THE OCCURRENCE OF COPPER ON PRINCE WILLIAM SOUND

By Fred H. Moffit

INTRODUCTION

The copper deposits of Prince William Sound attracted the attention of prospectors as early as 1897, when the properties of the Alaska Commercial Co. on Landlocked Bay, the Gladhaugh mine at Ellamar, and the Big Bonanza mine on Latouche Island were staked. Doubtless many deposits of copper minerals were known to the natives and perhaps to a few traders long before that time, yet little if any effort was made to investigate them. Interest in copper grew rapidly after 1897, but not until 10 years later did it reach its high point. By 1907 the number of men engaged in mining copper and in the search for copper in this region had increased many times, and the amount of money invested in such enterprises had reached large proportions. Furthermore the possibilities of the Sound region for producing copper had been presented to investors in many places outside of Alaska, so that the interest in it was by no means local. After 1907, however, the less favorable financial situation, the failure of most of the prospects to become mines, and finally the World War made the raising of money for developing copper properties difficult and reduced prospecting almost to the vanishing point. The only place where copper is now being produced on Prince William Sound is at the mines of the Kennecott Copper Corporation on Latouche Island.

The copper deposits of the Sound have been studied by many persons representing either the Federal Government or private investors, and a considerable literature on the subject has accumulated. This was summarized by Johnson[1] in a report published in 1915. Several papers dealing with the geology and copper resources of Prince William Sound or of particular districts in it have appeared since that time, notably papers by Johnson[2] and Bateman.[3]

[1] Capps, S. R., and Johnson, B. L., The Ellamar district, Alaska: U. S. Geol. Survey Bull. 605, pp. 52–61, 1915.

[2] Johnson, B. L., Mining on Prince William Sound; The gold and copper deposits of the Port Valdez district, Alaska: U. S. Geol. Survey Bull. 622, pp. 131–188, 1915. Mining on Prince William Sound, Alaska: U. S. Geol. Survey Bull. 642, pp. 137–145, 1916. Mining on Prince William Sound; Copper deposits of the Latouche and Knight Island districts, Prince William Sound: U. S. Geol. Survey Bull. 662, pp. 183–220, 1917. Mining on Prince William Sound; Mineral resources of Jack Bay district and vicinity, Prince William Sound: U. S. Geol. Survey Bull. 692, pp. 143–173, 1919.

[3] Bateman, A. M., Geology of the Beatson copper mine, Alaska: Econ. Geology, vol 19, pp. 338–368, 1924.

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The writer visited all the better-known copper deposits of Prince William Sound in 1923 and spent some weeks in studying the general geologic relations of the ore deposits to the rocks inclosing them. This paper therefore contains some new material, although it has drawn freely on the earlier observations of other workers, especially those of Johnson. It is written for the purpose of presenting information regarding the character of the copper deposits but is not intended to give descriptions of individual properties except so far as such descriptions illustrate principles which it is desired to make clear. It will be fully evident to the reader that many problems regarding both the general geology and the ore deposits still remain to be solved.

Prince William Sound lies at the most northern extension of the Gulf of Alaska. It is almost shut off from the Pacific by a chain of large islands extending southwestward across its south side. Numerous smaller islands are scattered through it, especially on the west side, where Knight Island, Latouche Island, and various other less well-known islands are situated. The shore line is long and intricate, for the sides of the Sound on the east, north, and west are a succession of deep bays and narrow inlets shut in by rugged mountains from which scores of glaciers descend. The country surrounding the Sound is all mountainous, and the higher part is covered by snow and ice. The greatest relief is found along the north side, where the tallest peak in this part of the Chugach Range reaches a height of over 13,000 feet and the crest line of the range is over 10,000 feet. The relief of the country east and west of the Sound and of the larger islands is less but is measured in thousands rather than hundreds of feet.

The whole of Prince William Sound was once filled with glacial ice, which doubtless covered the smaller islands and possibly may have pushed out to sea beyond Montague and Hinchinbrook islands. Presumably the gathering ground for the ice was in the highlands surrounding the Sound. Only the higher peaks could have risen above the ice surface at the time of maximum glaciation. At a later time Montague Island and the other islands to the west, which may have been entirely covered when the ice was thickest, were above the ice surface and directed the southward-moving currents through the passages that separate them. The passage between Montague and Hinchinbrook islands possibly served as another outlet at that time. Eventually, however, the supply of ice from the mountains diminished, and the glaciers were reduced to their present condition. Glaciation had a prominent part in giving their present form to the mountains and is of importance to the miner and student of ore deposits because glacial ice stripped away any oxidized ores that may have existed in preglacial time and protected the remaining ores from further oxidation for an indefinite time.

Prince William Sound is now characterized by an abundant precipitation, which in unusual years like 1912 has been known to amount to nearly 200 inches. Precipitation takes the form of snow in the winter. The snowfall is heavy, and the snow hangs on mountain sides and in many gulches till the early part of the summer—in fact, the highest ridges north of the Sound are above snow line the year round. The temperature is more moderate than that of interior Alaska, being neither hot in summer nor intensely cold in winter. These conditions are believed to have prevailed since the great glaciers disappeared, and in consequence oxidation of the ore bodies since then has been slight.

