfides. The whole deposit, however, is irregular in form and much faulted, and its original structure is difficult to learn.

The sulfide minerals are pyrrhotite, chalcopyrite, and sphalerite. Pyrrhotite is the most abundant mineral and includes grains and veinlets of chalcopyrite and sphalerite. The order of deposition of the ore minerals is the same as that in which they are named. They are believed to have replaced the fractured country rock of the shear zone rather than to have been deposited in the open spaces. The mineralization was greatest and the replacement was most nearly complete near the walls of the shear zone.

Evidence of copper-iron sulfide mineralization may be seen in all parts of Knight Island, especially in Drier Bay, but none of the deposits so far discovered is as large as that of Rua Cove. With one or two exceptions all that have been described are in fractured parts of the greenstone and present the same association of minerals. The two most common sulfide minerals are pyrrhotite and chalcopyrite, the pyrrhotite greatly dominant. Then follow pyrite, sphalerite, and chalmersite (cubanite). Chalcopyrite is the principal copper mineral in all places, though chalmeriste is probably more widely distributed than has been reported. Quartz and epidote commonly accompany the sulfide minerals.

The other islands of southwestern Prince William Sound seem to be outside the area of notable copper-iron sulfide mineralization, even in places where greenstone is the dominant country rock, for only a few prospects have been found in them that gave enough promise to encourage exploratory work. The same is true of most other parts of Prince William Sound, though copper-iron sulfides were prospected in the greenstone areas of Glacier Island and Cordova.

PRODUCTION

Copper production on Prince William Sound began in a moderate way with shipments of high-grade ore by many small mining companies. It increased gradually and continued for many years but stopped entirely in 1930 when the ore bodies of the mines at Latouche were worked out. In the years from 1900 to 1930 nearly 214,000,000 pounds of copper were produced by 15 operating companies. Of the quantity more than 96 percent was produced at Latouche and Ellamar by the Beatson Copper Company (Kennecott Copper Corporation) and the Ellamar Mining Company. Among the 15 companies referred to, the Fidalgo-Alaska Copper Company, the Midas Copper Company, and the Threeman Mining Company—all operating in the northeastern part of the sound—produced more than one million pounds of copper each.

GOLD

Gold and silver were produced as byproducts in the mining of copper on Prince William Sound, but their occurrence in the ore deposits as metals of primary rather than secondary interest is the subject of this section. The two metals are always associated, yet as the silver is subordinate in quantity and value the deposits are described as gold deposits. Both gold-bearing quartz lodes and deposits of placer gold are present. The known placer deposits, however, are few and small and have had little economic value. In view of the geologic conditions, it is improbable that notable placer deposits have accumulated anywhere on the sound since the glacial ice disappeared from the valleys. The occurrence of lode gold is therefore the subject of greater interest to prospectors as well as geologists.

LODE DEPOSITS

Gold-bearing lodes are known in many places on Prince William Sound, in rocks of both the Valdez and Orca groups, but are far more numerous in the northern part, throughout an area that extends from the Valdez Glacier to Passage Canal and is occupied almost entirely by rocks of the Valdez group. The gold-bearing quartz lodes of the Chugach Mountains are not restricted to localities within the area described as Prince William Sound. They are known also in adjacent areas to the east and to the west.

The rocks in which the minerals of the gold lodes were deposited are principally slate and graywacke. These sedimentary beds were intruded in a few places by large masses of granite, but much more commonly by dikes that include pegmatite, aplite, granite, quartz diorite porphyry, and more basic rocks. Some of the dikes are plainly offshoots of the larger granite bodies.

The sedimentary beds and the intrusives were broken by joints and faults and were locally shattered, allowing the entrance of mineral-bearing solutions that deposited quartz, calcite, gold and silver, metallic sulfides, and other minerals in small amount. A close genetic relationship between the intrusion of igneous rocks and the introduction of ore minerals is highly probable, one evidence of which is the occurrence of gold and primary sulfide minerals in some of the dikes. The mineralization appears to have taken place as part of the last phase of the intrusion by igneous rocks, which was late in the geologic history of the district. The metallic minerals form only a small part of the material deposited in the fracture planes of the broken rocks. Quartz, calcite, and included fragments of country rock make up most of the vein material. There seems to be less evidence of extensive replacement of the country rock by vein matter than is seen in the copper deposits.

The dominant mineral of the gold lode is quartz, which is accompanied by calcite in many places. In addition to gold and silver, other metallic minerals that have been recognized in the gold lodes are pyrite, galena, chalcopyrite, arsenopyrite, sphalerite, pyrrhotite, and stibnite, named in order of frequency of occurrence. Gold occurs in its native state. One or more of the other minerals may occur with it in the veins, but usually the number of different minerals appearing together is small. Limonite occurs as an oxidation product but is restricted to a shallow zone at the surface. The preglacial zone of oxidation that probably existed as the result of weathering in Tertiary time was removed by glacial erosion, which destroyed both the zone of oxidation, if it existed, and any accompanying zone of enrichment.

