Geology and Mineral Deposits of Jumbo Basin Southeastern Alaska

GEOLOGICAL SURVEY PROFESSIONAL PAPER 251

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By GEORGE C. KENNEDY

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A discussion of the contact metamorphism, geomagnetic surveys, magnetite deposits, and iron ore reserves of part of Prince of Wales Island.

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GEOLOGY AND MINERAL DEPOSITS OF JUMBO BASIN, SOUTHEASTERN ALASKA

By George C. Kennedy

ABSTRACT

The iron and copper deposits of the Jumbo basin, Prince of Wales Island, were investigated during the summer of 1944 as part of an appraisal of the iron and associated copper deposits of southeastern Alaska.

Jumbo basin is on the east side of Hetta Inlet, Prince of Wales Island. It is 40 miles airline and 110 miles by boat westerly from Ketchikan, 3 miles south of the abandoned town of Sulzer, and 15 miles by water from Hydaburg. The principal magnetite deposits are about 1,600 feet above sea level and about 1½ miles by pack trail from the beach. The basin ranges in altitude from sea level to 3,900 feet, and the slopes in many places are precipitous.

The oldest rocks in the Jumbo basin area are a thick sequence of intensely folded limestone and calcareous schist beds which are conformably overlain by quartz-mica schist. Massive greenstone flows overlie the metamorphosed sediments and possibly are separated from the older metamorphic rocks by an angular unconformity, as the greenstone in some places overlies the calcareous rocks and in others, the quartz-mica schist.

A large stock, predominantly granodiorite but of widely varying composition, and many andesite dikes and sills intrude the metamorphic rocks. Much orthoclase was introduced after the stock was largely crystallized and before the contact-metamorphic deposits were formed. Contact-metamorphic deposits may be associated with any variant of the stock.

Ore deposits and associated skarn bodies have formed by replacement of limestone in contact with the stock. The deposits have formed where tongues of intrusive rocks extend from the stock, and also in inclusions of limestone in the stock. Locally the rocks of the stock have been extensively replaced by contact-metamorphic minerals. Three such bodies were studied in detail. These deposits contrast in mineralogy and texture; the differences are attributed to varying conditions of pressure and temperature at the time the skarn was formed.

The contact-metamorphic minerals are believed to have been derived from hypothermal or mesothermal solutions, which, rising from a deep portion of the stock, encountered a limestone environment and formed a group of minerals rich in calcium. The deposits formed after the adjacent portion of the stock had crystallized and are not believed to be due to emanations coming directly from the adjacent stock.

The predominant contact minerals associated with the magnetite bodies are diopside and garnet. Some chalcopyrite in finely disseminated particles, or less commonly in irregular masses, is associated with the magnetite. The lenses of magnetite range in thickness from a few feet to as much as 60 feet, and the longest known body crops out for a length of 450 feet. The three principal bodies, aggregating about 370,000 tons of indicated and inferred ore, are within an area of a few thousand square feet on the north side of the Jumbo basin. These ore bodies contain approximately 45 percent iron and 0.73 percent copper.

No ore of minable grade remains exposed in the Jumbo mine, though approximately 10,000,000 pounds of copper were produced from the mine over the period 1907–23.

INTRODUCTION

The mineral deposits of the Jumbo basin have been known for many years and active mining was under way from 1907 to 1918, and again in 1923. One mine, the Jumbo, produced during this period 10,000,000 pounds of copper. No ore has yet been mined for its iron content. The investigations recorded here were part of a larger U. S. Geological Survey program to investigate the iron deposits of southeastern Alaska and to determine the tonnage and suitability of these ores for use in a proposed Pacific Coast steel industry.

PREVIOUS WORK

The mineral deposits of the Copper Mountain area, including Jumbo basin, have been investigated by a number of geologists of the U. S. Geological Survey. The results of their work are reported in several Survey publications, included in the list of references appended to this report. A. H. Brooks spent a day in the Jumbo basin area in 1901 in connection with studies of deposits in the Ketchikan district. F. E. Wright, assisted by C. W. Wright, began a systematic investigation of the deposits of Jumbo basin and vicinity in 1904 and continued his investigation in 1905. The area was studied again in 1907 and 1908 by C. W. Wright assisted by Sidney Paige. In 1908 R. H. Sargent made a detailed topographic survey of the area. Adolph Knopf, P. S. Smith, and Theodore Chapin have reported on this area. In 1943 J. C. Reed, W. S. Twenhofel, and L. A. Warner briefly examined the Jumbo basin and vicinity and recommended that a detailed geologic and magnetic study of the magnetite deposits be made. Such a study was made during the summer of 1944 and the results are embodied in this report.

PRESENT WORK

This report is based on field work done during the period of June 17 to September 24, 1944[1]. The field

[1] The present report was completed in 1946. The results of further laboratory research will be published in a separate report.

party included the writer, William T. Gorman as field assistant, and Stephen D. Becker as recorder. Joel Moss, of the U. S. Bureau of Mines, was attached to the field party as topographic engineer during the month of July.

Detailed topographic and magnetic maps were prepared of the two small areas that contain known magnetite deposits. Underground workings in the Jumbo copper mine were also mapped in detail, and the surrounding area, comprising about 10 square miles, was mapped on a scale of 1,000 feet equals 1 inch. The writer is responsible for the geologic mapping; Joel Moss and William T. Gorman mapped the topography and supplied the control for the detailed geologic mapping; and Stephen D. Becker conducted the dip-needle work.

During the months of June through August the U. S. Bureau of Mines maintained a camp in the area and trenched and sampled the magnetite deposits. This party was under the direction of W. S. Wright.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to the engineers of the U. S. Bureau of Mines, W. S. Wright and Earl L. Fosse, who aided the field party in many ways. For much of the field season the U. S. Geological Survey party occupied a cabin in the Jumbo basin belonging to Alfred Johnson of Hydaburg, to whom thanks are due. William S. Twenhofel, G. D. Robinson, and Lawrence A. Warner of the Geological Survey have given much helpful advice in the preparation of this report. The writer is especially grateful to Matt S. Walton of the same organization for help in interpreting the magnetic data. Professors L. C. Graton, E. S. Larsen, and M. P. Billings of Harvard University have kindly read the report and offered many helpful suggestions.

GEOGRAPHY

LOCATION AND ACCESSIBILITY

The Jumbo basin, so named for the principal mine within this area, is on the west coast of Prince of Wales Island about 40 miles airline and 110 miles by boat west of Ketchikan (figs. 1, 2). It is part of the so-called Copper Mountain area. Hydaburg, the nearest source of supplies, is a small Indian village 15 miles distant by boat. It contains a cooperative cannery, general store, and post office. Steamers rarely call at Hydaburg; and

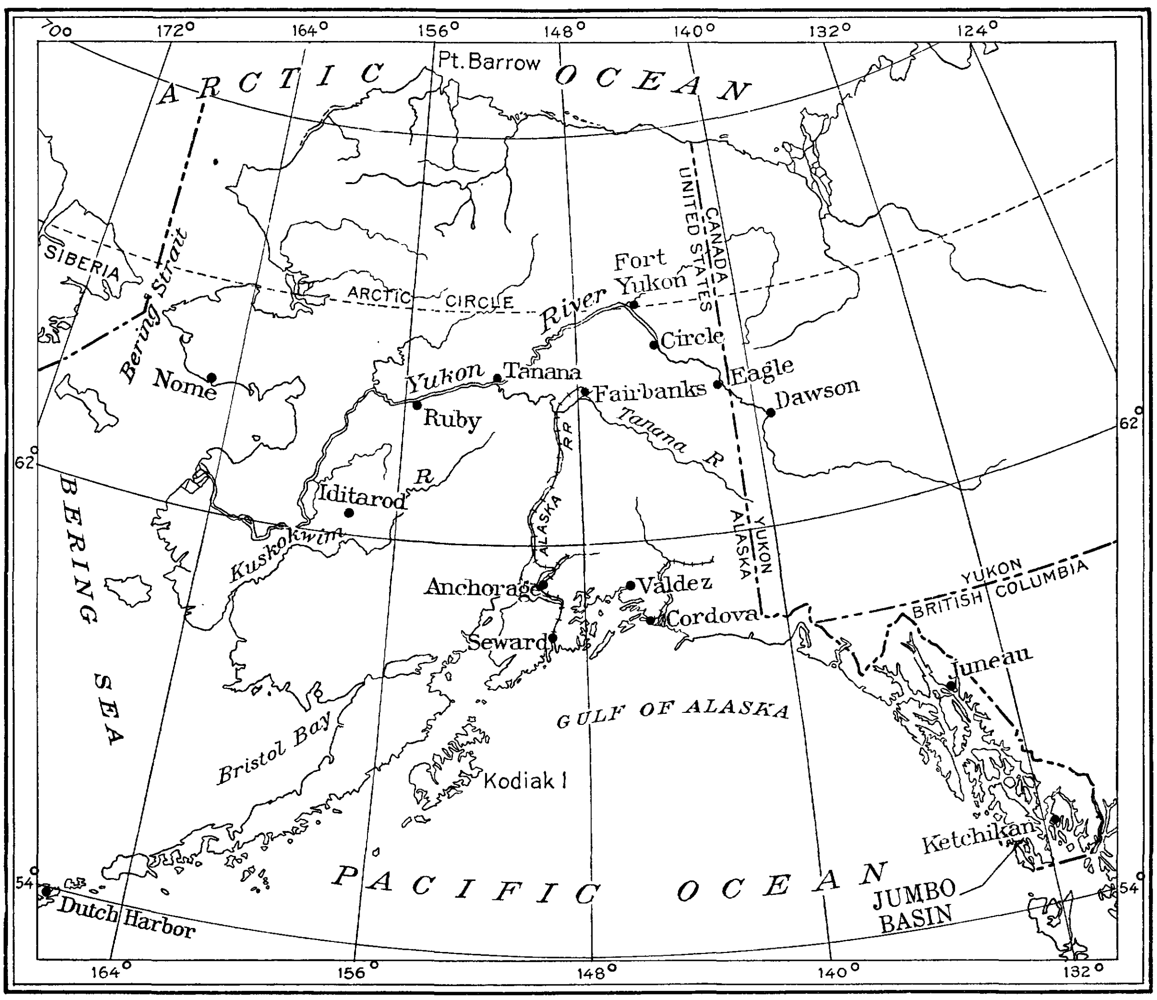

FIGURE 1.—Index map of Alaska showing the location of the Jumbo basin, Prince of Wales Island.

supplies from the States must be transshipped via Ketchikan. Weekly scheduled boat service is maintained from Ketchikan to Hydaburg and neighboring points, and supplies can be delivered at the Jumbo basin by special arrangement. Daily air service is maintained between Hydaburg and Ketchikan.

Hetta Inlet (fig. 2) provides a deep-water passage to the Jumbo basin. Boats may anchor safely in Copper Harbor or on the north side of Jumbo Island in Hetta Inlet.

Jumbo basin comprises the drainage basin of Jumbo Creek, an area of about two square miles east of Hetta Inlet. Three small areas within the basin were mapped in detail: the old Jumbo mine near the head of the basin; the Magnetite Cliff deposits which, in part, crop out as a cliff several hundred feet high on the north slope of the basin; and the upper magnetite deposits, which are northeast of the Magnetite Cliff bodies. A good trail extends from the beach near the mouth of Jumbo Creek to the workings of the old Jumbo mine near the head of the basin. During the summer of 1944 the Bureau of Mines constructed trails which lead from the Jumbo mine trail to the Magnetite Cliff and the upper magnetite bodies. No attempt was made to build permanent trails, and, within a few years, these trails will be obscured by brush.

TOPOGRAPHY

Prince of Wales Island in the vicinity of the Jumbo basin is a rugged, recently glaciated land mass characterized by numerous cirques, glacier-carved lake basins, fiords, and precipitous slopes. Deep, drowned glacial valleys radiate from the center of the island. Among these are Hetta Inlet, Nutkwa Inlet, Klakas Inlet, Twelvemile Arm, Cholmondeley Sound, Moira Sound, and many others. Numerous lakes, ranging in size from a few acres to several square miles, are scattered over the island at various elevations. Streams are youthful and their profiles extremely irregular. Glacial markings are present on knobs and shoulders of the more resistant rocks.

Jumbo basin is a short U-shaped valley with a cirque at its head. The side walls of the valley are precipitous. Slopes average about 40 degrees and rise to Mount Jumbo (alt. 3,464 ft) and Copper Mountain

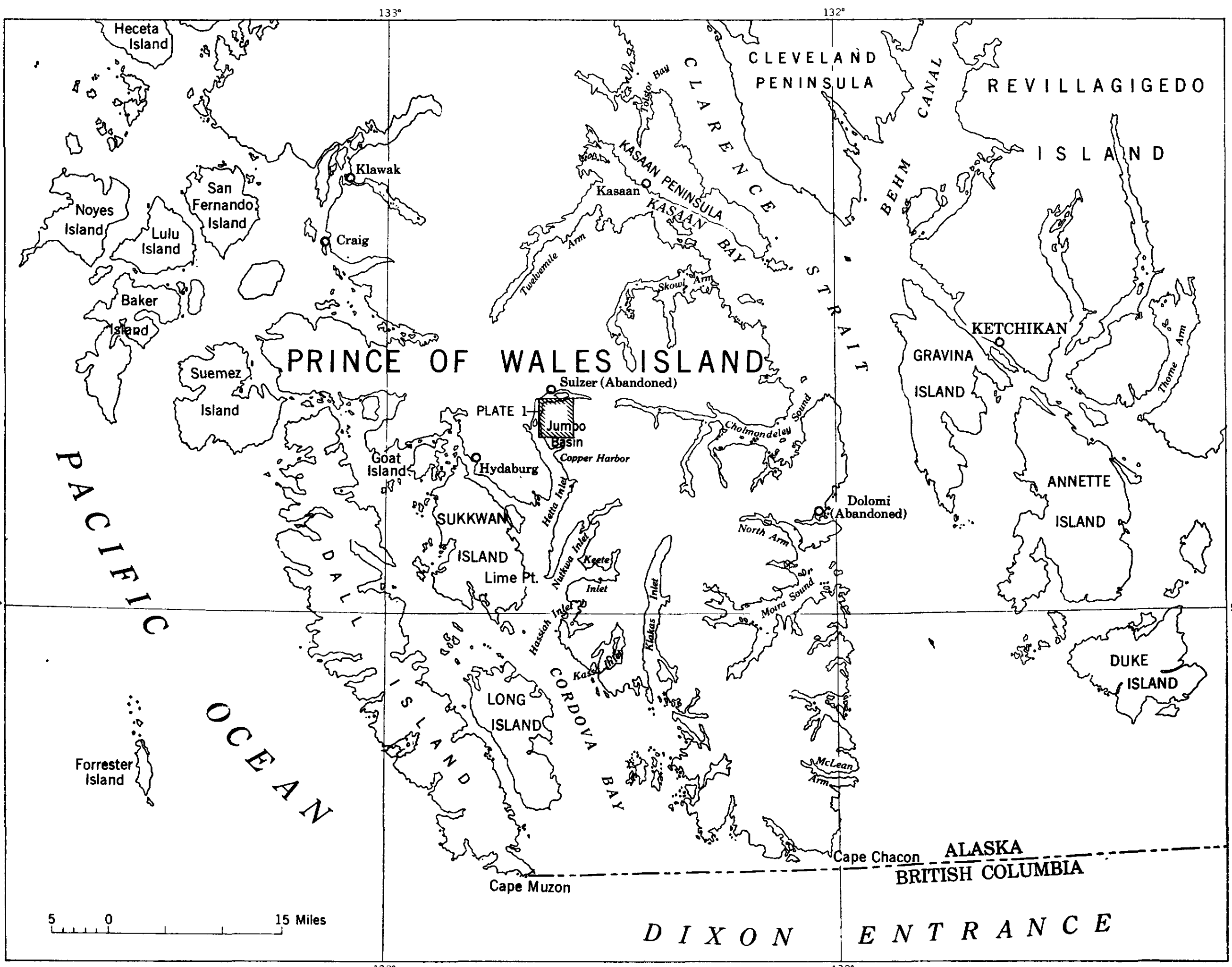

FIGURE 2.—Index map showing the southern portion of Prince of Wales Island and vicinity.

(alt. 3,946 ft), which bound the eastern portion of the basin.

Karst topography has developed in the trough of the basin. Sinkholes and caverns have formed in extensive limestone beds. Jumbo Creek flows through subterranean channels for a part of its course, locally disappearing into sinkholes and emerging from caverns.