GEOLOGY

General features.—The rocks of Prince William Sound are dominantly sedimentary but locally include dark-colored, more or less altered lava flows and intrusive rocks, commonly termed greenstones, and a few relatively small areas of granite. Light-colored porphyritic dikes, probably related to the granite, intrude the sedimentary rocks of the northern part of the Sound in many places. The sedimentary rocks are in the main closely folded graywacke and slate showing a varied degree of metamorphism, which is more noticeable on the north and west sides of the Sound than on the east side and on the large islands of the south side. Beds of conglomerate and of limestone are interstratified with the slate and graywacke in a few places, but limestone in particular is uncommon.

The sedimentry rocks of the Sound were separated by the early workers in the district into two "series" or groups designated the Valdez "series" and the Orca "series." This separation is indefinite, and its accuracy has been questioned, but it is accepted here for the present as being probably correct in a broad way. Schrader[4] states that the Valdez "series" or group may be only a more highly metamorphosed phase of the Orca "series" but that because of lithologic differences it seems desirable to distinguish the two by different names. The stratigraphic and structural relations of the Valdez and Orca groups are still undetermined, yet there is evidence to support the reversal of the relative ages assumed by Schrader and the assignment of at least a part of the Orca group to the Paleozoic era and of the Valdez group to the Mesozoic era. They may be as widely separated as the Silurian and the Cretaceous.

[4] Schrader, F. C., A reconnaissance of a part of Prince William Sound and the Copper River district, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, p. 408, 1900.

Orca group.—The rocks that have been designated the Orca group are typically displayed on the shores of Orca Bay. These rocks consist dominantly of black and gray slate interbedded with graywacke or arkose. The slate in most places has a fair cleavage but in some places lacks the cleavage and may be called argillite. The graywacke varies widely in color and in composition. It is a dense quartzitic sandstone made up of angular fragments of quartz, feldspar, and dark minerals. The proportions of the constituents vary, however, and in many places the dark minerals are so much reduced in relative quantity that the rock is distinctly lighter in color and may be called an arkose.

The beds of the slate and graywacke range in thickness from less than a foot to 100 feet or more, although the beds of graywacke are commonly not over 50 feet thick and in general are much less. Thick beds of slate are more common than thick beds of graywacke. Nearly everywhere the bedding is conspicuous, so that strike and dip observations are easily made, although structure is hard to determine because of close folding, overturning of folds, drag folds, and the scarcity of beds that can be correlated. The shore lines give excellent and almost continuous exposures. One type of exposure is a succession of alternating slate and graywacke in approximately equal proportions, or with graywacke predominant, in beds about a foot thick, more or less. Another type shows one or more thick beds of graywacke, vertical or dipping at a high angle, flanked by interbedded graywacke and slate and finally by slate alone. Beyond the slate is interbedded slate and graywacke and finally graywacke again. The succession of changes is rhythmical like waves on the sea and may all take place in 100 yards or less but is repeated over and over. This transition is gradual. The change from the graywacke begins with beds of graywacke of diminishing thickness separated by slate beds of increasing thickness which finally replace the graywacke entirely. These successive alternations of thick beds of graywacke with slate separated by interbedded thin slate and graywacke represent either similar conditions of sedimentation repeated with much regularity, or possibly in places a repetition of beds due to close folding.

Several prominent beds of conglomerate appear in the Orca group at different localities on the Sound. A few beds of dark impure limestone are also known. Occasionally scattered pebbles are seen in the slate, or the graywacke is coarse grained and becomes a grit or even a fine conglomerate.

The areas mapped as Orca sedimentary beds include dark-colored igneous rocks, described on page 145, and at least one area of granite, which lies on the east side of the Sound between the heads of Sheep Bay and Port Gravina.

The Orca rocks are closely folded and faulted, yet the regional metamorphism of the rocks of the southern part of Prince William Sound is not pronounced. The age of these rocks is not known, but fossils collected from Montague Island in 1923 suggest that they are Paleozoic and may be as low in the Paleozoic as Silurian or Devonian.

Valdez group.—The rocks in the vicinity of Port Valdez are chiefly thin-bedded slate and graywacke, but they are more metamorphosed regionally than the rocks of Orca Bay and show other differences. In places the rocks of this type are less thinly bedded than the sedimentary beds of Orca Bay, and the bedding is less conspicuous. Moreover, in the district north of Valdez and on the west side of the Sound the graywacke contains a larger proportion of dark particles and has less the appearance of sandstone than much of the graywacke or arkose of the southern part of the Sound, yet in the vicinity of Ellamar and elsewhere are slate and graywacke in alternating thin beds where the graywacke includes light-colored feldspathic sandstone like some of that in the Orca group. Locally the slate and graywacke are metamorphosed to a degree that would warrant calling them schists. The Valdez rocks, in spite of their slightly greater metamorphism, show little if any more folding than the Orca rocks. Like the Orca rocks, they were originally gray or black muds and feldspathic sands with more or less dark minerals. They were cemented and folded and metamorphosed to form the present beds. They were derived from older rocks which were undergoing weathering so rapid that the resultant sands and finer particles were not greatly oxidized and were not worn sufficiently to destroy their general angular form.