In comparing the minerals found in the gold lodes with those of the copper deposits it appears that pyrite rather than pyrrhotite is the common iron sulfide of the gold lodes. Galena and arsenopyrite are much more common in the gold lodes. Stibnite, which is not listed among the minerals of the copper ores, is found in the Port Wells district where veins consisting chiefly of stibnite are known.

The gold lodes are widely distributed but may be referred to several local areas, as the vicinity of Valdez Glacier, Mineral Creek, and the adjacent shore of Valdez Bay; the Shoup Bay area, including the Cliff mine; and the Port Wells district. The gold-bearing quartz veins at McKinley Lake near Alaganik were among the first in the region of the sound to be discovered and are almost the only gold lodes found within the area of the Orca rocks. The Cliff mine on Valdez Bay has thus far been the most productive of the gold lodes. Other gold-producing mines were the Ramsay-Rutherford mine on the east side of Valdez Glacier and the Granite mine on the west side of Port Wells, to which might be added a number of smaller mines that have contributed to the total gold production of the region.

The ore bodies of the Cliff mine may be taken as typical of the gold quartz lodes of Prince William Sound, although no two ore bodies should be expected to resemble each other in all details. The mine is on the north shore of Port Valdez, just east of Shoup Bay and is entered by an adit known as the 200-foot level, which is only 18 feet above the level of mean low tide in Port Valdez. Several distinct veins in addition to the Discovery or Cliff vein have been mined. The mine openings extend from the level of the Hughes vein, 442 feet above mean low tide, to the 550-foot level, 332 feet below it, or a total vertical distance of 774 feet. The Hughes vein was originally mined independently from the surface, through an adit on the Shoup Bay side of the ridge, but later was connected with the Cliff mine by a raise. The underground openings that were made in mining operations thus extended northwest from the outcrop of the Cliff vein, near the portal of the mine, for a horizontal distance of about 1,700 feet.

The bedrock of the southwestward sloping spur that includes the gold-quartz lodes of the Cliff mine is dominantly dark, slightly schistose graywacke in which are included beds of dark-gray or black slate. Near the entrance to the mine these beds strike east and dip steeply north. They are cut by a complicated system of faults that carries the ore deposits and is shown by the mining operations to extend northwest through the spur. Many of the faults that make up the system vary considerably from the general trend. The dips also are variable in both direction and degree but are commonly steep. Mining operations showed in addition a large number of nonmineralized faults of another system that strike east and dip approximately 60° N., conforming to the strike and dip of the bedding. The system of ore-bearing faults includes faults that dip southwest and others that dip northeast. The diversity causes confusion in understanding the structure of the ore bodies, for the faults branch or unite in a seemingly erratic manner and may appear to reverse themselves when followed vertically. The direction of movement of the walls in some places is plainly horizontal. This is well seen in the walls of the rich vein exposed in the stope above the 500-foot level where the horizontal displacement is clearly evident and seemingly is about 6 feet. Movement in a horizontal direction may explain some of the apparent reversals of dip shown by the veins at different levels. There are grounds for suspecting that the fault system may be made up of a primary fault or faults dipping east and a number of subordinate faults that branch off and dip to the west. These two groups of faults with opposed dips form structures that resemble the ridge and opposite sides of a steep roof (see fig. 68).

The gold-bearing quartz veins follow the fissures of the fault system. They show much bluish-white quartz together with minor amounts of calcite, albite, chlorite, and a brownish-weathering carbonate. The metallic minerals of the ore are gold, arsenopyrite, pyrite, sphalerite, and galena, but not all of these minerals are present together at one place. The gold is free and is readily seen in much of the ore. The sulfide minerals are not abundant and according to Johnson (1915, p. 172) form no more than 3 to 5 percent of the ore treated in the mill. The bedrock adjacent to the veins in places is heavily charged with pyrite and arsenopyrite in veinlets and fine grains or crystals disseminated through it.

The veins range in thickness from an inch or less to as much as 4¼ feet in exceptional places. Locally the vein filling is absent in the fracture planes. In places the vein material is accompanied by gouge or is shattered by later movements of the bedrock. In places also it shows a rough banding or contains vugs that are lined with small quartz crystals. The veins and fracture planes are usually distinct and clean cut where they pass through the graywacke but feather out and disappear where the fracture planes enter the black slate.

Some of the ore bodies are cut off or displaced by cross faults, showing that earth movement took place after the veins of the ore-bearing system were introduced. Vein quartz of more than one generation is present in the bedrock and in the ore-bearing vein system. The oldest was deposited in the foliation and joint planes of the schistose graywacke and is not a bearer of gold or other valuable metals. At a much later time quartz that makes up the veins was deposited. Some of the vein quartz of the ore bodies is cut by younger veins and it thus appears

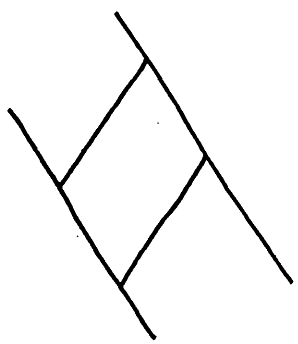

FIGURE 68.—Diagram of the suggested habit of faulting at the Cliff mine.

that the deposition of the vein quartz took place at different times or that if it was continuous, new sets of fissures were opened from time to time.