CLIMATE, WATER SUPPLY, AND VEGETATION

The climate of Prince of Wales Island is mild and wet. The mean annual temperature, recorded by the United States Weather Bureau in Ketchikan, is about 45° F and ranges from an average temperature of about 33° F above zero in January to an average of 58° F in July and August. The maximum recorded temperature is 96° F, the minimum recorded temperature is −8° F.

The mean annual precipitation at Ketchikan is about 151 inches and at Hydaburg is about 110 inches (Henshaw, 1933, p. 143). At Hydaburg the precipitation reaches a monthly high of about 16 inches in October and November and a monthly low of about 4.5 inches in June and July. Records of precipitation kept at the Jumbo mine indicate that precipitation is greater on the mountain slopes than at sea level.

At sea level the snowfall, as a rule, is light and soon disappears, but in the higher mountains snowfall is heavy and patches of snow remain during most of the summer months.

Jumbo Creek is small but is of sufficient size and has enough fall to provide some water power. Pipe lines were constructed and a Pelton wheel installed to utilize power from Jumbo Creek during the period of mining activity at the Jumbo mine; however the facts concerning this power development are unknown to the writer and no special study of the problem was made by him. There is throughout the year an adequate supply of water for ordinary camp needs.

A fine stand of hemlock with some cedar and birch covers the Jumbo basin area up to timberline, which ranges from 1,500 to 2,000 feet in altitude. Hemlock trees with trunks as large as 4 feet in diameter were noted on the floor of the Jumbo basin. Dense growths of underbrush appear wherever trees have been cleared, as along old tramlines and trails, and near mine buildings. This new growth, consisting of devil's club, alder, small cedar, spruce, and hemlock, is almost impenetrable.

HISTORY AND PRODUCTION

The earliest mining development in the Jumbo basin and vicinity began in 1879 (Wright, 1915, pp. 55, 56), although copper ores in this region were reported many years previously by the Russians and by the Indians. The first claims were staked and recorded in the fall of 1897 (Brooks, 1902, p. 37) by Charles Reynolds and Thomas Wright. The claims of the Jumbo mine were staked by Aaron Shellhouse and recorded in the spring of 1898. In 1899 William Sulzer organized the Alaska Industrial Company to develop these deposits. Exploitation began in 1902, and by 1905 considerable reserves of copper ore had been exposed at the Jumbo mine. Several short adits were driven also to explore the copper-bearing magnetite deposits of the Jumbo basin, but because of their low copper content, exploration of the deposits was discontinued. In 1905 the Alaska Industrial Company started construction of an 8,250-foot aerial tramway extending from the workings of the Jumbo mine to Hetta Inlet (Wright, F. E. and C. W., 1906, p. 52). This tram and an additional tram 600 feet long were completed in 1906, and 150 feet of wharf and ore bins of 4,000 tons capacity were erected at the beach. Early in 1907 shipment of ore to the Tyee smelter in British Columbia began. The cupriferous magnetite bodies of the Jumbo basin were leased by the Alaska Industrial Company to the Tyee Copper Company in 1906 (Knopf, 1910, p. 142). This company put down nine diamond-drill holes aggregating 700 feet. The results of the drilling have not been available to the writer. By 1913 the Jumbo mine was the major copper producer in the Ketchikan district. It employed approximately 50 men on a year-round basis and ores were shipped to the Tacoma smelter (Smith, 1914, pp. 83, 84). In November 1915, the Alaska Industrial Company leased the Jumbo mine to Charles A. Sulzer. Records of the Geological Survey indicate that mining ceased in 1918 and no further production is recorded until 1923, at which time the mine was reopened and a few thousand tons of ore shipped. No production is recorded since 1923. In the summer of 1944 most of the buildings and the tramlines were in ruins and little usable equipment was left at any of the mines.

The total production of the Jumbo mine has amounted to over 5,000 tons of copper. Appreciable quantities of gold and silver were recovered with the copper; no attempt has been made to mine iron ore in the district. The amount of copper, gold, and silver produced from the Jumbo mine is shown in the table below.

Ores produced from the Jumbo mine, Prince of Wales Island, southeastern Alaska, 1907–44

[Compiled from records of the U. S. Geological Survey]

Year	*Ore sold or treated* (short tons)	*Copper* (pounds)	*Gold* (fine oz)	*Silver* (fine oz)	*Total value*
1907	15, 492	1, 545, 941	1, 065. 02	13, 699	$340, 245
1908	20, 733	1, 724, 491	1, 240. 09	15, 299	261, 339
1909	12, 782	1, 023, 038	638. 16	8, 971	150, 852
1910	14, 700	1, 778, 000	735. 01	10, 329	170, 378
1911	6, 903	453, 528	358. 60	4, 133	66, 294
1912	10, 926	987, 840	711. 02	8, 781	183, 091
1913	5, 706	466, 673	273. 85	3, 445	80, 076
1914	6, 596	468, 660	449. 02	4, 122	65, 913
1915	2, 021	117, 116	112. 09	1, 333	23, 488
1916	9, 412	596, 281	593. 56	6, 102	162, 970
1917	9, 787	486, 043	455. 00	5, 512	146, 637
1918	4, 779	221, 153	173. 75	2, 361	60, 578
1919–22 [1]					
1923	3, 100	325, 500	271. 19	3, 691	56, 481
1924–44 [1]					
Total	122, 937	10, 194, 264	7, 076. 36	87, 778	1, 768, 342

[1] No production.

GEOLOGY

The southern portion of Prince of Wales Island is underlain by a thick sequence of folded and metamorphosed Paleozoic sedimentary and volcanic rocks. These are cut by numerous intrusive igneous bodies.

The layered rocks in the vicinity of the Jumbo basin are made up of beds of calcareous schist, marble with interbedded schistose quartzitic members, quartz-mica schist, greenstone, and graywacke. These beds have been mapped by Buddington and Chapin (Buddington and Chapin, 1929, pp. 45–49, pl. 1) as part of the Wales group, which underlies a semicircular area on Prince of Wales Island, extending westward across the island from Dolomi to Sulzer and along the east shore of Hetta Inlet to Lime Point, Hassiah Inlet, and Kassa Inlet. Rocks of this group cover all of Long Island located in Cordova Bay and underlie most of the southern half of Dall Island. The base of the Wales group is nowhere exposed. It is unconformably overlain on the north and south by sediments of Devonian age. The trend of this belt of rocks is northeasterly and is approximately at right angles to the regional trend of rocks in southeastern Alaska. However, the trend of individual beds of the Wales group within this belt is northwesterly. The Wales group is believed to occupy the core of a large anticlinorium with its axis at right angles to the trend of major folding.

The age of the Wales group is not certainly known. The lithology, together with poorly preserved fossils collected by Chapin from Lime Point, Prince of Wales Island, are suggestive of Silurian age for at least part of the limestone interbedded with upper greenstones. Buddington (Buddington and Chapin, 1929, p. 49) considers most of the Wales group, however, to be pre-Silurian and possibly pre-Ordovician in age.

The rocks of the Wales group are cut by several stocks that range in composition from monzonite to gabbro. These stocks, with an areal extent of as much as 30 square miles, are probably parts of a larger underlying batholith related to the Coast Range intrusive. The main axis of the Coast Range batholith lies a few tens of miles to the east.

Swarms of dikes, locally comprising as much as 50 percent of the bedrock, cut the sediments but, for the most part, do not cut the larger stocks. They are predominantly andesites and basalts, but some lamprophyre dikes were noted.

The bedded rocks have been intensely folded and metamorphosed. Presumably the major period of folding, metamorphism, and igneous intrusion was in Late Triassic or Early Cretaceous time.

The Jumbo basin is underlain by a series of intensely folded metamorphosed volcanic and sedimentary rocks. These beds are cut by a large intrusive mass which ranges widely in composition. Aureoles of contact-metamorphic minerals are present in marble and calcareous schist beds, both adjacent to the intrusion and marginal to inclusions within it (pl. 1). Lenticular bodies of magnetite and chalcopyrite are locally present in the zone of contact-metamorphic silicates.

BEDDED ROCKS

The bedded rocks within the Jumbo basin area comprise a thick sequence of metamorphosed limestones, fine-grained clastic rocks, and volcanic rocks of Paleozoic age. These stratified rocks form two units possibly separated by an angular unconformity. The lower unit is made up of the metamorphosed limestone and schist, and the upper, of greenstone and clastic rocks.

LIMESTONE

The oldest rocks exposed in the Jumbo basin comprise a series of limestone beds that form a broad north–south belt parallel to the western margin of the large intrusive stock (pl. 1). These beds crop out along the south shore of Hetta Inlet a few thousand feet east of Gould Island. They are also well exposed for several thousand feet along the shore of Hetta Inlet south of the Jumbo mine beach camp near Jumbo Creek and along almost the entire course of Jumbo Creek.

The limestone beds are very soluble and outcrops along the beach are deeply pitted and locally undercut by the waves. A youthful karst topography is well developed along Jumbo Creek, and many of the major streams on the northwest slope of Mount Jumbo emerge from small caverns. A diagnostic hummocky topography has developed in areas underlain by limestone; thus limestone can be mapped with some assurance in areas covered by a heavy soil mantle.

The thickness of the limestone beds may be as much as 1,000 feet; but the actual thickness is unknown as the base of the series is not exposed in the area studied.

A few thin beds of schist and at least one of quartzite are interstratified with the limestone. These beds nowhere make up more than 15 percent of the series. They are lenticular and cannot be traced for any considerable distance. The interstratified schist beds are less competent than the surrounding limestone layers and have been contorted and sheared.

Some of the limestone has been bleached and recrystallized by magmatic solutions. Elsewhere the limestone ranges from blue to black finely crystalline rock. Some carbonaceous material is locally present, evenly disseminated throughout the limestone or arranged along bedding planes. Where argillaceous material is present the rock is altered to slate. The limestone is, in general, exceptionally pure.

As seen under the microscope the limestone consists almost exclusively of intricately twinned calcite grains averaging 1 millimeter in size. Few accessory minerals are present. An analysis of limestone from the Jumbo mine (Wright, C. W., 1915, p. 87) follows.

Analysis of limestone from Jumbo mine, Prince of Wales Island, Southeastern Alaska

[George Steiger, analyst]

SiO_2	0.61	CO_2	44.07
Al_2O_3	.30	S	.06
Fe_2O_3	.48	MnO	.03
MgO	8.00		
CaO	46.45		100.22
H_2O	.22		

The above analysis indicates that the sample contains 36 percent of dolomite and 63 percent of calcite. Of a suite of marble specimens studied by means of the etching technique described by Rodgers (1940, pp. 788–798), only one specimen, a coarsely crystalline marble from near the Magnetite Cliff deposits, contained appreciable dolomite; calcite was the only carbonate noted in the remaining specimens. It is possible that some dolomitization took place at the time of contact mineralization, but such dolomitization, if any, was restricted in area and intensity.

All of the known contact ore deposits and most of the associated skarn minerals have formed by replacement of the marmorized limestone beds.

CALCAREOUS SCHIST

Calcareous schist beds conformably overlie the limestone beds and are interbedded with the upper few hundred feet of the limestone. Because of their importance as loci of skarn minerals they are here discussed separately but have been included in both the quartz-mica schist and marble map units (pl. 1).

The calcareous beds crop out along the shore about 1,500 feet north of the mouth of Jumbo Creek, in the northern portion of the Jumbo basin area, and at a point on the beach about a mile west of the entrance to Gould Passage on the south shore of Hetta Inlet. Calcareous schists are also well exposed in a small syncline that crops out at an altitude of 2,000 feet in a gully a few hundred feet west of the Magnetite Cliff deposit.

Beds of calcareous schist which overlie the limestone and are mapped with the quartz-mica schist unit range in composition from finely crystalline, almost pure limestones through biotite-amphibole and quartz-rich calcareous schists to fine-grained chlorite-epidote-albite schists containing some muscovite and calcite. The rocks are extremely variable in proportion of constituent minerals. They are typically composed of thin alternating laminae, 1–5 millimeters in thickness, of carbonate and silicate minerals. Locally they are graphitic. These beds form gradational phases between the marble beds below and overlying schists. For the most part the calcareous schist beds are only a few tens of feet thick and cannot be traced along the strike for any great distance.

Beds of calcareous schist, which locally grade into a quartzite, are interbedded with the marbles and have been mapped with them (pl. 1). These beds appear to be thin and discontinuous and crop out only within the upper few hundred feet of the marbles.

The calcareous schist beds are more brittle than are the marbles and more susceptible to chemical attack than are the calcite-free quartzite schists; they therefore appear to have been especially favored loci of skarn-mineral formation adjacent to the intrusive, though no large ore bodies are known to have formed in them. The extensive garnet deposits on the northeast slope of the Jumbo basin are derived partly from calcareous schist beds, and partly from the overlying quartz-mica schist. The calcareous schists deserve special attention in future prospecting.

QUARTZ-MICA SCHIST

Intensely folded quartz-mica schist crops out in the Jumbo basin in a belt roughly parallel to Hetta Inlet and in a syncline a few thousand feet north of the Magnetite Cliff body. The quartz-mica schist conformably overlies and grades into the marble and calcareous schist.

The apparent thickness of the zone of quartz-mica schist changes abruptly (pl. 1). Locally the zone has an outcrop width of as much as 1,500 feet, as along the south shore of Hetta Inlet about a mile east of the entrance to Gould Passage; elsewhere the beds have an outcrop width of less than 100 feet, as along the beach about a thousand feet north of the mouth of Jumbo Creek. The quartz-mica schist beds are not present on the northwest shore of Hetta Inlet about 1½ miles southwest of the abandoned town of Sulzer (Wright, C. W., 1915, pl. 5). At this point greenstone beds, which normally overlie the quartz-mica schist, overlie and are interbedded and interfolded with marble layers. Extreme variation in outcrop width and local disappearance of the quartz-mica schist beds are partly explained by thickening on the crests and thinning on the flanks of folds. However, the relations between marble and greenstone southwest of Sulzer suggest strongly either that an angular unconformity is present between the schist and limestone beds and the overlying greenstone beds or several greenstone beds are present. The extreme variation in outcrop width of the schist beds may be partially or largely due to such an unconformity.

The quartz-mica schists are predominantly dense black thin-bedded rocks, composed largely of finely crystalline quartz grains, 0.01–0.02 millimeters in diameter, with numerous sericite and a few biotite flakes oriented in planes parallel to the foliation of the rocks. Locally thin beds are composed predominantly of sericite. A small percentage of graphite is generally present, though in amounts smaller than is suggested by the dark color of the beds. Locally the beds are white to pink and are almost pure quartzites. At least one fine-grained marble bed and several beds of volcanic material, altered to an amphibole-chlorite schist, are present.

These beds exhibit textures and mineralogical relationships typical of low-grade regional metamorphism and are, in general, similar to beds classed by Harker as phyllites (1939, pp. 161, 211, 215). Locally, as near the intrusive body, the schists have been recrystallized to a medium- to coarse-grained biotite-quartz gneiss made up dominantly of feldspar and clinopyroxene with accessory magnetite. Extensive zones of contact-metamorphic minerals, predominantly garnet, have developed locally in the schists.

In spite of the high quartz content the beds of this sequence are relatively incompetent and have been intensely folded. Numerous small folds and crenulations may be seen even in thin section, marked by zones rich in micaceous minerals. Some of the quartzite in thin sections likewise shows a pronounced foliation of sericite grains and graphite flakes oriented parallel to the axial planes of small folds (fig. 3).

GREENSTONE SCHIST

Greenstone schist is believed to overlie unconformably the older bedded rocks of the Jumbo basin. The beds of this series underlie Jumbo Island and crop out along most of the east and west shores of Hetta Inlet.

The thickness of the greenstone-schist sequence is unknown. The beds have an outcrop width of about four miles in the vicinity of Hetta Inlet (Buddington and Chapin, 1929 pl. 1), and may be many thousands of feet thick. Probably intense folding and also faulting have made the thickness of the beds appear much greater than is actually so. More than one greenstone layer may be present.

The beds of the greenstone-schist sequence are predominantly composed of igneous material interbedded with some siliceous sedimentary material. The igneous material consists largely of water-laid tuffs and agglomerates with a few thicker flows ranging in composition from rhyolite to basalt. The feldspar of the flows has been altered to zoisite and sericite, and the original dark minerals have altered to amphibole, epidote, and chlorite.

The greenstone-schist beds grade into and are interbedded with schists containing partly pyroclastic and partly arenaceous and argillaceous material, which in turn grades into argillites, almost pure quartzites, and graywackes. The sedimentary beds composed predominantly of arenaceous material can be differentiated in thin sections from comparable beds in the underlying quartz-mica schist series. All quartz schists interbedded with the greenstones and grading into them contain 5–25 percent of coarse angular detrital feldspar in grains 0.2–1 millimeter in diameter, in a ground mass of quartz and feldspar having an average grain size of 0.05 millimeter (fig. 4). No coarse feldspar was observed in the beds of the underlying quartz-mica schist sequence. In a few beds the proportion of coarse detrital grains in a fine matrix is high enough for the beds to be classified as graywacke (Pettijohn, 1943, pp. 941–956).