The age of the rocks about Port Valdez is not known. Fossils have been collected at a number of places from rocks regarded as belonging to the Valdez group. They are not diagnostic but make the Paleozoic age of the rocks seem doubtful and indicate rather that they may eventually be shown to be Mesozoic, possibly Cretaceous.

Greenstones.—The term "greenstone," so frequently used in describing the geology of Prince William Sound, is applied to certain altered igneous rocks, including lava flows that welled out over the surface from vents in the crust; tuffs and agglomerates; and other igneous rocks, subordinate in amount, that were intruded into the crust as dikes, sills, and larger masses of less regular form. The two outstanding localities where greenstones are abundant are Knight Island and the vicinity of Landlocked and Boulder bays, both of which were centers of volanic activity where lava flows, tuffs, and agglomerates were especially developed. Centers of less importance are Glacier Island and the south end of Elrington Island. The intrusive greenstones, although occupying less area than the flows and other extrusive forms, are more widely distributed and are particularly abundant in the islands between Latouche and the mainland.

The greenstones as described by Johnson[5] range in color from light gray through shades of green to greenish black and show a wide range of texture. Some are of fine, even grain; others are coarse grained. The diabasic texture is common. Both porphyritic and nonporphyritic lavas are found, and also amygdaloidal lavas in which the vesicles have been filled with epidote, quartz, and chlorite, as well as ellipsoidal lavas.

The greenstones appear to be differentiates from a single magma but range in composition from that of andesite and diorite to that of gabbro, diabase, and peridotite. In most places they are considerably altered. Calcite resulted from the alteration of the more feldspathic (dioritic) varieties, and calcite, sericite, chlorite, epidote, quartz, and leucoxene from that of the more basic varieties. Shearing and chemical alteration by circulating waters changed the greenstone locally to chloritic schist or brought about epidotization or silicification.

A most noticeable feature of many of the lava flows is the ellipsoidal or pillow structure. This is well developed in the Ellamar district and especially on Knight Island, where the bare ledges of the mountains and the shores of the north end of the island display the ellipsoidal structure on a large scale and in many places suggest the appearance of giant conglomerates because of it.

The greenstones with some possible exceptions are thought to belong to one period of volcanism, although they were not formed simultaneously. Repeated intrusions and extrusions of molten magma took place, so that earlier flows and dikes are cut by younger dikes, and new lava flows were poured out over older flows. Because of the uncertainties regarding the age of the sedimentary rocks, the age of the greenstones is also in doubt. All the sedimentary rocks of the district are cut by greenstones and are therefore older than the greenstones. This suggests a possible Cretaceous or later age for the greenstones, if the Valdez group is correctly interpreted as being in part Cretaceous.

Brooks[6] regards the last two great epochs of diastrophism affecting Alaska as having been in Jurassic or Cretaceous and post-Kenai (Eocene) time. These two epochs of diastrophism were times of great igneous activity and are most significant in relation both to the tectonic history of Alaska and to the formation of many of the

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[5] Johnson, B. L., unpublished manuscript.

[6] Brooks, A. H., Outline of tectonic history of Alaska (in preparation).

ore deposits. So far as the evidence is known at present, the greenstones of Prince William Sound may belong to the earlier rather than the later of these two epochs, but they can not now be assigned definitely to either.

CHARACTER OF THE SULPHIDE DEPOSITS

FORM OF THE SULPHIDE BODIES

The copper deposits of Prince William Sound are simple in form and in mineral composition, and all with the possible exception of a few in the vicinity of Cordova belong to one general type. They consist of copper and iron sulphides, notably chalcopyrite, pyrite, and pyrrhotite, deposited from mineralized solutions along fault planes or fracture planes in fault zones, or of these same sulphides disseminated through the country rock adjacent to such planes. Ordinarily veins of sulphides and disseminated sulphides are associated together in the same deposit. The vein deposits are of tabular or lenticular form. The disseminated ore bodies, on the other hand, are irregular in form and variable in copper content. The disseminated sulphide minerals are present as a multitude of veinlets or as grains replacing minerals of the rock between veinlets. As a rule the boundary line between disseminated ore and waste rock is not evident to the eye and is determined only by systematic mine sampling, for the quantity of the replacing sulphides ordinarily varies inversely with the distance from the more open channels of the mineral-bearing solutions, and the ore body grades finally into barren rock. In the ideal case a perfect gradation exists from ore with a maximum of metallic sulphides to country rock. In many deposits good evidence may be found to show that the mineral-bearing solutions made their way along openings, such as fault planes and joint planes, which they found available and deposited their sulphides either in these openings or in the adjacent rock walls. The sulphide bodies or veins along the fault planes are probably in part a filling of open cavities but may be much more largely formed by the replacement of beds particularly susceptible to replacement, or of wall rock and the fragmental material in the fault zone.