Assay maps drawn to show the distribution of the gold recovered in mining make it evident that the gold was not distributed evenly through the vein material but followed chutes, which in the stope of the 550-foot level pitch steeply north.

The most productive part of the Cliff mine has been the section near the bay. Much exploration work was done by extending drifts to the northwest and by driving numerous crosscuts. This work did not reveal ore in the lower levels toward the northwest, and thus the Hughes vein remains the most distant as well as the highest ore body of the mine. Figures showing the total production of the Cliff mine are not available, but it is known that the average value of much of the ore treated in the mill was about $50 per ton.

The types of rock and the structural relations of the lodes at the Ramsey-Rutherford mine on the east side of Valdez Glacier, about 10 miles by trail from Valdez, are much like those at the Cliff mine. The bedrock is dominantly graywacke with included beds of argillite, striking east and dipping steeply north. These beds are cut by mineralized quartz veins that range in strike from about north to northwest and dip east or west. The veins are principally quartz and range in thickness from a few inches to several feet. In places they are made up in part of crushed country rock. The gold is free. Some silver is present. The dominant sulfide mineral is pyrrhotite rather than pyrite or arsenopyrite and is accompanied by pyrite, chalcopyrite, sphalerite, and galena. Quartz is the principal gangue mineral, but calcite, probably siderite, and country rock may accompany it. The sulfide minerals commonly are only a small part of the ore. The gold content of the veins is smaller and less constant than that of the Cliff mine, but has made an important contribution to the production of gold in the district.

The Granite mine on the west side of Port Wells was at one time the chief producer of gold in the Prince William Sound area. The gold deposits of the Granite mine differ from those of the Cliff mine in their association with igneous rocks in addition to the sedimentary rocks, although a genetic connection between the mineral deposits and the igneous rocks has not been established. Much development work has been done in the mine and the openings have been greatly enlarged since the property was visited by a geologist of the U. S. Geological Survey, and the underground extent of the vein system is not known to the writer.

The interbedded graywacke, slate, and argillite, which are the dominant country rocks in the vicinity of the mine, are cut by bodies of altered granite of medium grain and light-gray to greenish-gray color.

These rocks are broken by faults that are transverse to the trend of the sedimentary beds but appear to have a more westerly direction than the fault system of the Cliff mine, ranging from about northwest to west-northwest. The dip of the original discovery vein is also variable but in general is steep to the north. The hanging wall of this vein is granite in places.

The gold-bearing veins are controlled by the fissure system. They consist chiefly of quartz but include calcite and crushed country rock, especially in the thicker parts of the veins.

The sulfide minerals are pyrite, sphalerite, stibnite, galena, arsenopyrite, and chalcopyrite. Stibnite, which has not been listed as a mineral of the Valdez district, seems to be characteristic of the Port Wells district and occurs at various places, some of which have been prospected for this mineral alone.

Many gold-bearing quartz veins were discovered in the neighborhood of the Granite mine on Port Wells and the nearby Culross Island. Several of them produced a small quantity of gold but probably none of them has been mined with profit.

The ore body of Thomas Bay, Culross Island, is unique in that it lies entirely in a fissure in greenstone that is included in the slate-graywacke succession. The vein is chiefly quartz and, in addition to gold, carries the same assemblage of sulfide minerals that appears in the gold veins of the Port Valdez area. Stibnite seems to be absent although the nearby stibnite-bearing vein of Port Wells might suggest its presence among the ore minerals of Culross Island.

PLACER DEPOSITS

Colors of gold found at various places in the gravels of Prince William Sound raised the hope that workable gold placers might be present. Although efforts have been made from time to time to recover gold from the gravel of different streams, such undertakings have met with indifferent success. Probably the larger part of the rich gold placers of Alaska that have been exploited in the past were formed by the reconcentration of gold which was widely distributed through old gravel deposits, especially gravel deposits that accumulated during the long period of erosion in Tertiary time. The gravel deposits of Prince William Sound are, for the most part, of glacial and postglacial origin. They are not deeply weathered and so far as is known have not been reworked in a way that produced notable concentration of heavy minerals. Such conditions are not favorable for the formation of deposits of placer gold.

Most of the attempts to recover gold from the gravels were made on streams flowing into Port Valdez. The more promising localities were on the upper part of Mineral Creek and on Gold Creek where small mining operations were carried on over a period of several years.

Placer mining on a still smaller scale was undertaken on Lowe River and Solomon Gulch. It was not successful and was given up many years ago.

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