Locally some limestone beds are interbedded with greenstone. These beds are lens-shaped and appear to grade laterally into beds of pyroclastic material.

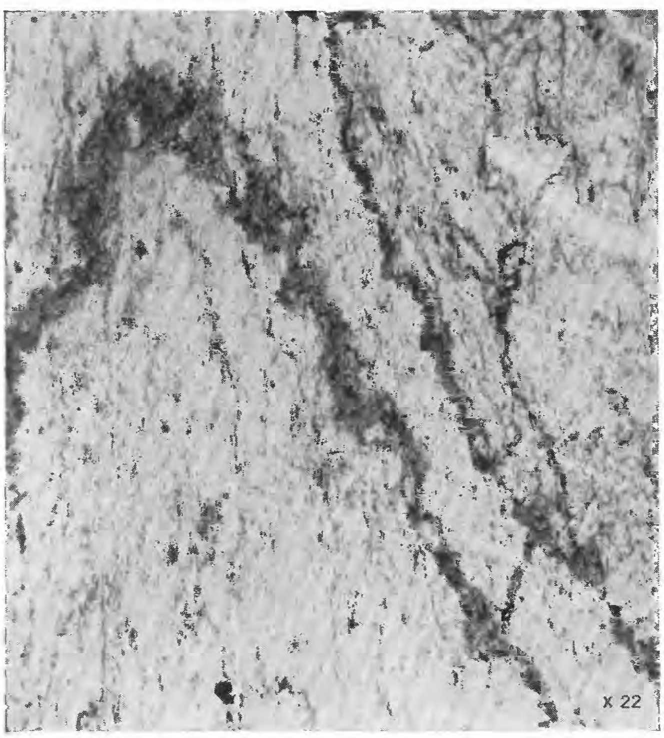

FIGURE 3.—Fold in fine-grained quartzite, Jumbo basin, Alaska. Graphite flakes are oriented parallel to the axial plane of the fold. Plane light.

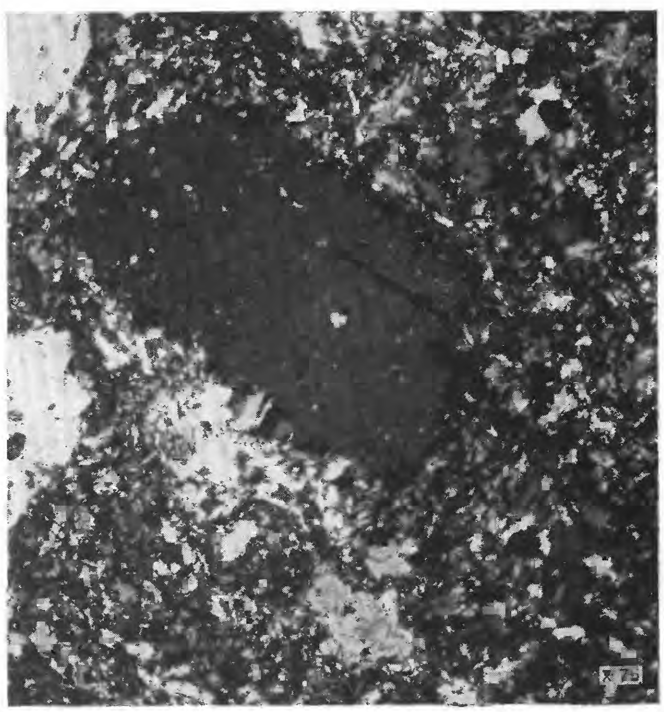

FIGURE 4.—Coarse detrital feldspar grains present in typical fine-grained sedimentary beds associated with greenstone schist, Jumbo basin, Alaska. Crossed nicols.

Fossils in limestone collected from Lime Point in rocks similar to those of the Jumbo basin have been identified by Edwin Kirk and "suggest that some of the limestone intercalated with the greenstone is of Silurian age" (Buddington and Chapin, 1929, p. 49). The marble beds that apparently underlie the greenstone unconformably are believed by Buddington and Chapin (1929, pp. 49, 391) to be pre-Silurian and possibly pre-Ordovician in age. Inasmuch as the greenstone is believed to be unconformably overlain by Devonian rocks, considerable orogenic disturbance may have both opened and closed the Silurian period in southeastern Alaska.

INTRUSIVE ROCKS

Igneous rocks that range widely in composition and texture crop out in the Jumbo basin area. H. E. Merwin (Wright, C. W., 1915, pp. 33–43) has described many of the rocks of the Jumbo basin and vicinity, and his studies have been drawn upon freely in the following discussion.

Part of a large, coarse-grained intrusive stock about 10 square miles in area occupies the eastern portion of the Jumbo basin. This has been mapped as granodiorite (pl. 1), but the rocks of the stock range in composition from syenite to gabbro.

Numerous intrusive dikes, which locally comprise a large portion of the outcrop area, are present. These dike rocks include pegmatite, andesite, lamprophyre, and related rock types.

GRANODIORITE AND RELATED ROCKS

STRUCTURE

The stock in the Jumbo basin, predominantly granodiorite in composition, is believed to be the apically truncated part of a large deep-seated mass. Where they can be observed, contacts between the intrusive mass and the surrounding bedded rocks dip away from the middle of the stock exposure. In cross sections, therefore, the size of the body appears to increase with depth. The outward dip of the contact may be noted in the underground workings in the vicinity of the Magnetite Cliff deposits (pl. 5) and at points where the contact between granodiorite and bedded rocks crosses creek valleys.

PETROGRAPHY AND PETROLOGY

COMPOSITION

The composition of the stock varies markedly from place to place. This variation arises both from differing proportions of constituent minerals and from the widely varying composition of these minerals within the one structurally homogeneous mass. Rock types within the stock appear to grade into each other; no evidence of successive intrusion was noted.

Wright (1915, pp. 33–43) refers to Merwin's work on the composition of rocks found in various portions of the stock. Some of the specimens thus studied presumably came from apophyses and offshoots of the main stock. Wright's report contains a map of the stock area and gives locations from which the specimens were taken. Some of the rocks, tabulated below, are here assigned new type names.

Modal composition of rocks from the Jumbo basin stock, Prince of Wales Island, southeastern Alaska

Rock name	Locality No.	Plagioclase	Orthoclase	Quartz	Hornblende	Augite	Biotite
Augite granite	626	5(An_{10-15})	75	10	----	8	----
Quartz monzonite	128	50(An_{10})	35	15	----	----	----
Hornblende granodiorite	121	50(An_{10-15})	20	5	15	5	----
Hornblende granodiorite	133	60(An_{25})	10	10	20	(1)	----
Biotite granodiorite	127	60(An_{30})	5	20	----	----	15
Augite-hornblende granodiorite.	677	40(An_{30})	25	10	10	10	----
Granodiorite	No. 4 claim	50(An_{35})	30	10	5	5	----
Hornblende monzonite	39	35	20	----	35	5	5
Augite-hornblende monzonite.	37	40	25	----	20	10	5
Hornblende monzonite	643	60(An_{40})	20	(1)	15	5	----
Augite diorite	662	60(An_{35})	5	(1)	----	30	5
Hornblende gabbro	98	15(An_{60})	7	----	60	10	(1)
Hornblende gabbro	45	20(An_{60})	----	----	70	10	----
Average of group		42(An_{30})	21	7	19	8	2

[1] Minor constituent.

The average rock corresponds to a granodiorite. A complete analysis of a typical granodiorite from the Jumbo basin (Wright, 1915, p. 34) and a calculation of the normative mineral composition follow:

Composition of a granodiorite sample from the Jumbo basin, Prince of Wales Island, southeastern Alaska

[George Steiger, analyst]

Chemical Analysis

SiO_2	59.44	H_2O	0.62
Al_2O_3	17.40	TiO_2	.66
Fe_2O_3	3.30	P_2O_5	.28
FeO	2.77	S	.02
MgO	1.81	MnO	.17
CaO	6.51	BaO	.07
Na_2O	4.22	SrO	.05
K_2O	3.12		
			100.44

Normative minerals

Quartz	8.94	Hypersthene	1.93
Orthoclase	18.35	Magnetite	4.87
Albite	35.63	Ilmenite	1.37
Anorthite	19.46	Apatite	.67
Diopside	8.68	Water	.62

The modal percentages of minerals shown in the table above emphasize the extreme variability of rocks from the Jumbo basin stock; yet the major part of the stock is granodiorite of which the specimen analyzed above is believed to be typical. It is noteworthy that the average of a group of specimens collected at random from the stock shows a composition similar to that of the main mass of the stock, and suggests that the variants represent differentiates of the granodiorite.

IGNEOUS SUITE FROM THE JUMBO BASIN AND VICINITY

The writer collected a suite of specimens from the Jumbo basin and vicinity, representative of a portion of the intrusive stock in contact with ore-bearing zones. The approximate mineral composition of a group of these rocks is recorded below.

Modal composition of igneous rocks from the Jumbo basin, Prince of Wales Island, southeastern Alaska

Rock name	Specimen No.	Plagioclase	Ortho-clase	Quartz	Horn-blende	Augite	Biotite	Acces-sories
Augite granodiorite	44-AK-74	40 (An_{47})	30	20	----	10	----	tr.
Augite monzonite	44-AK-4	50(An_{30})	30	1	2	10	5	3
Augite monzonite	44-AK-20	50(An_{35})	25	5	----	12	6	2
Quartz diorite	44-AK-11	65 (An_{40})	----	10	----	17	----	8
Diorite	44-AK-131	60(An_{50})	----	----	----	25	13	2
Gabbro	44-AK-43	55(An_{55})	----	----	7	30	3	5

These analyses indicate that ore-bearing contact-metamorphic zones are adjacent to widely differing variants of the stock. No particular variant of the stock is preferentially accompanied by ore.

MONZONITE, GRANODIORITE, AND QUARTZ DIORITE

Petrographic examination of these specimens affords some possible reasons for the wide variation in composition within the stock.

In thin section plagioclase is seen to be present as strongly zoned laths, 1–1.5 millimeters in length, in many specimens poikilitically included in large orthoclase grains 0.5–1 centimeter in length. The orthoclase feldspar appears to have flooded the rock (figs. 5, 6) and to be replacing earlier quartz, plagioclase and possibly biotite. The evidence of late-stage introduction and attack by orthoclase of the earlier rock-forming minerals is clear. The *B* index of refraction of the plagioclase ranges from 1.545 to 1.554, which, according to Calkin's feldspar curves (Kennedy, G. C., 1947, pp. 561–574), indicates a range in anorthite content of An_{25}–An_{40}. A small amount of hornblende, pleochroic in yellow to yellow green, is present in some specimens. This hornblende is being centripetally attacked by later pyroxene and is ragged in appearance. About 5 percent

FIGURE 6.—Plagioclase replaced by late orthoclase, with Carlsbad twin boundary retained in orthoclase, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

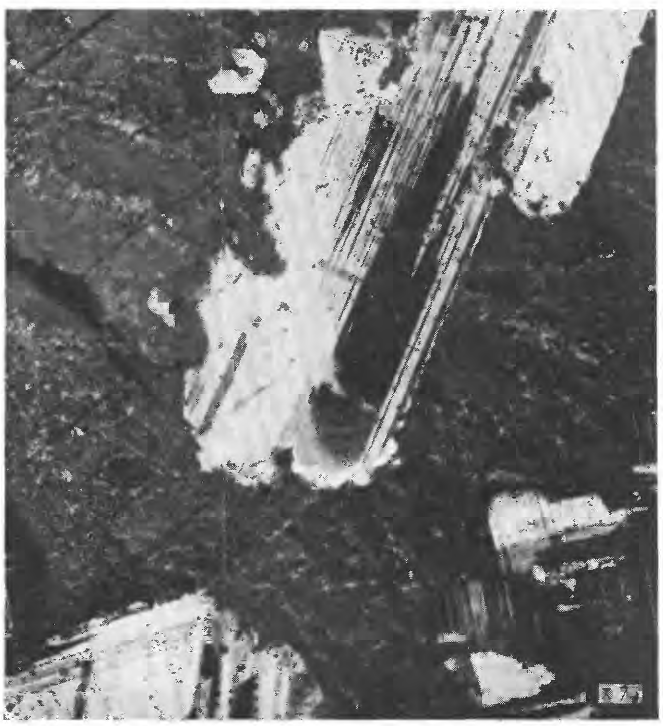

FIGURE 5.—Residual crystals of plagioclase surrounded by orthoclase, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

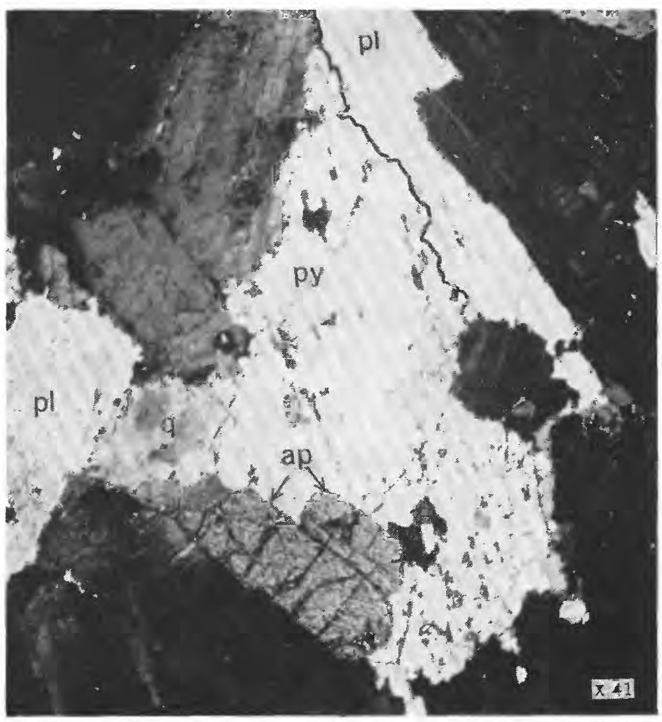

FIGURE 7.—Apatite and late pyroxene in quartz diorite, Magnetite Cliff, Jumbo basin, Alaska. Plagioclase, pl; pyroxene, py; quartz, q; apatite, ap. Crossed nicols.

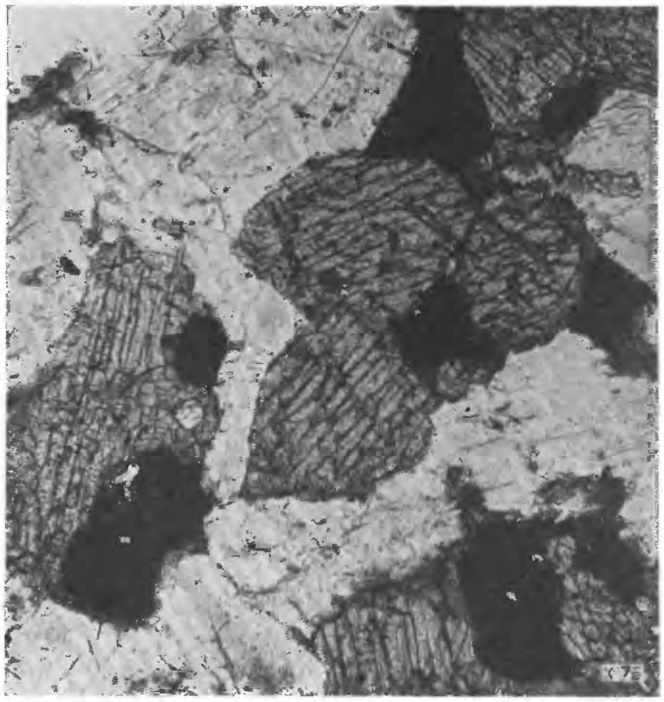

FIGURE 8.—Magnetite preferentially replacing diopside in gabbro, Jumbo mine, Alaska. Plane light.

of primary pyroxene, showing typical crystal outline, is present. Pyroxene is also present in minute veinlets cutting the plagioclase and replacing the amphibole (fig. 7). The pyroxene has a *B* index of refraction of about 1.693. If the assumption is made that only small amounts of sesquioxides are present, this index is that of a pyroxene containing 33 percent of the hedenbergite molecule and 67 percent of the diopside molecule (Kennedy, G. C., 1947). Coarse euhedral grains of sphene and apatite ranging in size to 1 millimeter are abundant. Magnetite is present in considerable quantity and almost always replaces earlier grains of pyroxene, as illustrated by figure 8.