Possibly the walls of the fault may have been separated or forced apart as the vein grew, so that large open cavities did not exist at any time, or it may be that the pressure of the solutions was sufficient to support the walls of cavities along the fault planes and allow the formation of cavities of considerable size. Although they were probably formed at the same time by the same solutions, the veins and the disseminated sulphides were deposited under somewhat different conditions. The massive tabular bodies of sulphides were deposited by solutions having considerable freedom of movement along channels that followed the fault or fracture planes. The resulting sulphide bodies, although limited in extent and varying in width, are practically continuous. The disseminated ores, on the other hand, were deposited from solutions that made their way through the intricate channels formed by a multitude of tiny openings in shattered country rock. The solutions followed even microscopic openings and not only filled open cavities but took into solution the minerals of the rock itself and replaced them with metallic sulphides and gangue. The circulation of such solutions must have been much less rapid than that of the solutions in the trunk channels along the faults. It is readily seen that the form of the disseminated deposits produced under such conditions is likely to be far less regular in outline than that of the vein deposits.

The location of most of the ore bodies is evidently dependent on faults that cut the country rock. These faults provided the channels by which the mineralized solutions made their way toward the surface from the depths, and their shattered walls were especially subject to the attack of the solutions. The weakness of the rocks adjacent to faults finds topographic expression in hundreds of places on Prince William Sound in depressions produced by the more rapid weathering of the fractured rock of the fault zones.

In a few places, however, the rock of the fault zone was cemented with material that made it more resistant than the adjacent country rock, and an elevation rather than a depression marks the location of the fault. A few prospectors have made extensive use of the topographic expression of faults in their search for ore bodies.

OXIDATION OF THE ORE BODIES

The copper deposits of Prince William Sound show only surface oxidation. Enrichment or impoverishment of the deposits through alteration due to oxidizing surface waters is not recognized, and the ore bodies are seemingly unchanged from their original condition. If an oxidized zone were ever present, it was completely removed from all the known ore bodies during the time when the region was covered with glacial ice, and a new oxidized zone has not been formed, for oxidation since the retreat of the ice has not been sufficient to affect more than the surface of exposed ore bodies. This condition is in strong contrast with that of the copper deposits at Kennicott, where a considerable proportion of the ore mined from the lowest levels yet reached, 1,750 feet, is carbonate ore. The condition of the copper deposits of Prince William Sound in preglacial time is not known. Possibly they were below sea level and were not subject to oxidation. Whether this is true or not, it is probable that glacial erosion was profound and was competent to remove a considerable thickness of oxidized ores if any existed. The present climate is cool and damp and not calculated to promote rapid oxidation of rocks or ores. Probably similar climatic conditions or possibly conditions even less likely to promote oxidation have prevailed since the time of maximum glaciation.

MINERALS OF THE COPPER DEPOSITS

The usual minerals associated together in the copper deposits of Prince William Sound are a few metallic sulphides and a much smaller number of gangue minerals. The more common valuable minerals are pyrite, pyrrhotite, chalcopyrite, chalmersite (cubanite), sphalerite, galena, and quartz. Gold and silver in varying amounts are present. These minerals may be regarded as typical of the Prince William Sound copper deposits with the exception of a few prospects near Cordova, where the more abundant copper sulphide is chalcocite rather than chalcopyrite and is accompanied by a little native copper. Chalcopyrite and chalmersite (cubanite) are the only copper minerals among those listed as typical of the Sound deposits which are of present or probable future commercial importance, although several other copper minerals have been recognized. It is of considerable interest that nickel has been reported from the copper deposits at four or five localities.

The occurrence of copper sulphides and other associated minerals of the Ellamar district was described by Johnson,[7] and as the minerals of that district are typical of the other copper deposits of the Sound the list prepared by him is presented here with slight modification.

Minerals occurring in the ore deposits of the Ellamar district

Mineral	Composition	Occurrence
Arsenopyrite	$FeAsS$	Associated with other sulphides at old Alaska Commercial Co.'s property, Landlocked Bay.
Azurite	$2CuCO_3.Cu(OH)_2$	Oxidation product of the copper sulphides.
Calcite	$CaCO_3$	Gangue mineral of the ores.
Chalcopyrite	$CuFeS_2$	Principal copper-bearing mineral of the ores.
Chalmersite	$CuFe_2S_3$	Intimately associated with chalcopyrite at Threeman Mining Co.'s mine on Landlocked Bay and elsewhere.
Chlorite	Complex hydrous silicate of Fe, Mg, and Al.	
Copper	Cu	Oxidation product of copper minerals of ore.
Epidote	Complex hydrous silicate of Ca, Al, and Fe.	A gangue in some of the ores.
Galena	PbS	One of the sulphides of the ores. Not very common.
Gold	Au	Present in most of the ores. Relationship unknown.
Limonite	$2Fe_2O_33H_2O$	Oxidation product of iron minerals.
Malachite	$CuCO_3.Cu(OH)_2$	Oxidation product of the copper sulphides.
Pyrite	FeS_2	Abundant ore mineral at some prospects.
Pyrrhotite	$FeS(S)x$	Abundant ore mineral at most prospects.
Quartz	SiO_2	Gangue mineral of the ores.
Silver	Ag	Presence in ores shown by assays.
Sphalerite	Zn(Fe)S	A common ore mineral.

[7] Capps, S. R., and Johnson, B. L., The Ellamar district, Alaska: U. S. Geol. Survey Bull. 605, pp. 68–72, 1915.

Several other copper sulphides, such as bornite, chalcocite, and covellite, the sulphantimonide tetrahedrite, and the oxide melaconite, together with sulphides of other metals, as marcasite and stibnite, and the carbonates siderite and ankerite have been reported from different parts of Prince William Sound. The presence of one or two of these minerals, however, has not been confirmed.

The primary ore minerals and those of later origin are listed by Johnson for the Ellamar district as follows:

Primary	*Secondary*
Native metals:	Native metal:
Gold, silver.	Copper.
Oxide:	Oxide:
Quartz.	Limonite.
Sulphides:	Sulphide:
Arsenopyrite, chalcopyrite, galena, pyrite, sphalerite, chalmersite (cubanite).	Chalcocite (?).
	Carbonates:
	Malachite, azurite.
Carbonate:	
Calcite.	
Silicates:	
Chlorite, epidote.	

The sulphide minerals are of present commercial value only for the copper which they contain and for the gold and silver associated with them. Chalcopyrite is the important copper mineral of all the copper deposits. The pure mineral contains 34.5 per cent of copper, but as chalcopyrite is invariably associated with one or more of the other sulphides the richest ore bodies contain only a fraction of this amount of copper. Chalmersite, or cubanite, the other copper mineral, contains 23.5 per cent of copper when pure and has been an important constituent of the copper ore shipped from Landlocked Bay. Chalmersite has a wide distribution in the Prince William Sound region and has been recognized at various places. It is present in the ores from Latouche Island but is of little importance in the copper production of that place.

Pyrite is present in all the ore bodies, and pyrrhotite is usually present also. Pyrrhotite is more abundant than all the other sulphides in some localities. At the Beatson mine, on Latouche Island, it is the most abundant mineral of a solid vein of sulphides, in places 10 feet thick, along the Beatson fault, which forms the hanging wall of the ore body. This vein, however, has a low copper content and is not mined. Pyrrhotite is abundant at other localities on Latouche Island and on Knight Island. Arsenopyrite is reported from a few places, as at Landlocked Bay, yet it has been recognized more frequently in the gold deposits of Prince William Sound than in the copper deposits.

Sphalerite appears to be present in practically all the copper deposits in the form of small crystals or grains scattered through other sulphides, and at the Ellamar mine it forms veins which are gold bearing. Galena also has been noted at several localities, both in the rough hand specimen and in polished surfaces examined under the microscope. It is much less common than sphalerite and has no commercial value.

Gold and silver are shown by the assays and are recovered from the ores treated at the smelter, but they have not been recognized by the eye in hand specimens from any of the deposits. Probably they are present as native metals in pyrite or some other sulphide.

The principal gangue mineral accompanying the metallic sulphides is quartz, which is commonly found intergrown with the massive sulphides of the veins and as replacement quartz in the country rock that contains disseminated sulphides. Like the sulphides it filled cavities and replaced original constituents of the rock itself. Calcite and ankerite are associated with the ores in places. Chlorite and epidote were also formed in some of the veins by chemical reactions between the mineralized solutions and the wall rocks.

Although the copper deposits do not show more than superficial oxidation several secondary minerals are seen on some of the outcrops of the ore bodies. Among these are native copper, chalcocite (?), malachite, and azurite. Melaconite and one or two other minerals are also reported, and it is probable that a detailed study of the copper deposits would extend the list of copper and associated minerals.

ORIGIN OF THE ORE DEPOSITS

The copper deposits of Prince William Sound exhibit an association of metallic sulphides classified by Lindgren[8] as belonging to the metalliferous deposits formed at intermediate depths by ascending thermal waters and in genetic connection with intrusive rocks. Such deposits are supposedly formed by alkaline waters at depths ranging from 4,000 to 12,000 feet and at temperatures ranging from 175° to 300° C. The pressure of water at such depths, calculated as hydrostatic pressure, ranges from 140 to 400 atmospheres, but the actual pressure may be greater if the water and gases do not have free communication with the surface. The pyritic replacement deposits are divided by Lindgren into (1) those associated with certain silicates such as amphibole, pyroxene, epidote, tourmaline, and garnet, part of the sulphide being present as pyrrhotite, and (2) those associated with calcite, barite, and quartz as gangue minerals. Deposits of the first class indicate considerably higher temperature

[8] Lindgren, Waldemar, Mineral deposits, 2d ed., pp. 546–549, 635–637, 1919.

and probably greater depth than those of the second class. Lindgren says of the second class, " The ores, while consisting mainly of pyrite or pyrrhotite, derive their value from a small percentage of chalcopyrite; there are usually minute quantities of gold and silver, and frequently also zinc blende and a little galena; other sulphides are rare." This description applies well to most of the copper deposits of Prince William Sound.

A direct genetic relationship between the copper-bearing sulphide bodies and intrusive igneous rocks has not yet been demonstrated for this district. It is a notable fact, however, that almost every known copper deposit of southern Alaska, including Prince William Sound and the Copper and Susitna river basins, is either in the altered igneous rocks usually designated greenstones or in the sedimentary rocks in the vicinity of such igneous rocks. The deposits, however, are younger than the rocks that inclose them and were not formed till the greenstones had solidified and had been more or less deformed and faulted. Students of ore deposits of the kind under consideration have long been inclined to the belief that they are genetically connected with the intrusion of igneous rocks and were deposited from mineral-bearing solutions which originated in the molten magma or in some localities from mineralized solutions stimulated to circulation by the heat of the magma. If the deposits of Prince William Sound were derived from such a source and have some intimate connection with the greenstones, as seems highly probable, it is reasonable to suppose that the extrusion or intrusion of the greenstones and the deposition of the sulphide bodies were expressions of deep-seated igneous activity such as is already known to have occurred in parts of the Sound, and that although they are phases of one geologic event they differ somewhat in time, the formation of most of the greenstones coming first.