From these data we may infer that early crystallization of pyroxene, plagioclase, quartz, and hornblende was followed by extensive introduction of orthoclase. The amphibole was partly converted to pyroxene, and pyroxene was recrystallized along minute veinlets in the plagioclase and replaced by magnetite, presumably at the time when the magnetite deposits in the marble adjacent to the monzonite were formed.

The range in composition of the rocks even in a very restricted area must be emphasized. Rock containing 30 percent orthoclase may grade within a few feet into material containing no orthoclase and 40–65 percent of plagioclase. The content of quartz shows an even wider range. Locally, it may be as high as 20 percent or it may be absent. Surprisingly, the mineral most constant in amount is pyroxene.

The specimens studied by the writer show a slight correlation between the albite content of the plagioclase feldspars and the amount of orthoclase in the rock (table, p. 9); however, the much larger and more representative suite of rocks studied by Merwin indicates little if any correlation (table, p. 8). Rocks described by Merwin as containing plagioclase with an average composition of An_{40} may contain as much orthoclase as rocks with plagioclase An_{25}, or more. Such an extreme range in content of orthoclase and lack of correlation between soda and potash content is decidedly unusual for rocks that have followed a normal process of crystallization from a magma and which are part of the same stock or are comagmatic (Bowen, 1928, pp. 54–174). This statistical evidence of the ratios of the minerals in the rocks, coupled with the evidence from thin sections, suggests that late-stage, nonuniform introduction of potash into a partly or largely crystallized magma may account for much of the variation in composition of the stock. At the time of introduction of potash, the preexisting plagioclase may have been slightly enriched in albite, and some sodic plagioclase may have been introduced.

CONTAMINATED ROCKS

Some assimilation of country rock and contamination of the magma has taken place, though, in general, the amount does not seem large. Schlieren and reworked inclusions are rare.

Specimen 44–AK–131 was collected near the contact of the stock and the bordering feldspathic schist. This rock contains about 40 percent of fine-grained plagioclase averaging about 0.02 millimeter in diameter, intermixed with fine-grained pyroxene. Coarse pyroxene grains and biotite flakes show a marked parallelism and are arranged in zones throughout the rock. Pyroxene, biotite, and large plagioclase grains poikilitically include the groundmass feldspar grains. The parallelism of the dark minerals and the poikilitic texture of the coarse plagioclase, biotite, and pyroxene suggest that the rock is a partly reworked schist, now mineralogically equivalent to a diorite.

GABBROIC ROCKS

Gabbroic rocks were noted at two localities in the stock. Specimens collected from the mouth of adit 4, the lowermost adit of the Jumbo mine (specimen 44–AK–43), are of a fresh, coarsely crystalline gabbro containing about 30 percent of diopside (*B* index 1.693) and 60 percent of labradorite feldspar. The limits of this body of gabbro were not determined, and its relations to the surrounding more silicious rocks are unknown. The gabbro is believed to be locally gradational into surrounding diorite.

Hornblende gabbros crop out along the beach on the south shore of Hetta Inlet opposite the western limit of Gould Island. Some field evidence suggests that these rocks are part of the main intrusive stock (pl. 1), though Wright (1915, pl. 5) has mapped them as a separate mass. The gabbros are characterized by hornblende which in places constitutes as much as 70 percent of the rock. The hornblende is extremely variable in grain size. Locally, the rock has a pegmatite texture and contains hornblende crystals as long as 10 centimeters. Merwin describes specimens of hornblende gabbro from a small intrusive, presumably an apophysis of the Jumbo basin stock which contains 7 percent of orthoclase (Wright, 1915, p. 37), indicating the close affinity between these rocks and the orthoclase-bearing, more siliceous rocks of the stock.

DISTRIBUTION OF ROCK TYPES WITHIN THE STOCK

In general, the more mafic rocks of this stock, the gabbros and the calcic diorites, occur near the margins of the stock and as small outlying intrusives. The core of the stock is composed largely of granodiorites and monzonites of a fairly uniform composition. Wright (1915, pp. 36, 37) notes further that the rock that contains the largest percentage of orthoclase and that is near syenite in composition "forms parts of the batholithic mass occurring near its margins. . . . It is also found in outlying dikes and in tongues branching from the main intrusive masses. . . ." No simple explanation seems to account adequately for the localization of both the more calcic variants and the more potassic variants near the margins of the stock.

COMPARISON OF ROCKS OF THE INTRUSIVE STOCK WITH ROCKS OF THE COAST RANGE BATHOLITH

The average composition of the igneous rocks of the stock in the Jumbo basin is compared with the composition of the rocks of the Coast Range batholith in the following table:

Average mineral composition of Jumbo basin stock and Coast Range batholith, southeastern Alaska

	Plagioclase	Plagioclase feldspar	Quartz	Pyroxene	Hornblende	Biotite	Accessories
1	42 (An_{30})	21	7	8	19	2	1
2	51 (An_{34})	21	9	12		3	4
3	44 (An_{30})	21	22		5	6	2
4	54 (An_{40})	2	20		11	12	1
5	44 (An_{30})	21.6	20		6	7	1.4
6	57.5 (An_{40})	5	9.5	1.5	20.5	3.5	2.5
7	55 (An_{40})	6	9	3.5	20	4	2.5
8	47.4 (An_{41})	6.6	19.4		7.6	11.6	2.9

1. Average of 13 specimens collected by Wright from stock in the Jumbo basin and vicinity.
2. Average of four specimens collected by the writer from the vicinity of the Magnetite Cliff deposits, Jumbo basin.
3. Average of 19 specimens taken completely across the batholith at intervals along the Stikine River, 23 specimens taken at intervals along Portland Canal, and 18 specimens taken along Chikamin River, obtained by averaging Buddington's data (Buddington, 1929, pp. 178–180).
4. Average of 20 specimens from western portion of Coast Range batholith, in southeastern Alaska (Buddington, 1929, pp. 178–180).
5. Average of 44 specimens from core of Coast Range batholith between Portland Canal and Stikine River (Buddington, 1929, p. 180).
6. Average of 65 specimens from Prince of Wales-Chichagof belt (Buddington, 1929, p. 188).
7. Average of 27 specimens from Prince of Wales and Etolin Island (Buddington, 1929, p. 188).
8. Average composition of 7 representative specimens from Upper Jurassic or Lower Cretaceous intrusive rocks in the Ketchikan and Wrangell districts (Wright, F. E. and C. W., 1908, pp. 63–65).

The rocks are similar in that they generally range in composition from monzonite through granodiorite and quartz diorite to diorite. They may be assumed to be comagmatic largely because of their geographic distribution and similar structural relation to the surrounding bedded rocks. To a much smaller extent their chemical and mineralogical composition indicate consanguinity.

Mineralogical and chemical dissimilarities between the Jumbo basin rocks and those of the Coast Range intrusive are evident by comparing columns 1 and 2 with columns 3–8 of the foregoing table. The plagioclase feldspar of the Jumbo basin rocks is similar in amount and composition to that of the core of the Coast Range intrusive but is slightly more sodic than the plagioclase of the rocks of the western margin of the Coast Range batholith or of the typical stocks that lie in the Alexander Archipelago. The average percent of orthoclase is strikingly similar to that of the rocks of the core of the Coast Range batholith but is much greater than that of the rocks that lie along the western margin and to the west of the batholith. Notwithstanding the high alkali content of the Jumbo basin rocks, they contain much less quartz than do the rocks of the core of the Coast Range batholith of similar alkali content and even less quartz than the typical more calcic rock of the western border of the Coast Range batholith. The most distinguishing feature of the rocks of the Jumbo basin intrusive is the presence of minor to essential amounts of augite in almost all specimens studied. Augite is present in even the most alkalic variants of these rocks and only locally gives way to hornblende. In contrast, the dark constituents of the Coast Range intrusives are principally hornblende and biotite; augite is rarely observed.

In summary, the rocks of the Jumbo basin intrusive appear to have stronger alkalic affinities than do the rocks of the Coast Range batholith and the stocks which crop out along the western margin of the batholith in the Alexander Archipelago.

IGNEOUS ROCKS IN RELATION TO ORE DEPOSITS

All known ore deposits in the area, except a few very minor prospects, are in contact with the intrusive stock or lie within a contact-metamorphic aureole adjacent to the stock. The mineralizing fluids may be presumed to have come directly from the stock with which the deposits are in contact or, as is more likely, to have migrated from a deeper portion of the stock to their present position. Whichever is the case, the deposits are undoubtedly closely related to the stock, both genetically and geographically. Similar copper-bearing magnetite deposits on Kasaan Peninsula are closely associated with orthoclase-rich intrusive rocks (Goddard, Warner, and Walton), which have alkalic affinities somewhat like those here described. As these types of intrusives are definitely abnormal in this region, they may prove a guide in the search for other contact-metamorphic ore deposits bordering the Coast Range batholith.

DIKE ROCKS

Many different types of dike rocks crop out in the Jumbo basin. The dikes range in composition from granite to diabase and range in width from a few feet to several hundred feet.

DISTRIBUTION

Most of the dikes in the Jumbo basin cut the older metamorphosed bedded formations, and few dikes cut the intrusive stock. Locally, in the quartz-mica schist and in the greenstone schist beds, the dikes constitute as much as 50 percent of the outcrop area. Elsewhere they are sparsely distributed. For the most part the dikes in the older bedded rocks trend approximately east–west, and are fairly continuous along their strike.

Several apophyses of the intrusive stock, which are dike- and sill-like, cut the surrounding limestone in the Magnetite Cliff area and have controlled the localization of the magnetite deposits. Such apophyses are not common.

VARIETIES

Wright (1915, pp. 39–43) has reported a considerable variety of dike rocks in the vicinity of the Jumbo basin. Among these rocks are aplite, pegmatite, pyroxene-orthoclase diorite porphyry, lamprophyre, and andesite. Only the lamprophyre and diorite dikes are common.

The lamprophyre dikes are predominantly made up of hornblende and plagioclase, which ranges in composition from andesine to bytownite. Hornblende generally constitutes 45–65 percent and plagioclase 35–55 percent. The rocks have a seriate ophitic texture. Hornblende generally occurs as coarse phenocrysts 0.5–1 centimeter in length and as part of a finer-grained groundmass. A few phenocrysts of plagioclase were noted, but for the most part the plagioclase is present in fine grains 0.1–0.2 millimeters in length. Some of the coarser amphibole grains contain remnants of pyroxene. Locally, the dikes contain small amounts of chlorite, clinozoisite, biotite, and calcite.

Several large diorite dikes, as much as 200 feet wide and 1,500 feet in length, cut the bedded rocks (pl. 1), and in appearance and texture they seem to be related to the rocks of the intrusive stock. They are composed predominantly of plagioclase feldspar, augite, and biotite. Locally they contain some orthoclase.

AGE

All the observed lamprophyres and andesite dikes are restricted to the bedded rocks and are believed to be older than the intrusive stock. The large diorite dikes are believed to be of the same age as the intrusive stock. Only one small aplite dike, about 1 inch in width, was observed clearly to cut the intrusive stock. All the dikes are believed to be older than the contact-metamorphic deposits, though here too evidence is insufficient. Several of the dikes of the lamprophyre and andesite groups, which lie within the zone of contact alteration, are intensely altered to scapolite, garnet, diopside, and epidote and are clearly older than the contact metamorphism.

STRUCTURE

REGIONAL FEATURES

The Jumbo basin is on the crest of the Prince of Wales–Kuiu anticlinorium, a major structural feature of southeastern Alaska (Buddington and Chapin, 1929, pp. 304–306), which comprises all of Prince of Wales Island, most of Kuiu Island, and the archipelago west of Prince of Wales Island. The anticlinorium, which trends about N. 30° W., is 150 miles long and averages 40–50 miles in width.

The rocks of the Jumbo basin area lie in a folded belt of pre-Devonian sediments that trends at right angles to the major axis of the Prince of Wales anticlinorium. These beds probably occupy a culmination along the axis of the main anticlinorium. East of the Prince of Wales–Kuiu anticlinorium is the Keku–Gravina synclinorium, an extension of the Juneau synclinorium. These major features are made up of numerous synclines and anticlines, whose axes, in general, strike northwest but which are locally modified by forcefully emplaced intrusive bodies.

LOCAL FEATURES

FOLDS

The bedded rocks of the Jumbo basin area have been thrown into folds of several orders of magnitude. The intrusive stock is bordered directly on the west by a syncline of limestone, schist, and volcanic beds. The syncline immediately west of the stock can be traced from Jumbo Creek north about 1½ miles to Hetta Inlet (pl. 1). This fold is about 2,000 feet broad and is composed largely of limestone beds. An anticline lies parallel to and west of this syncline. The anticline is flanked by isoclinally folded beds of quartz-mica schist and graywacke which dip under Hetta Inlet.

The quartz-mica schist and greenstone beds appear to be much less competent than are the marble beds and have been thrown into tight isoclinal folds. These folds measure a few hundred feet from crest to crest; they are asymmetric, and their axial planes dip 60°–70° W. and NW. The folds are made up of numerous smaller drag and flowage folds a few inches to a few feet across.

The attitude of the folds is in a large measure dependent upon the intrusive body. The stock forced its way into the complex of previously folded sediments and partly made room for itself by pushing these rocks aside. The strike of the fold axes generally trends parallel to the contact between the granodiorite and the older bedded rocks. In the area immediately north of Jumbo Creek the fold axes trend north; in the northwestern portion of the area shown on plate 1, the fold axes trend northeast.

A series of crests and troughs with east-west axes is superimposed upon the dominant north-south direction of folding. In this connection it is again noted that the Jumbo basin rocks are part of a belt of pre-Devonian rocks that trends east and is overlain by formations that, in general, strike north-northwest. The east-west warping is clearly shown on plate 1 by the undulating trend of the contacts between schist and marble and between schist and greenstone. Three anticlinal and two synclinal east-west fold axes are present in the mapped area north of Jumbo Creek. The crests of these east-west folds are about 2,000 feet apart.

The major period of intense folding and deformation was probably in middle Cretaceous time, though deformation may have begun in the Jurassic. The cross folds may be the results of the same period of orogeny that produced the north-south system of folds, or they may represent much later, possibly Tertiary, folding. In support of the latter view, Buddington and Chapin (Buddington and Chapin, 1929, pp. 303, 304) note that the Jurassic(?) beds on the south side of Admiralty Island

> appear to have been folded along two axes—the usual north-northwest axis and another about parallel to Frederick Sound—that is, east-west. The axis of cross folding is reflected in the east-west strike of the beds between Cape Fanshaw and Bay Point.

The Jurassic(?) formations are exposed along what is believed to be the core of a dome in the Tertiary formations; it is deduced that the forces which effected the folding of the Tertiary formations

> were oriented almost at right angles to those that effected the folding of the Mesozoic formations in pre-Tertiary time.

Goddard[2] has described similar cross folding in the Mount Andrew-Mamie area on Kasaan Peninsula, Prince of Wales Island. There a system of gentle folds trending N. 80° E. is superimposed upon an intricate series of asymmetric anticlines and synclines which trend about N. 10° W.

FAULTS

No major faults were mapped in the Jumbo basin though it is possible that faults with a displacement of a few hundred feet may be associated with the east-west cross warping.

Minor faults, with a displacement ranging from a few inches to a few feet, are common. Numerous small faults were mapped in the Jumbo mine (pl. 7). Most of these fractures belong to two sets that intersect at right angles. The earlier set of small faults trends approximately N. 20° W., dips steeply west, and is essentially parallel to the contact between the granodiorite intrusive and the replaced marble. This set is cut by a later set of fractures which range in trend from N. 53° E. to N. 70° E. and dip steeply north. The footwalls of these later faults have been displaced to the southwest along the fault strike, a few inches to a few feet.

Faults of small displacement parallel to the contact between diorite and adjacent sediments were also noted in the workings of the Magnetite Cliff bodies.

Many dikes occupy earlier fractures along which displacement of a few feet can be noted. These dikes are well exposed along the beach a few thousand feet north of the mouth of Jumbo Creek.

CONTACT METAMORPHISM

A zone of contact-metamorphic or pyrometasomatic minerals, which replace both bedded and igneous rocks near the margin of the stock, includes the principal ore deposits within the area. The rocks, composed predominantly of garnet, diopside, calcite, clinozoisite, epidote, and scapolite, with which are associated magnetite, chalcopyrite, and pyrite, have been designated "skarn" on the maps and in the text of this report.