Johnson [9] has stated his conclusion regarding the relation of the copper-bearing sulphide bodies and the greenstones as follows:

> The close association of the ore deposits and the greenstones and the character of the mineral association in the ore deposits point thus to a close relationship between the copper deposits and the greenstones, and it is therefore suggested here that the copper deposits of these islands are attributable to hot, alkaline copper-bearing solutions of magmatic origin deriving their heat and metallic content from the same parent magma as the greenstones, circulating through fissure and shear zones in both greenstones and sedimentary rocks throughout much of the period of igneous activity and immediately thereafter.

The copper deposits of Ellamar and Latouche, because of their production and commercial importance, have been more carefully studied than the other deposits of the Sound. No mining has been done at Ellamar for several years, and the mine is filled with water

[9] Johnson, B. L., unpublished manuscript.

and is inaccessible. The areal geology of the district was mapped in detail, however, by Capps and Johnson during the productive days, and the mine was studied by Johnson.

The country rock inclosing the ore body at Ellamar consists predominantly of soft black slate with which are interbedded black limestone, dark-colored argillite, and a few beds of fine-grained graywacke. No igneous rocks are known in the mine or nearer than the greenstone lava flows north of Gladhaugh Creek, nearly half a mile away. The ore body consists of two parts[10]—(1) a large lens of solid pyrite, forming the hanging wall for (2) smaller, closely packed parallel lenses, consisting largely of other sulphides. A series of polished specimens of the ores of the district, studied by Johnson, showed the primary sulphide minerals chalcopyrite, chalmersite (cubanite), pyrrhotite, pyrite, sphalerite, and specks of a bright reflecting mineral that possibly is galena. Johnson[11] says of these sections:

The order of deposition of the various sulphides is well brought out by this metallographic study. Pyrite, where present, was invariably the first mineral to be deposited. This was true in all sections in which pyrite was visible. It was followed later by the deposition of the other sulphides, which in most places appear to have been deposited contemporaneously. At the Ellamar mine, however, tiny veinlets of chalcopyrite with a little sphalerite cut earlier sphalerite.

In the ore from the mine of the Threeman Mining Co. on Landlocked Bay a slightly different order of deposition occurs—contemporaneous chalcopyrite, galena, and an unknown sulphide, which are definitely later than the pyrrhotite in the ore. The chalcopyrite and the unknown sulphide occur intimately intergrown. In polished specimens from the old Alaska Commercial Co.'s property a little arsenopyrite is present and appears to have been the first sulphide to form. No pyrite was seen in the specimen of this ore which was examined.

Naturally most interest attaches in an investigation of this sort to the occurrence of the economically important metals, which are copper, silver, and gold. One of the results of this investigation has been to show that the copper occurs apparently as a definite mineral, chiefly chalcopyrite, and not chemically combined with pyrite. This agrees with the conclusions of Simpson on the copper ores of Butte, Mont., and with Finlayson on the pyritic deposits of Huelva, Spain.

The pyrite, under the metallographic microscope, is shown definitely to be of a slightly earlier generation, cut and replaced by the later chalcopyrite. The massive pyrite lens of the Ellamar mine shows very little copper content in assays. Metallographic examinations of the pyritic ore invariably show the copper content to be contained in the later chalcopyrite. Qualitative tests on a pale brass-yellow sulphide intimately associated with the chalcopyrite at the mine of the Threeman Mining Co., on Landlocked Bay, show that this mineral has apparently a low copper content. A careful determination of this mineral[12] is being made. No other primary copper-bearing minerals are found in the

[10] Johnson, B. L., op. cit. (Bull. 605), p. 91.
[11] Idem, p. 71.
[12] This mineral is now known to be chalmersite.—F. H. M.

ores, and no evidence of any copper silicates were seen in any of the ores or rocks examined in the Ellamar district.

Gold has not been observed in any of the specimens examined. Its presence in both copper and gold ores of the district, however, is amply proved by the results of assays. The Ellamar mine, formerly chiefly a copper producer, has in recent years produced large quantities of gold. This metal is also found in the Threeman ore. Though it is not definitely known that the gold occurs native, no tellurides or other gold minerals are known to occur in this district, and by analogy it is presumed, until further evidence is produced, that here, as in other parts of the Pacific coast region where similar genetic relationships exist, the gold occurs native.

Assay returns show the presence of silver in the gold and copper ores of the Ellamar district, but the metal has not been seen in any specimen examined. Inasmuch as all lode gold contains some alloyed silver, a part at least of the silver in the ores of the Ellamar district is presumed to occur alloyed with the gold of the lodes. No silver minerals have been found in this district.

The country rock of the Beatson mine at Latouche consists of interbedded slate and graywacke, with graywacke predominating. The graywacke is made up of angular fragments of quartz, feldspar, and dark minerals, including fragments of slate. Unlike the slate, it has no well-developed cleavage. In addition to the slate and graywacke, two other rocks are notable in the mine. They are a green chloritic schist which caves badly in mining and a very hard cherty or flinty rock which does not conform to the bedding of the slate and graywacke but crosses them irregularly and it appears to be an alteration product of the country rock. Similar cherty or flinty rocks are associated with the copper deposits at other places on the Sound. Another rock of much interest in the mine is a dark basic dike which resembles the graywacke. This dike was brought to the writer's notice by Dr. Bateman, who determined it to be an altered lamprophyre. It cuts the graywacke in the ore zone and is made up of alteration products of olivine in a matrix completely altered to calcite, chloritic material, and sericite. Basaltic hornblende, magnetite, and apatite are present. Limestone is not known in the mines at Latouche, but beds of light-gray siliceous limestone were disclosed by the shaft on the property of the Reynolds Alaska Development Co. at Horseshoe Bay, 3 miles south of Latouche.

Bateman[13] found on examination of polished specimens of the Latouche ore that the sulphides present are pyrite, pyrrhotite, chalcopyrite, chalmersite (cubanite), sphalerite, and galena, associated with quartz and a little siderite (ankerite?) as gangue minerals. Chalcopyrite constitutes about half the total quantity of sulphides and pyrrhotite and pyrite the other half. Sphalerite is widely distributed, although present in small quantity. Chalmersite is rare. Pyrite was the first sulphide to form, and the remaining sulphides

[13] Bateman, A. M., Geology of the Beatson mine, Alaska: Econ. Geology, vol. 19, pp. 354–357, 1924.

were practically contemporaneous, occurring singly or in combination. Quartz and chalcocite, quartz and pyrrhotite, or quartz alone are as common as mixtures of chalcopyrite, pyrrhotite, and quartz. Inclusions of chalcopyrite in pyrrhotite are almost as common as inclusions of pyrrhotite in chalcopyrite, yet there seems to have been a tendency for the pyrrhotite to form earlier. Veinlets of chalcopyrite cutting pyrrhotite or of pyrrhotite cutting chalcopyrite are not present. Sphalerite occurs as numerous small blebs or grains of microscopic size within pyrrhotite or chalcopyrite or by itself in quartz. It commonly contains specks of chalcopyrite that are visible only with higher powers of the microscope. In general the sphalerite is slightly earlier than the chalcopyrite and pyrrhotite, although the specks of chalcopyrite may be older than the sphalerite. Chalmersite (cubanite) is associated with pyrrhotite and chalcopyrite, occurring with both sulphides and in quartz adjacent to the other sulphides. The grains are without regular outlines and appear to have been formed simultaneously with the chalcopyrite and pyrrhotite. The principal gangue mineral is quartz, although siderite (ankerite?) is present in small amount, and chlorite, which is conspicuous in some of the country rocks, may have been introduced in part at the time of metallization. Quartz occurs as veinlets and irregular grains and was introduced before and with the sulphides. The gangue quartz is mostly of irregular form, although having crystal outlines in places, and is clear and thus distinguishable from the original quartz in the graywacke, which shows strains and inclusions. The continuity of the quartz veinlets is broken by sulphides in many places, and the plates show embayments where the quartz was replaced by sulphides. Most of the quartz appears to have replaced the country rock.

The similarity of mineral associations of the copper deposits of Prince William Sound and their common apparent connection with certain kinds of igneous rocks immediately suggest the probability that these deposits had a common origin and that although they may not have been formed simultaneously they nevertheless belong to one period of mineralization. The rare mineral chalmersite had formerly been found at only one locality outside of Prince William Sound,[14] and only in small quantity at that locality, the Morro Velho gold mine, in Brazil. More recently, however, it has been found at other localities in the United States and Canada. It occurs at many widely separated localities in Prince William Sound and was present at Landlocked Bay in sufficient quantity to be an important constituent of the ore shipped from the property of the Threeman Mining Co. It is probable that other localities for the

[14] Johnson, B. L., Preliminary note on the occurrence of chalmersite, $CuFe_2S_3$, in the ore deposits of Prince William Sound, Alaska: Econ. Geology, vol. 12, p. 519, 1917.

mineral will be found. This feature alone suggests a relationship between the copper deposits. Another tie appearing to indicate a relationship between the copper deposits of the Sound is the metal nickel. This metal was revealed in assay samples from Latouche[15] and is also reported from a number of places on Knight Island.[16] These reports are not sufficiently definite to form the basis for any general conclusions, but as nickel is always associated with basic igneous rocks the suggestion immediately arises that the solutions which formed the copper deposits at Latouche originated from a basic magma and that a similar condition holds for the other similar deposits.

The causes that lead to the deposition of the metallic sulphides in such large tabular or lens-shaped bodies as those at Ellamar, Latouche, Horseshoe Bay, Rua Cove, and elsewhere in this region are difficult to determine. Johnson[17] found that white calcite and metallic sulphides had replaced beds of original black limestone in the Ellamar mine. Limestone is not known in the Beatson mine, at Latouche, and if the hanging-wall vein has replaced limestone or other calcareous rocks the replacement is complete and has left no trace of the original beds. Moreover, Bateman regards the chloritic schistose rock adjacent to the great fault of the Bonanza mine, rather than limestone beds, as having had a prominent part in controlling the deposition of the copper and iron sulphides. Limestone is interbedded with the slate and graywacke at Horseshoe Bay, but the great sulphide body there is not known to be formed by replacement of limestone, and this mode of formation seems improbable, for no limestone beds of such thickness have been discovered anywhere in Prince William Sound. Limestone, furthermore, could hardly have had a part in the formation of sulphide deposits in the greenstones, although the greenstones are in places interbedded with sediments that may have had calcareous members, or they may themselves have contained sufficient secondary calcite to influence the deposition of the sulphides.