DISTRIBUTION OF THE SKARN ROCKS

Bands of skarn that range in width to as much as 1,000 feet occur along portions of the margin of the intrusive stock. Inclusions or roof pendants of the bedded rocks lying within the stock are partly or completely replaced by contact-metamorphic minerals. Bands of skarn are locally present along contacts between the igneous rocks of the stock and limestone, quartz-mica schist, and calcareous facies of the quartz-mica schist. The skarn area of greatest outcrop width, near the summit of Copper Mountain (pl. 1), is a replacement largely of calcareous schist and quartz-mica schist. By contrast, considerable portions of the contact between marble and the igneous rocks of the stock, as for several thousand feet south of Jumbo Creek, show no evidence of contact mineralization. Inspection of the map suggests that there is a strong tendency for bodies of skarn to replace area where both schist and marble are in contact with the intrusive rocks. At least four of the major bodies of skarn mapped are present at such localities, including those of the Magnetite Cliff deposits and of the Jumbo mine.

Roof pendants or inclusions of the bedded rocks within the stock have been especially favored spots for development of skarn minerals. Several inclusions of limestone on the west slope of Mount Jumbo have been almost entirely replaced by skarn (pl. 6). In some places, only a few small remnants of marble remain to indicate the type of rock replaced. Marginal replacement in these inclusions has, likewise, been extremely erratic. The northern margins of two large limestone inclusions, lying about 1,500 feet southwest of the summit of Mount Jumbo, are bounded by skarn minerals, whereas at the southern margins of the in-

[2] Goddard, E. N., Warner, L. A., and Walton, M. S., Jr., 1943, Copper-bearing iron deposits of the Mount Andrew-Mamie area, Kasaan Peninsula, Southeastern Alaska; U. S. Geol. Survey open-file report.

clusions recrystallized marble is directly in contact with the intrusive rocks (pl. 6).

MARMORIZATION

Marmorization of the limestone adjacent to the intrusive stock is extensive and is not everywhere accompanied by the development of contact-metamorphic minerals. Near the stock the typical gray to black fine-grained limestone has been recrystallized to a white, locally bluish, coarsely crystalline marble composed of calcite grains as large as a centimeter in diameter. The zone of extensive recrystallization of the marble around the stock varies greatly in width, from twenty to several hundred feet, and pronounced bleaching and some recrystallization of the limestone is evident as much as a half mile away from the stock (horizontal distance). The outer limits of the zone of strong metamorphism were not mapped.

Recrystallization of the limestone blocks (upper magnetite deposits) included in the igneous mass is strikingly uniform. Texture and color are the same near the margin as in the center of the inclusions. This textural uniformity suggests uniform conditions of pressure, temperature, and flux (probably some recrystallizing agent such as water or CO_2 gas) during the period of development of the marble.

The relationship between the development of skarn and ore minerals adjacent to the stock and the extensive recrystallization and bleaching of limestone is not clearly understood. The areal extent of the recrystallized marble is several hundredfold that of the skarn zone. An extremely coarsely crystalline phase of the marble, which yields cleavage rhombs of calcite as much as four inches along a face, is locally associated with the skarn zone at the Jumbo mine and clearly is related genetically with the skarn rocks. Likewise, much of the coarsely crystalline marble immediately adjacent to the skarn bodies at Magnetite Cliff almost certainly is related to the skarn mineralization. However, this coarsest marble is but a small fraction of the vast amount of bleached and recrystallized marble that forms a halo around the intrusive stock.

METAMORPHISM IN VICINITY OF MAGNETITE CLIFF BODIES

GENERAL RELATIONS

Metamorphic phenomena in the vicinity of the Magnetite Cliff deposits include (a) the exomorphic transformation of marble into skarn, with development of magnetite-chalcopyrite deposits and (b) the endomorphic transformation of the intrusive rock by gradational steps into massive garnet-diopside skarn. Typical skarn minerals have also developed in dike rocks and in schists. The skarn rock produced in the intrusive rock is subordinate in amount to that produced in the marble, and endomorphism occurs only in intimate contact with the products of exomorphism.

EXOMORPHISM OF THE MARBLE

LOCALIZATION OF METAMORPHIC PRODUCTS

Skarn composed almost entirely of diopside and garnet has formed extensively at Magnetite Cliff along contacts between the intrusive rock and the invaded marble. Places where apophyses of the intrusive rock extend into the marble appear to have been especially favorable to the development of skarn. Locally bands of skarn a few inches to a few feet thick completely sheath apophyses in the marble. The skarn is in tabular masses which are closely limited to the contact of the intrusive rock and the marble. No skarn minerals were found in the marble more than 75 feet from the intrusive rock.

Large replacement bodies of magnetite and chalcopyrite are within or marginal to the skarn. Although the largest magnetite-chalcopyrite concentration lies directly in contact with the intrusive rock, it is common for them to be on the marble side of the skarn zone, that is, to be separated from the intrusive rock by a zone of skarn (pl. 4). Contacts between the magnetite-chalcopyrite bodies and the marble, wherever observed at Magnetite Cliff, were extremely sharp, though highly irregular (fig. 9). In general, skarn-marble contacts also are irregular but sharp.

FIGURE 9.—Knife-edge contact between marble and magnetite, Magnetite Cliff, Jumbo basin, Alaska. Marble, mr; magnetite, mg. Crossed nicols.

A halo of coarsely crystalline calcite (5-millimeter to 2-centimeter grains) borders the skarn and the magnetite-chalcopyrite on the side away from the intrusive. This coarse-textured marble grades outward, from 2–100 feet, into the main body of marble, the grain size of which is 2–5 millimeters. A very few irregular but sharply bounded lenses of pure marble, 2–5 feet across, were noted within the skarn and magnetite.

MINERALOGY, PARAGENESIS, AND TEXTURAL RELATIONS

The skarn in the vicinity of Magnetite Cliff is composed almost entirely of diopside and garnet. Minute amounts of feldspar, biotite, and clinozoisite were noted. Diopside is the earliest of the minerals formed. It is the chief component of the skarn that replaces marble and is also the major gangue mineral in the magnetite deposits. The fresh glassy green grains are arranged in mosaic pattern. The grain size ranges from 1 to 10 millimeters; but at any given place, it is remarkably uniform. The *B* index of refraction of diopside taken from the gangue in magnetite samples and from the central portion of the skarn zone, ranges from 1.683 to 1.694. This indicates, if the assumption is made that MnO and the sesquioxides of Al and Ti are negligible, a range of 18–33 percent of the hedenbergite ($Ca\ Fe\ Si_2O_6$) molecule in solution in the diopside ($Ca\ Mg\ Si_2O_6$) molecule (Kennedy, 1947, pp. 561–574). The *B* index of refraction of diopside from narrow skarn veins projecting into the marble near the outer limits of skarn mineralization ranges from 1.697 to 1.704, indicating a higher iron content of 37–48 percent of the hedenbergite molecule. It appears, thus, that the decrease in intensity conditions (Graton, 1933, pp. 521–522) from the center of the skarn zone outward to the zone of marmorization is reflected in an increase in the iron–magnesium ratio of the diopside.

Crystallization of diopside was followed by formation of garnet, which veins and extensively replaces the diopside. Residual partly replaced grains of diopside are present in almost all garnet specimens, and most diopside shows some garnet replacement. The garnet in some specimens is present as anhedral units replacing diopside along grain boundaries, and in others as large black idiomorphic crystals, as much as 2 inches in diameter, replacing diopside and containing poikilitic diopside remnants (fig. 10). Near the margin of the skarn zone, garnet replaces marble. Most of these garnets which replace marble are weakly and irregularly anisotropic, with birefringence ranging from 0.001 to 0.005.

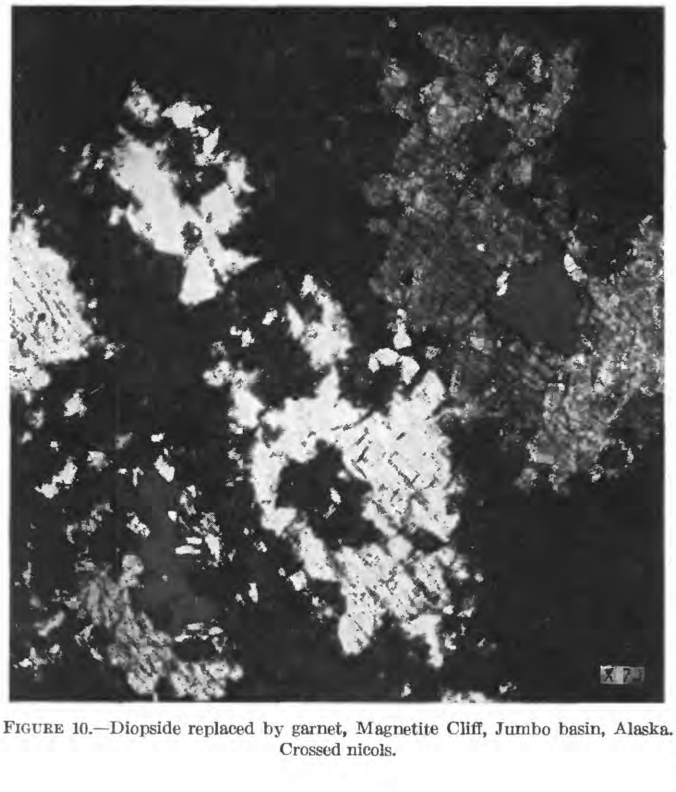

FIGURE 10.—Diopside replaced by garnet, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

The garnets are made up almost exclusively of various proportions of andradite ($3CaO.Fe_2O_3.3SiO_2$) and grossularite ($3CaO.Al_2O_3.3SiO_2$) molecules. One analysis, by W. T. Schaller (Wright, C. W., 1915, p. 50), of garnet from the Jumbo mine is available. It is compared in the following table with analyses of garnet from contact-metamorphic deposits elsewhere.

Analyses of garnets occurring in contact deposits

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	H_2O	TiO_2	$CaCO_3$	P_2O_5	MnO	Total
1	35.5	------	31.5	------	------	33.0	------	------	------	------	------	100.0
2	36.26	0.78	32.43	0.32	0	29.67	0.57	0	0	0.06	0.27	100.36
3	35.18	5.15	25.05	.40	.09	33.36	.42	0	0	------	------	99.65
4	37.15	6.98	19.40	------	------	32.44	------	------	4.20	------	------	100.17
5	36.92	8.75	16.85	.50	.17	33.01	.60	.26	1.65	.30	.67	99.68
6	37.79	11.97	15.77	1.31	.37	32.57	.09	------	------	------	.31	100.18
7	40.0	22.7	------	------	------	37.3	------	------	------	------	------	100.0

1. Theoretical composition of andradite, $3CaO.Fe_2O_3.3SiO_2$.
2. Garnet, Morenci, Ariz., U. S. Geol. Survey Prof. Paper 43, p. 134, 1905, George Steiger, analyst.
3. Garnet rock, Jumbo mine, U. S. Geol. Survey Prof. Paper 87, p. 50, 1915, W. T. Schaller, analyst.
4. Garnet, San Jose, Mexico, Am. Inst. Min. Eng. Trans., v. 36, p. 193, 1905.
5. Garnet, Mackay, Idaho, U. S. Geol. Survey Prof. Paper 97, p. 63, 1917, Chase Palmer, analyst. (K_2O and Na_2O, totalling 0.52, not included.)
6. Garnet, Mackay, Idaho, Am. Inst. Min. Eng. Trans., v. 38, p. 286, 1908, T. T. Read, analyst.
7. Theoretical composition of grossularite, $3CaO.Al_2O_3.3SiO_2$.

Although inspection indicates that some of the garnets are not of pure material, the analyses show the well established dominance of the calcium-ferric and calcium-aluminum garnets in contact deposits, and the very small amounts of the FeO, MgO, and MnO garnet molecules present. The range, however, of the ratio of the grossularite to the andradite molecules is great.

The grossularite-andradite ratios of the garnets in the Magnetite Cliff bodies were determined by refractive index measurements (Fleischer, 1937, pp. 751–759). In these determinations the assumption was made that FeO, MgO, and TiO_2 were negligible.

Most hand specimens contain garnets of differing ages and compositions. Veinlets of later garnet may cut earlier massive garnet or earlier veinlets. In almost every specimen the later garnets, as determined by refractive index, are richer in the andradite molecule than is the earlier garnet. Within a single hand specimen younger garnets may contain as much as 30 mole percent more of the andradite molecule than does an older garnet.

The garnets likewise vary systematically in composition according to their position in the metamorphic zone. The garnets in veins of skarn minerals which extend into the marble at the outer limits of the metamorphic zone have a high grossularite and low andradite content. Refractive index measurements of these gar-

FIGURE 11.—Typical magnetite ore with fine-grained magnetite (black) replacing diopside, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

nets range from 1.767 to 1.792, indicating ratios from $Gr_{77}An_{23}$ to $Gr_{65}An_{35}$. The garnets present as gangue within the magnetite bodies are of extremely high index, ranging from 1.890 to 1.895, and indicating a composition from Gr_4An_{96} to Gr_0An_{100}. Those in magnetite-free skarn are for the most part intermediate in composition. They range from $Gr_{55}An_{45}$ to $Gr_{15}An_{85}$.

FIGURE 12.—Coarse-grained magnetite replacing diopside, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

The garnets and the diopsides thus tend to show contrasting behavior within the metamorphic zone. In general the diopside becomes richer in iron and poorer in magnesium, while garnet becomes poorer in iron and richer in aluminum toward the marble (outer) side of the metamorphic zone.

Skarn minerals other than diopside and garnet are rare. Sparse grains of feldspar, clinozoisite, and biotite were noted in a few sections. These minerals are later and replace the garnet and diopside or fill fractures in them. Magnetite and sulfide minerals are in all cases later than the major silicate minerals (figs. 11, 12, 13).

Broadly speaking, two general paragenetic paths of mineral development were noted: that of the inner skarn and the magnetite deposits, and that of the skarn in veinlets cutting marble and along the margin of the marble. The sequences in the inner skarn and magnetite bodies are:

1. recrystallization of limestone into marble,
2. introduction of low-iron diopside,
3. introduction of low-iron garnet,
4. introduction of high-iron garnet,
5. introduction of magnetite,
6. introduction of sulfide minerals.

The sequences in the outer skarn, near the peripheral marble are:

1. recrystallization of limestone into marble,
2. introduction of high-iron diopside,
3. introduction of low-iron garnet,
4. sparse formation of fractures filled with feldspar,
5. alteration of feldspar to clinozoisite,
6. introduction of scant sulfide minerals.

These are generalized sequences that grade into each other, but they reflect real differences in the mineralogy of contrasting positions in the zone characterized by metamorphic silicates. By means of these criteria it is

FIGURE 13.—Zoned isotropic garnet with included diopside grains. Chalcopyrite (black) is preferentially replacing certain garnet zones, Magnetite Cliff, Jumbo basin, Alaska. Plane light.

possible to infer the approximate location in the skarn zone of any chance exposure. High-iron andradite garnet is an especially reliable indicator of proximity to magnetite ore.

CHEMICAL CHANGES

A quantitative estimate of the changes by which the marble was converted to skarn may be obtained by comparing the chemical composition of an average sample of marble with that of an average sample of skarn rock, formed by replacement of the marble. Assuming that the analysis on page 6 represents the average marble, that the average skarn rock is composed of 60 percent pyroxene (made up of 75 percent of the diopside molecule and 25 percent of the hedenbergite molecule) and 40 percent garnet (made up of 85 percent of the andradite molecule and 15 percent of the grossularite molecule), and that the density of marble is 2.7 and of skarn is 3.5, the changes effected in the metamorphism may be represented as follows:

Computed chemical changes of marble in exomorphosed zone, Magnetite Cliff area, Prince of Wales Island, southeastern Alaska

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	CO_2	Total
Marble: Analyzed composition...percent..	0.6	0.3	0.5	0	8.0	46.5	44.1	100.0
Skarn: Computed average composition...percent..	46.8	1.4	10.6	4.4	8.3	28.5	------	100.0
Change of rock constituents:								
Gain...kg per cu m..	1,622	37	358	154	64	------	------	2,235
Loss...do...	------	------	------	------	------	253	1,190	1,143

The foregoing table shows the tremendous amounts of silica and iron oxides that have been introduced into the marble during metamorphism, while calcium oxide and very large quantities of CO_2 have been expelled. The computations emphasize the constancy of the alumina and the magnesia as the marble was changed to skarn during metamorphism. The percentage of alumina recorded for skarn may be low, however, as an unknown amount of alumina may proxy for silica in the diopside molecule.