It would appear, therefore, that although some of the copper sulphide bodies, and the most valuable at that, may have resulted from the replacement of limestone or calcareous beds, some more general cause for the deposition of most of the deposits must be sought. This cause may have been the changes of temperature or of pressure in the mineralized solutions or the chemical reaction between solutions of different composition.

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[15] Lincoln, F. C., The Big Bonanza copper mine, Latouche Island, Alaska: Econ. Geology, vol. 4, p. 209, 1909.

[16] Johnson, B. L., Copper deposits of the Latouche and Knight Island districts, Prince William Sound: U. S. Geol. Survey Bull. 662, p. 203, 1917.

[17] Capps, S. R., and Johnson, B. L., The Ellamar district, Alaska: U. S. Geol. Survey Bull. 605, p. 92, 1915.

AGE OF MINERALIZATION

The age of the rocks of Prince William Sound is undetermined, and this statement applies equally well to the copper sulphide deposits, for no direct evidence that would restrict the age of the deposits within narrow limits has been found. A few facts bearing on the problem can nevertheless be stated.

The sulphide deposits of Knight Island are cut by dikes of greenstone, which are necessarily younger than the deposits and than the greenstone inclosing the deposits. Similarly the disseminated ore body of the Beatson mine at Latouche incloses a lamprophyre dike which cuts mineralized graywacke and is much altered but contains no sulphides [18] and consequently is thought to be later than the mineralization. These two occurences lead to the conclusion either that the deposition of the copper minerals took place in the midst of a protracted epoch of volcanism, for the earlier rocks were faulted and penetrated by the mineral-bearing solutions before the dikes were intruded, or that the earlier greenstones and the later greenstone dikes belong to two distinct periods of volcanism. The writer is inclined toward the first view.

Some of the deposits, such as those at Ellamar and Latouche, are in rocks that have been regarded as belonging to the Orca group. Others, like that of the Midas mine, on Port Valdez, are in rocks of the Valdez group. This would signify that the sulphide deposits are younger than the youngest of the sedimentary beds, provided they belong to one period of mineralization, as appears to be probable. As the Valdez rocks, which formerly were considered older than the Orca group, are now thought to be Mesozoic and probably in part Cretaceous, a Cretaceous or later age for the copper deposits is suggested. In this connection, however, it should be stated that, as was pointed out previously, the copper deposits in the vicinity of Cordova show an association of minerals different from that which is typical of the other deposits in the Sound region and that this fact suggests a possible difference in age.

According to Brooks [19] the epoch of diastrophism which first outlined the Pacific Mountain system of Alaska involved the folding of beds of Lower Cretaceous age. He assigns to this epoch a Jurassic or Cretaceous age, regarding its greatest intensity as having occurred in late Jurassic time. This epoch of diastrophism was the epoch of greatest metallization in Alaska. It was followed in post-Kenai (Eocene) time by another epoch of widespread igneous intrusion, which was also a period of metallization, more localized but of greater intensity than that of the Mesozoic. The copper sulphide

[18] Bateman, A. M., Geology of the Beatson copper mine, Alaska: Econ. Geology, vol. 19, p. 347, 1924.

[19] Brooks, A. H., Outline of the tectonic history of Alsaka (in preparation).

deposits of Prince William Sound are thought to have originated in one of these two periods of mineralization, but a definite assignment can not now be made.

CONCLUSIONS

The copper sulphide deposits of Prince William Sound are of a simple type, involving a comparatively few characteristic minerals, one of which, chalmersite, is elsewhere of rare occurrence, although it is widespread in this district. They are commonly associated with greenstones and are believed to have been deposited from hot solutions at intermediate depths. The solutions originated from a basic rather than an acidic magma, and their principal channels of circulation were governed by faults or fault zones. The deposits are either tabular or lenticular bodies, deposited along fault planes by the filling of cavities and the replacement of the walls, or disseminated bodies of sulphides, deposited in part as veinlets in a multitude of small fractures and in part as grains or small irregular bodies replacing the country rock adjacent to faults. Oxidation of the sulphide bodies is superficial, and if a zone of oxidized vein material were ever present it has been completely removed by glaciation. It follows, therefore, that little change in the character of the ore bodies, other than the differences that may have existed at the time of deposition, should be expected as mining is carried to lower depths. The ore bodies for the most part are of low grade, and the surface exposures are a fair indication of what may be expected below.

Prospectors who are seeking to trace out the continuation of an ore body will do well to study the topography of the vicinity of the known body, for in many places the fault or fault zone that directed the mineral-bearing solutions has been particularly susceptible to weathering and is plainly expressed in the surface topography by gulches, notches on ridges, or other depressions.