ENDOMORPHISM OF THE INTRUSIVE STOCK

LOCALIZATION OF THE METAMORPHIC PRODUCTS

At places, the band of skarn minerals spreads over into and profoundly replaces the igneous rock in the immediate neighborhood of the intrusive contact. The evidence for this is afforded best, and almost exclusively, by the microscope; for, as seen in the field or in hand specimens, the skarn produced by alteration of the igneous rock and that which replaced the limestone are at many places indistinguishable. No attempt was made, therefore, to separate on the map the skarns of the two derivations.

From field observation, certain generalizations can be made about the endomorphosed intrusive rock.

1. Magnetite or chalcopyrite deposits are not found in skarn believed to be a replacement of the intrusive rock.

2. Skarn rock derived from igneous rock is always in contact with skarn derived from marble, although the converse is not true.

3. The skarn zone formed by replacement of igneous rock is extremely variable in thickness, ranging in width up to 20 feet or more. The margin of the skarn against the recognizable intrusive is extremely irregular; moreover, kidneys of skarn, ranging in length from a few inches to a few feet, have been found in the igneous rock a few feet beyond the limits of the main body of skarn. The contact between the skarn zone and the fresh igneous rock is always somewhat gradational, and not sharp as is the contact between skarn and marble.

4. No particular variant of the igneous rock is preferentially replaced. Skarn is found replacing, apparently with equal ease, granodiorite, augite monzonite, quartz diorite, and gabbro.

MINERALOGY, PARAGENESIS, AND TEXTURAL RELATIONS

A series of specimens, studied microscopically, establishes clearly the succession of events in the transformation of igneous rock to skarn rock. The stages in the replacement are as follows:

1. The first stage of alteration, shown in thin sections of seemingly fresh igneous rock collected a few feet from the skarn zone, is the transformation of primary amphibole and biotite to diopside, and the introduction of minute amounts of diopside as veinlets cutting and replacing the primary minerals (fig. 7).

2. Orthoclase crystals and large plagioclase crystals of intermediate composition are broken down and replaced by minute crystals of calcic plagioclase that show pronounced pericline twinning. The anorthite content of these small secondary plagioclase crystals ranges from 60 to 92 percent (fig. 14). By the end of this stage all original ferromagnesian minerals have been converted into large diopside grains 1–3 millimeters in diameter, which range in composition from Di_{78}–Hed_{22} to Di_{58}–Hed_{42}.

3. Minute crystals of relatively high-aluminum garnet, ranging from $Gr_{68}An_{32}$ to $Gr_{30}An_{70}$, partially replace feldspar (fig. 15).

4. The remaining feldspar is altered to fine-grained clinozoisite of the calcium-rich, iron-poor variety.

5. Clinozoisite is replaced by diopside. Direct evidence of this stage is not clearly shown by thin sections but is inferred. Sections of successively more intensely metamorphosed rock show decreasing amounts of clinozoisite and increasing amounts of diopside.

6. The final stage in the history of the metamorphism of the rock is the conversion of diopside to garnet. Evidence of replacement of diopside by garnet is clear-cut and was observed in almost every section of skarn studied. Complete replacement by garnet of all earlier minerals appears to be the end product of this meta-

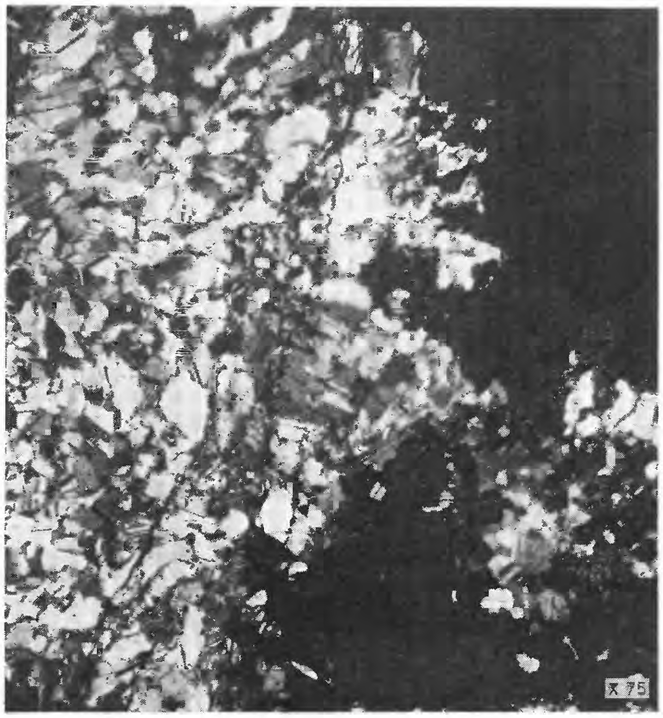

FIGURE 14.—Plagioclase lath broken down to an aggregate of many small plagioclase crystals of higher anorthite content, garnet surrounding and replacing feldspar, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

somatism. The end-product garnet is much richer in iron than is the early garnet which replaces feldspar in stage 3. Average composition of the late garnet is about $Gr_{25}An_{75}$, but the garnets range in composition from $Gr_{28}An_{72}$ to $Gr_{8}An_{92}$. The pure andradite garnet, abundant near and in the magnetite bodies, was not noted in skarn derived from igneous rocks.

FIGURE 15.—Fine-grained garnet (black) replacing orthoclase feldspar, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

FIGURE 16.—Altered granodiorite, showing garnet (black) replacing diopside and clinozoisite, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

These stages represent the sequence of events (figs. 16, 17). That is to say, introduction and formation of diopside in stage 1 probably continued until stage 6 and introduction of garnet in stage 3 continued throughout stages 4, 5, and 6. The sequence of replacement may perhaps be better indicated in figure 18.

Accessory minerals, such as titanite and apatite, remained unaltered throughout the replacement and

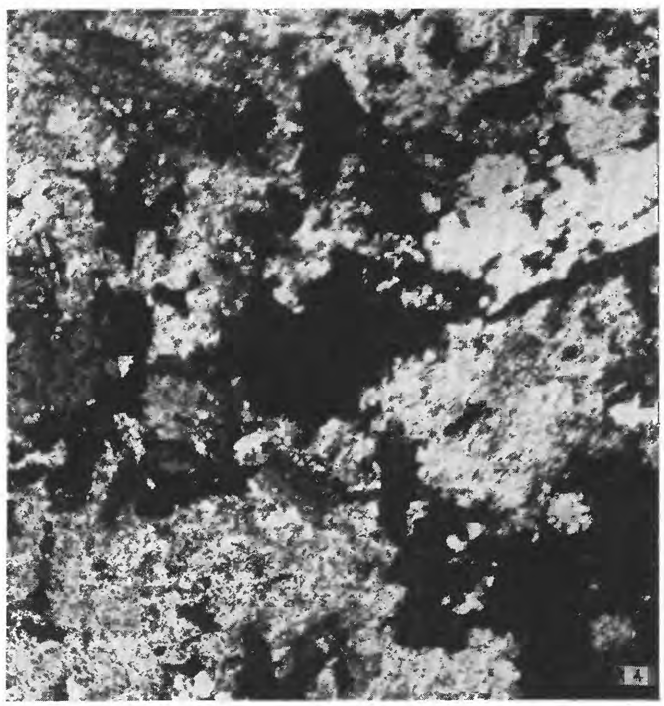

FIGURE 17.—Sericitized feldspar of intrusive rock followed by clinozoisite (lath-shaped twinned crystals), diopside (light crystals), and garnet (black irregular areas), Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

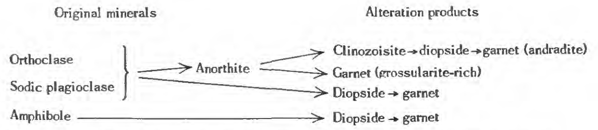

FIGURE 18.—Sequence of replacement in the endomorphosed zone.

are present in the altered skarn rock in about the same proportion and with the same grain size and distribution as in the original intrusive rock (fig. 19).

CHEMICAL CHANGES

Major changes in the composition of the igneous rock have taken place during metamorphism. The most intensely altered rock in the endomorphosed zone is estimated to contain approximately 80 percent of garnet ($Gr_{25}An_{75}$) and 20 percent of diopside ($Di_{70}Hed_{30}$). Average specific gravity of the granodiorite is assumed to be 2.9 and that of the skarn 3.6. Constancy of volume during metamorphism is assumed. The calculated composition of skarn is compared below with that of analyzed granodiorite.

Computed chemical changes of granodiorite in endomorphic zone, Magnetite Cliff, Prince of Wales Island, southeastern Alaska

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
Granodiorite: Analyzed composition percent	60.3	17.7	3.4	2.9	1.8	6.6	4.2	3.1	100.0
Skarn: Computed average composition percent	39.9	4.5	18.9	1.8	2.6	32.3	------	------	100.0
Change of rock constituents:									
Gain____kg per cu m of rock	------	------	584	------	42	974	------	------	1,600
Loss__kg per cu m of rock	290	335	------	16	------	------	122	90	853

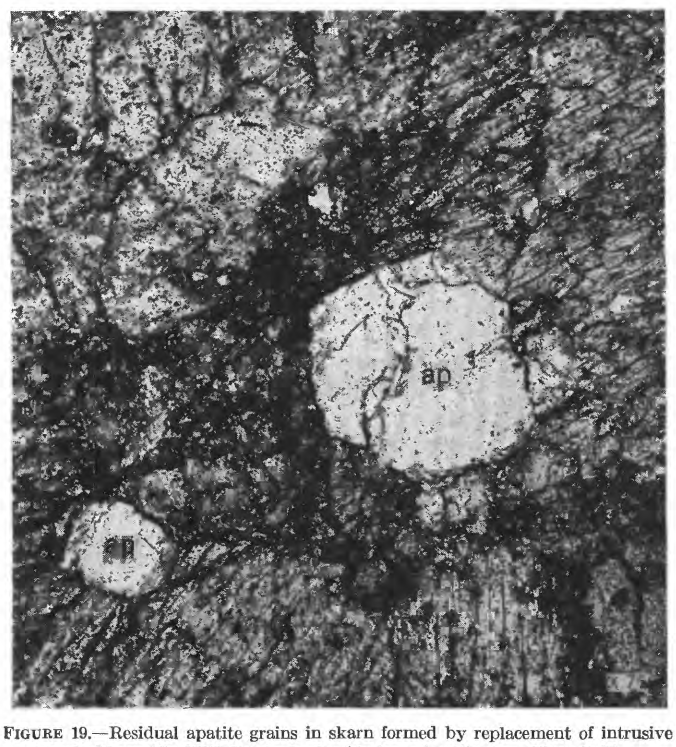

FIGURE 19.—Residual apatite grains in skarn formed by replacement of intrusive rock, Magnetite Cliff, Jumbo basin, Alaska. Apatite, ap. Plane light.

Both silica and alumina, here shown as loss in granodiorite alteration, appear as gain in the table (see p. 17) showing change in composition of the limestone. Conversely, calcium, one of the substances expelled in great quantity during alteration of the limestone, shows the greatest gain in the intrusive rock. If it were assumed that CaO was not removed from the metamorphic zone as a whole, the amount expelled by the alteration of four volumes of marble would supply CaO added in the conversion of one volume of the granodiorite to skarn. Field evidence suggests that skarn of the two derivations may be present in about those proportions, but the evidence is not compelling. Moreover, it is by no means certain that CaO, one of the most mobile of the components involved, would escape partial removal during so vigorous a process as skarn formation. It is certain, however, that very large quantities of imported silica and iron oxides have been added to the composite metamorphosed zone, and that CO_2 and alkalies have been expelled.

CRITERIA FOR DISTINCTION OF METAMORPHIC PRODUCTS

Several criteria, no one of which is in itself conclusive, aid in distinguishing the endomorphic from the exomorphic products. These may be grouped as field criteria and as hand-lens or microscope criteria.

Among the field criteria are the following:

1. Garnet-diopside bodies which lie in sharp smooth contact with the intrusive rock probably represent a replacement of the marble, whereas if contacts are irregular and gradational they probably indicate at least a partial replacement of the granodiorite.
2. Broad field relationships, such as the trend of contacts, may establish the probability that a given skarn body is a replacement of marble or of igneous rock or in part of each.
3. Small kidneys and irregular gradational masses of contact skarn within the intrusive rock, a few feet from the main skarn zone, are most likely replacements of the intrusive rock. These bodies apparently are not replaced limestone inclusions in the intrusive rock.
4. The texture of the intrusive rock may locally be preserved in the texture of the contact silicates which replace it. Similarly the bedding of the marble may be locally preserved in the replacing rock.

Among microscope or hand-lens criteria are the following:

1. Coarse grains of apatite and titanite are relatively abundant in the primary igneous rock; they were noted in every thin section of skarn believed, from other evidence, to be a replacement of the igneous rock (fig. 19). No apatite or titanite was noted in any of the sections of contact silicates definitely known to have been derived from the limestone. Likewise no apatite or titanite was noted in any of the ore, which itself is regarded invariably as a replacement product of limestone.

2. Diopside rock formed by replacement of limestone shows, in thin sections, a mosaic of more or less equigranular texture, whereas diopside-rich rock formed by replacement of igneous rock generally shows a wide variability in grain size, with coarse 1- to 3-millimeter diopside grains interspersed with patches of very fine diopside grains. Coarse diopside grains are believed to have replaced magnesian minerals in the igneous rock, and patches of minute diopside grains of 0.1-millimeter size are believed to have been derived from clinozoisite, itself formed by breakdown of the feldspars of the original rock (fig. 20).

3. The garnets in metamorphic rock formed by replacement of limestone are coarsely crystalline and many show euhedral outline even in massive skarn, whereas the garnets in skarn derived from the igneous rock are generally fine-grained and the outlines of the individual crystals are obscure.

Some obvious criteria, such as residual calcite or residual feldspars and clinozoisite in the metamorphosed rock, indicate the nature of the rock replaced.

The evidence of extensive alteration of the intrusive rock by the contact-metamorphosing solutions is most striking and compelling in this district. The extensive alteration, coupled with the fact that all types of igneous rock present in the intrusive mass are similarly altered, is of the greatest significance to any genetic interpretation of these deposits.

METAMORPHISM OF THE SCHISTS

Calcareous schist and quartz-mica schist near the western limits of Magnetite Cliff have been converted to skarn along the margin of the intrusive mass (pls. 1, 4). Locally, alteration is complete and the schist beds are composed almost entirely of garnet. Scattered grains of magnetite and a few blebs of chalcopyrite were observed in this rock, but nowhere in the metamorphosed schist were ore deposits of appreciable size or grade noted.

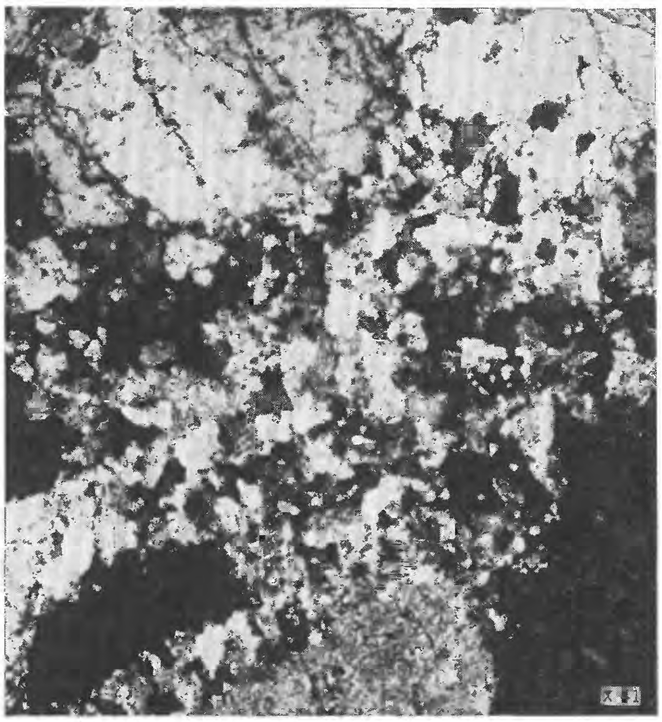

FIGURE 20.—Diopside rock, showing dual grain size characteristic of diopside formed by replacement of intrusive rock, Magnetite Cliff, Jumbo basin, Alaska. Crossed nicols.

The massive garnet skarn produced from schist is unique in appearance, and can be distinguished easily from skarn produced by metamorphism of limestone or of intrusive rock. The garnet skarn produced from schist is porous, containing many small vugs lined with deep-red euhedral garnets. The rock breaks readily and the brilliant garnet facets are conspicuous on the fresh surface. The composition of the garnets is variable; andradite may make up 95 percent of the garnet. Diopside was not noted in the more intensely altered schist.

A less intense metamorphism of the schists marginal to the garnet skarn has converted them largely to iron-poor clinozoisite. Locally, these areas contain a small amount of amphibole and minute veinlets of epidote.

METAMORPHISM OF THE DIKE ROCKS

Numerous dikes, ranging from andesite to basalt, cut the limestone in the vicinity of Magnetite Cliff. These dikes are, for the most part, pre-ore and pre-intrusive, and have been intensely altered by the contact-metamorphosing solutions.

A decrease in the intensity of alteration of the dike rocks can be noted outward from the center of metamorphism. The most intensely altered dike material was found in the three dikes in the center of the metamorphic zone that cuts the Magnetite Cliff body and is exposed in the adit at 1,540 feet elevation (pls. 4, 5). This material in composed almost entirely of extremely fine diopside grains, 0.005–0.05 millimeters in diameter. It also contains a few minute garnet veinlets, some clinozoisite, and scattered grains of magnetite.

A much more complex mineral assemblage was noted in dikes near the skarn-marble contact, here composed predominantly of extremely fine-grained diopside but with substantial amounts of garnet, sericite, clinozoisite, feldspar, amphibole, and chlorite and lesser amounts of titanite, pyrite, and chalcopyrite.

Dikes cutting the marble as much as 30 feet from the skarn zone locally show intense alteration. In a narrow crenulated dike cutting the marble in the lowermost adit of the Magnetite Cliff bodies, about 35 percent of fine diopside and amphibole crystals are poikilitically enclosed in large scapolite crystals that comprise the remainder of the rock (fig. 21). Optical data indicate that this scapolite contains about 40 percent of the marialite molecule and 60 percent of the meionite molecule. Scapolite was noted in other altered specimens of dike rock some tens of feet from the main skarn zone,

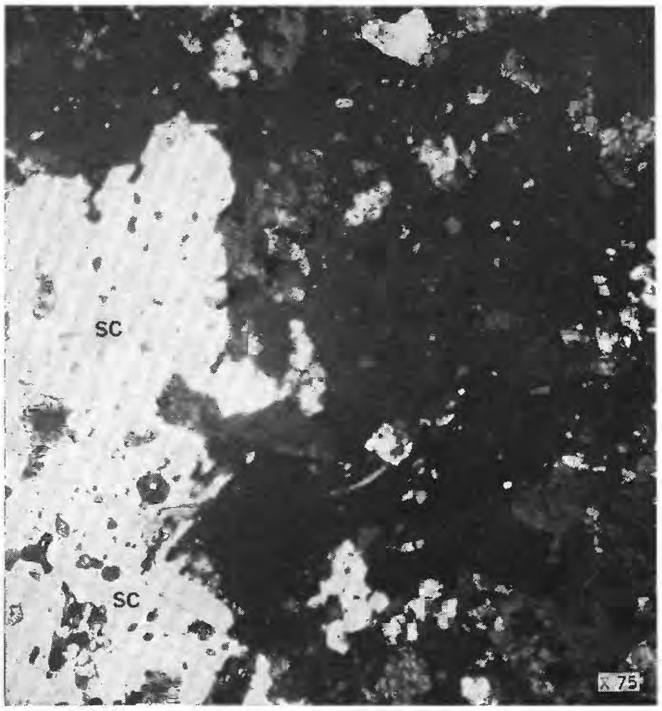

FIGURE 21.—Altered dike rock. Scapolite poikilitically includes pyroxene and amphibole (small grains with high relief). Magnetite Cliff, Jumbo basin, Alaska. Scapolite, sc. Crossed nicols.

but no scapolite was noted in rocks intimately associated with the intense garnet–diopside type of alteration.

METAMORPHISM IN THE VICINITY OF THE UPPER MAGNETITE BODIES

A few small magnetite-chalcopyrite deposits, at an altitude of about 2,300 feet, 1,500 feet southwest of the summit of Mount Jumbo, have been designated the upper magnetite bodies (pls. 1, 6). These deposits lie in a group of limestone inclusions in the intrusive stock. The limestone has been completely recrystallized to marble and is locally replaced by contact silicates and magnetite-chalcopyrite. The granodiorite, likewise, has been locally altered to skarn rock in the vicinity of the replaced limestones. Contact metamorphism has been extremely erratic. Locally marble containing no silicate minerals is in contact with fresh intrusive rock, whereas elsewhere the marble inclusion may be almost completely replaced by skarn minerals. The controlling factors in ore-mineral localization are here obscure. The largest body of skarn contains no ore minerals; the magnetite and chalcopyrite may be in hosts of skarn, marble, or granodiorite (pl. 6).

The massive skarn and magnetite concentrations of Magnetite Cliff, which contain no residual calcite and are in sharp contact with marble, contrast markedly with the upper magnetite area where contacts between skarn and marble are generally gradational and calcite is present within the skarn zone (fig. 22).

EXOMORPHISM OF THE MARBLE

The mineralogy and texture of the upper magnetite skarn which replaces marble differ markedly from the

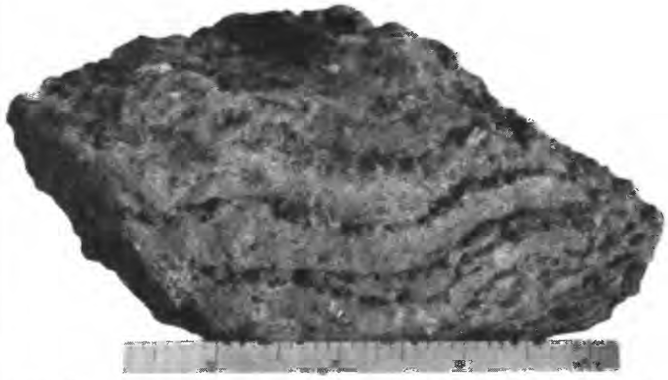

FIGURE 22.—Bedding planes in marble, preserved by garnet, Jumbo basin, Alaska.

skarn of the previously described Magnetite Cliff area. The suite of metamorphic minerals includes diopside, garnet, actinolite, biotite, quartz, magnetite, pyrite, and chalcopyrite.

Diopside is almost ubiquitous and was the first mineral to form. It is present as minute grains, 0.01–0.05 millimeters in diameter, intermixed with calcite; in aggregates of mosaic texture with average grain size about 1 millimeter; as residual partly replaced remnants in garnets; as extremely coarse euhedral crystals as much as 5 centimeters in length marginal to magnetite veins cutting the marble; and as coarse crystals marginal to skarn bodies and projecting into large calcite crystals. Diopside and calcite are the most common and locally the only gangue minerals in the magnetite. The diopside accompanies magnetite in ramifying and highly irregular kidneys enclosed in recrystallized marble (fig. 23). The two minerals are therefore believed to be close in age, though in polished section magnetite always appears to replace diopside.

Optical properties were determined of five samples of diopside from various portions of the skarn. These rather uniformly have a ratio of diopside to hedenbergite of about 46 to 54, and thus contrast with the wider range in portions noted in the diopside from Magnetite Cliff. At Magnetite Cliff such high-iron

FIGURE 23.—Magnetite-diopside intergrowths replacing marble, upper magnetite bodies, Jumbo basin, Alaska.

diopside was observed only in veins marginal to the main skarn body.

Much of the diopside, in particular the large crystals 2–5 centimeters in size, bordering veins and projecting into calcite, has been partly or entirely uralitized. The alteration product is an extremely fibrous green actinolite with a mean index ranging from 1.655 to 1.663. This indicates a tremolite–ferrotremolite ratio between 50 to 50 and 45 to 55 (Winchell 1933, p. 246), and is comparable to the original diopside–hedenbergite ratio of 46 to 54, which suggests that the magnesium–iron ratio has been changed but little by alteration. In a few intensely altered diopside grains a small amount of biotite (mean index, 1.653) was noted.

Garnet is present as small euhedral units 5–10 millimeters in diameter perched on the coarse diopside crystals, and as small grains replacing diopside in the massive, fine-grained skarn. A small amount of garnet is associated with the magnetite, but it is not an abundant gangue mineral. Garnets from the upper magnetite area differ strikingly from those of Magnetite Cliff in that they are twinned, with $2V$ approximately 90° and with notable birefringence, estimated at 0.005 (fig. 24). Most of the garnets are zoned, with the composition of the various layers within a single crystal ranging from $Gr_{50}An_{50}$ to $Gr_{35}An_{65}$. Each garnet shows essentially the same range in refractive index; the extreme range in the aluminum–iron ratio noted from place to place in the Magnetite Cliff deposits is not present.

Quartz is present, in places, as an important gangue mineral of the magnetite, and elsewhere as coarse euhedral crystals, as much as 3 centimeters long, in the marble. The latter quartz has a typically greenish hue, owing to numerous inclusions of minute diopside grains 0.02–0.03 millimeter in diameter.

FIGURE 24.—Coarsely twinned garnet characteristic of upper magnetite bodies. Garnets are cut by fine veinlets of calcite, Jumbo basin, Alaska. Crossed nicols.

ENDOMORPHISM OF THE INTRUSIVE ROCKS

Criteria such as those indicated for the Magnetite Cliff deposits (pp. 19–20) suggests that at the upper magnetite bodies much of the skarn, if not the largest part, has formed by replacement of granodiorite. The skarn in the northern portion of the area shown in plate 6 and the extension of this zone in the area immediately north of that shown on the detailed map is believed to be of such origin.

Skarn derived from granodiorite is massive, without calcite remnants or cavities, and is composed predominantly of pale garnet of waxy luster and anhedral outline. Garnet comprises 60–100 percent of the rock and probably averages about 70 percent. The composition of the garnet is remarkably constant. It is of the iron-poor variety and averages about $Gr_{75}An_{25}$. The remainder of the rock is made up of diopside, present as unreplaced grains and partly replaced remnants in the garnets. Grain size averages 0.5–2 millimeters. The diopside, like the garnet, contains much less iron than the diopside in skarn rocks which replace the marble. The average composition is about $Di_{75}Hed_{25}$ (B index, 1.688).

Dikes which cut the marble (southeast portion of area shown in pl. 1) are predominantly latite and andesite. They have been locally impregnated with finely disseminated pyrite, but in general show little other alteration.

METAMORPHISM IN THE VICINITY OF THE JUMBO MINE

The Jumbo mine copper deposits occur in an extensive skarn zone marginal to the nose of a large limestone and schist inclusion or roof pendant engulfed in the intrusive stock (pl. 7, fig 41). Skarn minerals have developed, for the most part, in limestone, and the limestone has been extensively recrystallized to coarse-textured marble. Locally, alteration of dikes and rocks of the intrusive stock to albite and epidote is intense,but, unlike the Magnetite Cliff and the upper magnetite deposits, no extensive skarn zone has formed by replacement of the intrusive rocks.

Replacement of limestone is typically erratic and incomplete. Lenses of partly replaced and unreplaced marble are present in the skarn zone, and contacts between skarn and marble are gradational. Interstitial calcite is present in almost all skarn examined.

The predominant ore mineral of the Jumbo mine is chalcopyrite. This is associated with skarn minerals near the contact between skarn and marble (fig. 41) or in massive sulfide veins in the marble near the skarn zone. No magnetite was observed in the workings of the mine.

EXOMORPHISM OF THE MARBLE

A complex group of minerals has formed in the skarn zone by replacement of marble. These include diopside, garnet, uralite, epidote, albite, orthoclase, quartz, epidesmine, and talc. Ore minerals noted are specularite, molybdenite, chalcopyrite, and sphalerite.

Diopside, the earliest of the skarn minerals to form, occurs in coarse crystals, 2–5 centimeters in length, and as small residual grains surrounded and included in garnet. In contrast to the previously described magnetite bodies, diopside is only sparingly present; nowhere does it constitute more than a small proportion of the skarn minerals. Diopside in the replaced limestone is characteristically intensely uralitized, and the original composition of the mineral is difficult to determine (figs. 25, 26).

Garnet is later than and replaces diopside. It is the dominant mineral of the skarn zone in the Jumbo mine and constitutes about 80 percent of the silicate minerals of that zone. It occurs, for the most part, in large crystals of dodecahedral outline 1–5 centimeters in diameter.

The garnets are strikingly zoned, and show in cross section concentric bands ranging in a single crystal from pale cream through red to green, brown and black (figs. 27, 28). There is no systematic variation in com-

FIGURE 25.—Uralitized diopside crystal, partially replaced and surrounded by garnet. Jumbo mine, Alaska.

FIGURE 26.—Uralitized diopside crystals, Jumbo mine, Alaska.

FIGURE 27.—Rythmically zoned garnet, Jumbo mine, Alaska.

FIGURE 28.—Zoned garnet with grossularite-rich cores and andradite-rich margins. Jumbo mine, Alaska.

position from zone to zone, zones of brown, red, and tan alternating with cream-colored garnet. The cream-colored core and zones are high in alumina, analysed as $Gr_{78}An_{22}$. The tan and brown zones have the composition $Gr_{62}An_{38}$, and the red zone is composed of $Gr_{65}An_{35}$. One zoned garnet contained a 3-centimeter core composed of almost pure iron garnet of Gr_4An_{96}. The core is bordered by a zone about 2 millimeters thick of green garnet of $Gr_{64}An_{36}$ composition. This zone in turn is enclosed by a thin outerzone of red garnet of $Gr_{13}An_{87}$. In contrast to this garnet containing cores rich in andradite is the garnet shown in figure 26 having cream-colored cores of $Gr_{35}An_{35}$ to $Gr_{45}An_{55}$ and a black outer rim of Gr_0An_{100} with a narrow peripheral zone of $Gr_{30}An_{70}$. These specimens were collected from mine workings within a few hundred feet of one another. Unfortunately no study was made to ascertain whether zoning in the garnets is related to position within the metamorphic aureole.

Dark zones within a given crystal generally contain a greater percentage of the andradite molecule than do the light zones. From specimen to specimen, however, it is impossible to estimate the grossularite–andradite ratio of the garnet by its color. In some specimens optical data indicate that pale cream-colored garnets contain as much as 94 percent of the andradite molecule, whereas some dark reddish-black garnets consist of $Gr_{60}An_{40}$.

Under the microscope the garnets from the Jumbo mine can be readily distinguished from those from the Magnetite Cliff or upper magnetite deposits. The Jumbo garnets are birefracting and show fine lamellar twinning parallel to growth zones and coarse, somewhat irregular, diamond-shaped twins superimposed on the fine lamellar twin pattern (figs. 29, 30). Garnets with this twin pattern contrast with the garnets from the upper magnetite bodies which show regular diamond-shaped twin patterns and no lamellar twinning, and with those from Magnetite Cliff which are, for the most part, isotropic with no discernible twinning. Twinning appears to be independent of the composition of the garnets.

FIGURE 29.—Zoned garnet, showing coarse penetration twinning and fine lamellar twinning, Jumbo mine, Alaska.

FIGURE 30.—Zoned garnets characteristic of Jumbo mine, Alaska. Crossed nicols.

Locally epidote is an abundant mineral in the skarn zone at the Jumbo mine. It occurs as medium-sized irregular grains replacing garnet, (fig. 31) in groups of radiating crystals surrounded by later quartz and calcite, and as coarse crystals of exceptional beauty and complexity of crystal form lining the walls of vugs. The epidote specimens from the Jumbo area are rivaled only by those from the Tyrol. Optical properties of the epidote are $\alpha=1.741$, $\beta=1.760$, $\gamma=1.782$, $2V=75°$, which indicates a ratio of Al:Fe=(65 to 70):(35 to 30). The epidote in the vugs is locally coated with many small crystals of quartz, epidesmine, and albite.

Orthoclase (adularia variety) is present as coarse crystals, as large as 10 centimeters, coating the walls of

FIGURE 31.—Zoned anisotropic garnet replaced by epidote, quartz, and calcite. Replacement is preferential along certain zones, Jumbo mine, Alaska. Quartz, q; garnet, ga; epidote, ep; calcite, ca. Crossed nicols.

cavities. Orthoclase was occasionally noted interstitial to coarse dodecahedrons of zoned garnet.

Albite was noted only in small crystals associated with epidote in druses.

Quartz is present in transparent crystals 2–5 centimeters in length, associated with epidote in vugs, and as irregular grains replacing epidote and garnet in the massive skarn (fig. 31). Euhedral quartz is of trigonal habit and therefore was formed below the inversion temperature. The anhedral quartz in the massive skarn is characteristically of greenish hue, imparted by numerous inclusions of epidote(?).

Numerous yellow zeolite crystals, 2–5 millimeters in length, coat much of the epidote in cavities. The optical properties of this zeolite correspond with those reported by Larsen (Larsen and Berman, 1934, p. 152) for epidesmine, an orthorhombic calcium-aluminum zeolite closely related to stilbite.

Calcite is everywhere present in the Jumbo mine skarn zone. Its relations indicate that it was among the last minerals to crystallize; locally calcite selectively replaces garnet along certain zones and also replaces quartz (fig. 31).

Talc of greenish hue is present as coarse flakes in veinlets cutting calcite and along the cleavage of coarse calcite fragments but is nowhere associated with abundant skarn silicates.

The distribution of contact-metamorphic silicates in the skarn zone appears, for the most part, to be highly erratic, though some evidence indicates that quartz and epidote are more plentiful in that part of the metamorphic aureole nearest the marble, whereas garnet and diopside are more plentiful near the intrusive stock.

ENDOMORPHISM OF THE INTRUSIVE ROCKS

Intrusive rocks in contact with the skarn zone in the Jumbo mine area range in composition from gabbro to augite monzonite. Locally, as along fractures and adjacent to the skarn zone, these intrusive rocks have been intensely altered, but not to the extreme garnet-diopside type of alteration typical of the Magnetite Cliff and upper magnetite deposits.

Near the mouth of the lowermost Jumbo adit, fractures in gabbro guided altering solutions that penetrated as much as 3 feet into the wall. Scapolite is the principal product. It completely destroyed the original feldspar but left virtually unattacked the diopside and apatite, which are now pseudopoikilitically included in scapolite crystals ranging upward to 2 centimeters in length (fig. 32). As a rule, however, scapolite replacement is quantitatively unimportant and was noted only in the more basic rocks.

The more typical alteration of the intrusive rocks is that shown in figure 33. Originally of augite monzonite, the specimens illustrated came from the main intrusive body within a few feet of the skarn zone. They show progressive alteration from a relatively

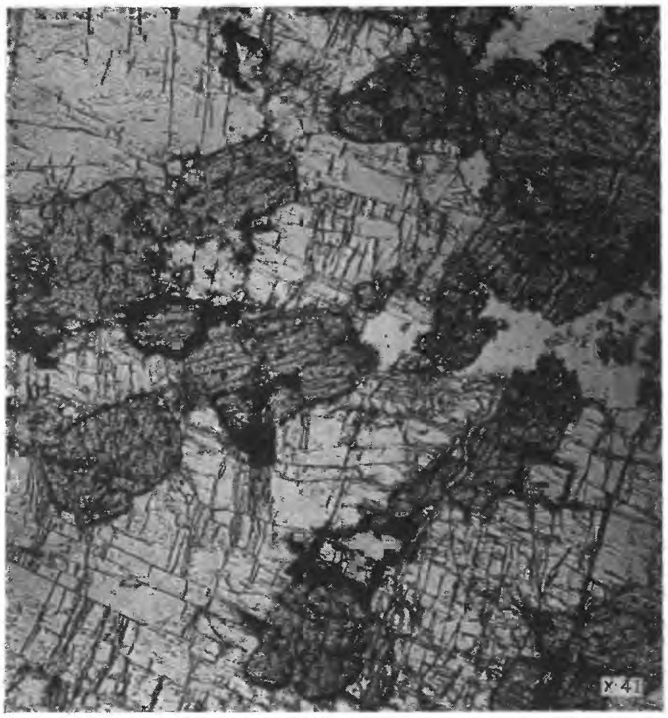

FIGURE 32.—Replaced gabbro, showing coarsely crystalline scapolite, pseudopoikilitically including diopside, Jumbo mine, Alaska.

fresh rock to one composed essentially of albite and epidote. The first stage in the alteration was the breakdown of pyroxene grains and conversion of pyroxene to uralite, accompanied by some sericitization of the feldspar. Replacement of the uralitized pyroxene by epidote and calcite followed, with continued sericitization of plagioclase feldspar (fig. 34).

The end product of alteration is a rock composed almost solely of turbid albite grains and epidote. Much of the albite probably has been derived from the original plagioclase feldspar, but some probably has been introduced. In the early stage of alteration potash presumably was added to the rock in the form of sericite, but in the end stage of alteration most of the potash minerals, sericite and orthoclase, were displaced by the albite. Figure 33 shows typical albite-

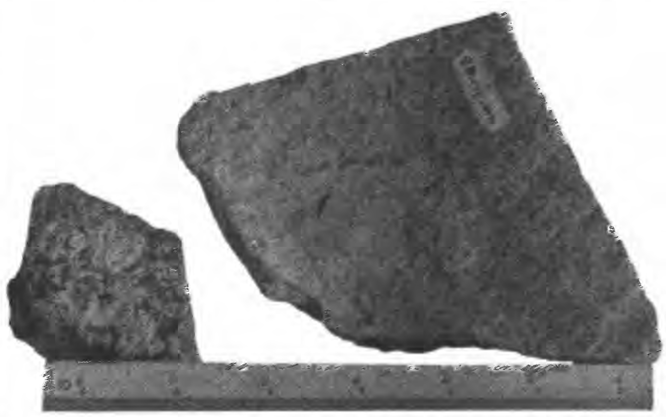

FIGURE 33.—Gradation in altered augite monzonite from (right) fresh rock to (center) sericitized and chloritized rock to (left) rock composed of coarsely crystalline epidote and albite, Jumbo mine, Alaska.

FIGURE 34.—Feldspar of augite monzonite replaced by sericite and epidote, Jumbo mine, Alaska. Epidote, ep; sericite, se. Crossed nicols.

epidote relations of altered rock. Apatite and titanite remained essentially unaltered throughout the transformation.

METAMORPHISM OF THE DIKE ROCKS

Numerous dikes, believed to be older than the intrusive stock, cut the skarn zone in the Jumbo mine. The dikes, presumed originally to have been andesites or related rocks, have been intensely altered to extremely fine-grained, pale greenish-gray rocks which resemble hornfels. They are composed of 50–60 percent of diopside in grains of about 0.1 millimeter average diameter with remaining minerals chlorite, clinozoisite, feldspar (partly altered), amphibole, some garnet, and sphene. The rocks are brittle, fracture readily, and locally are impregnated with chalcopyrite.

METAMORPHISM OF SCHISTS ON THE NORTHEAST SLOPE OF THE JUMBO BASIN

A broad zone, locally as much as 1,500 feet in width, of metamorphic silicate minerals bounds the northern portion of the schist limestone inclusion in which the Jumbo mine is located. This zone extends from the Jumbo mine eastward for several thousand feet and passes out of the Jumbo basin immediately north of Copper Mountain (pl. 1). Remnants of schist in the skarn zone suggest that this zone has formed by replacement of quartz-rich schist, though locally it may have included calcareous members.

The minerals of the metamorphic suite consist predominantly of garnet with smaller amounts of diopside, epidote, and quartz. Some adularia, specularite, and pyrite were noted. Garnet is present, for the most part as small euhedral crystals, 5–10 millimeters in diameter, of deep green-black color, locally ranging to pale tan. The index of refraction of these garnets ranges from 1.79 to 1.85. This has not been interpreted in terms of molecular percentages, for the intense color and peculiar occurrence of the garnets (replacing schists) suggests that they may not be of the grossularite-andradite series.

Replacement of the schist unlike that of the marble, has not been volume for volume. The metamorphic rock formed is friable and contains many cavities, and much of it is composed of loose aggregates of garnet crystals. The rock can, in some cases, be crumbled by little more than hand pressure and reduced to a mass of brightly faceted, loose garnets. The typical porous texture of the garnet rock is illustrated in figure 35.

The walls of many of the vugs are coated with small black garnet crystals. These crystals are frequently aggregated, one crystal against another, to form a vertical fluting along the walls of the cavity (fig. 36). Garnet ropes of stalactite-like habit form vertical bars across several of the cavities. The vertical stalactite-like growths observed are about the diameter of a pencil and are as much as several inches in length. They are made up of complexly twinned garnets, about 5 millimeters in diameter, intergrown and abutting against one another. Many such druses contain, in addition to the garnet, well-formed crystals of adularia. Typical stalactite-like garnet growths are shown in figure 37. E. P. Henderson (oral communication, 1945) noted and collected from this locality similar aggregates of

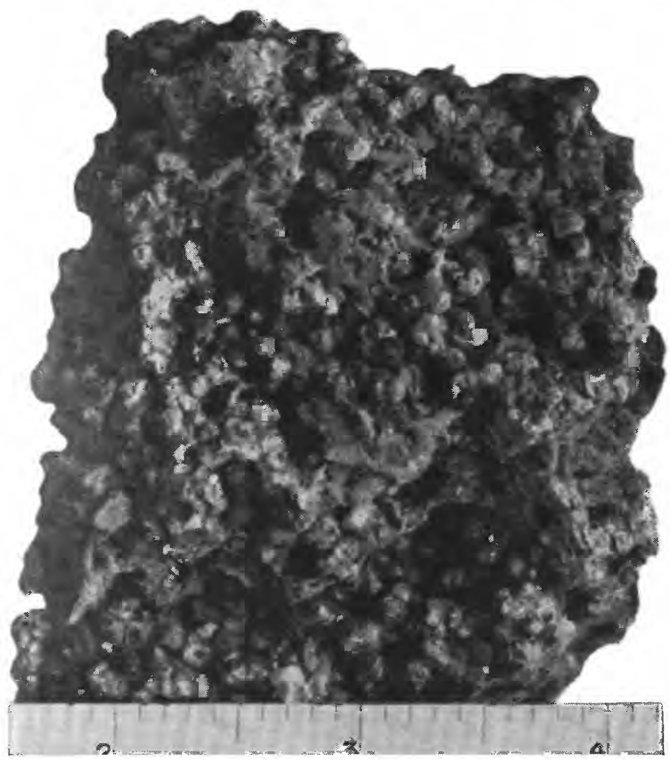

FIGURE 35.—Porous garnet aggregate characteristic of schist replacement, Jumbo mine, Alaska.

FIGURE 36.—Fluted garnet growth characteristic of walls of vugs in replaced schist, Jumbo basin, Alaska.

FIGURE 37.—Stalactite-like garnet growths from vugs in replaced schist, showing adularia and pencil-shaped growth, Jumbo basin, Alaska.

garnet crystals, which resemble corncobs in size and appearance.

Aggregates of quartz crystals locally comprise much of the skarn zone. These aggregates are composed of interlocking groups of euhedral crystals, generally with a small amount of associated epidote. One such mass crops out on the divide about 2,000 feet south of the summit of Copper Mountain. This outcrop is roughly circular, about 100 feet in diameter, and has the appearance of a pipe of quartz crystals. Numerous smaller porous aggregates of well-crystallized quartz were noted elsewhere in this zone.

CONTRASTS BETWEEN THE SKARN ZONES

The three areas studied in some detail, the Magnetite Cliff, upper magnetite, and Jumbo mine areas, differ much in their mineralogical and geological details. These differences are believed by the author to be due primarily to differences in the intensity of metamorphism rather than to differences in parent rock, structure, or original source and composition of the invading solutions. The author believes that the Magnetite Cliff deposit was formed under conditions of greatest intensity, the upper magnetite under conditions of slightly less intensity, and the Jumbo deposits under conditions of considerably less intensity. The main features of the three deposits believed to reflect the intensity conditions at time of formation are contrasted as follows:

Magnetite Cliff.—

1. The dominant ore mineral is magnetite, with associated subordinate chalcopyrite and no molybdenite.

2. The mineral suite in the replaced limestone is extremely simple with only diopside and garnet noted. Diopside is the dominant and earliest mineral to form and is unaltered. Similarly, magnetite, the earliest of the ore minerals to form, is the dominant ore mineral.

3. Replacement of limestone by skarn is complete, with no interstitial calcite remaining in skarn zone.

4. Contacts between the skarn-magnetite zone and unreplaced marble are sharp.

5. Rocks of the intrusive stock are extensively replaced by diopside-garnet skarn minerals. The end-stage of replacement is a monomineralic garnet rock, from which the potash and soda have been displaced.

6. Cavities are absent.

Upper magnetite.—

1. Magnetite is the dominant ore mineral with subordinate chalcopyrite and no molybdenite.

2. Quartz is present in addition to garnet and diopside in replaced marble. Much of the diopside has been uralitized.

3. The limestone is incompletely replaced by skarn minerals and interstitial calcite remnants are common in skarn rocks.

4. Most contacts between skarn zone and marble are gradational.

5. Rocks of the intrusive stock are replaced by diopside and garnet.

6. Vugs and cavities are present but not plentiful.

Jumbo mine.—

1. No magnetite was noted; chalcopyrite is the dominant ore mineral, and considerable molybdenite is present.
2. The mineral suite in replaced limestone is complex, with the earliest mineral, diopside, present in minor amounts and intensely uralitized: much late quartz, epidote, talc, and, locally, zeolite is present.
3. Replacement of limestone by skarn is erratic; much unreplaced calcite is intermixed with the skarn.
4. Contacts between skarn zone and marble are gradational.
5. Rocks of intrusive stock are not garnetized but have been replaced by a typical "hydrothermal" suite of minerals—sericite, epidote, and albite. Potash and soda have been added.
6. Vugs and cavities are plentiful.

GENESIS OF CONTACT-METAMORPHIC DEPOSITS OF THE JUMBO BASIN

The following features of the Jumbo basin deposits must be explained in reaching an acceptable hypothesis of the origin of these deposits:

1. Lime-silicate minerals are extensively developed in the metamorphic zone.
2. Mineral deposits occur commonly but not invariably along contacts between intrusive rock and limestone. The deposits typically border the intrusive or occur in inclusions of carbonate rock within the intrusive stock.
3. Alteration is endomorphic as well as exomorphic.
4. Minerals are zoned within the metamorphic aureole.
5. Outer limits of the metamorphic zone are irregular and contact-metamorphic products are erratically distributed around the margin of the intrusive.
6. The local sharp contacts between the metamorphic rock and the unreplaced carbonate rock is in contrast to the usual gradational contacts of replacement masses.

EXISTING VIEWS OF CONTACT METAMORPHISM

A remarkable unanimity of opinion has been expressed within the last twenty-five years in published discussions of the origin of contact-metamorphic deposits. With but few exceptions such bodies have been attributed, at least in part, to the action of vapors which have emanated from a nearby magma soon after the magma was emplaced and before much more than a thin border phase of the magma had solidified. Many of the proponents of the role of gases in contact metamorphism concede that such gases are primarily active only in the early stages of metamorphism and give way to liquids in the later stages. Among the American geologists who have in the last two decades endorsed these views are Bateman (1942, pp. 52, 55–56, 84–85), Fenner (1933, p. 98), Gallagher (1937, pp. 1–85), Gillson (1929, pp. 111–121), Jahns (1944, pp. 173–205), Knopf (1933, p. 540), Kristofferson (1936, p. 202), Osborne (1929, pp. 729–732), Schmitt (1939, p. 812), Wells (1938, pp. 477–507), and Vitaliano (1944, pp. 921–950). Foreign geologists who have expressed opinions substantially in agreement with their American coworkers are Derviz (1938, pp. 5–44), Geijer (1925, pp. 687–690), Jamotte (1934, pp. 22–55), W. Q. Kennedy (1931, pp. 76–139), Sobolev (1935, pp. 783–791), Stirnemann (1926, p. 60), Sundius (1934, pp. 658–661), and Vogt (1926, pp. 316–319). Among the earlier writers who have supported such views of the origin of contact-metamorphic deposits are Goldschmidt, C. K. Leith, E. C. Harder, and Calkins.

The gaseous emanation theory has been strengthened by Ingerson (1934, pp. 454–470) and also by Greig, Merwin, and Sheperd (1933, pp. 61–74), demonstrating that nonvolatile compounds can be carried by volatile compounds at super-critical temperatures. A summary of the evidence in support of such an origin and an excellent bibliography have been published recently by Jahns (1944).

Umpleby (1917, p. 79) has made the useful distinction between metamorphic products formed by escaping constituents, ". . . (1) as an advance wave of intrusion, (2) at the moment of intrusion, and (3) after the consolidation and fracturing of a magma shell." He sets apart the third stage from the first and second and believes them separated by a period during which the unfractured magma crust forms a comparatively impervious barrier to the escape of the volatile constituents.

Lindgren's ideas on the problem of gases versus liquids are somewhat contradictory and apparently changed during his lifetime. His earlier writings stress the importance of gaseous emanations, and in the 1933 edition of his "Mineral Deposits" (p. 710) he states that the view that ". . . the heavy metals were introduced as chlorides, fluorides, etc., is very likely correct." However, elsewhere in the same volume (p. 124) he says,

> From the fact that in most kinds of replacements large amounts of material, such as difficultly volatile compounds of potassium, sodium, calcium, magnesium, and other substances, were consistently carried away, we may conclude with confidence that the agents which effected this were mainly liquids and not gases. This applies to pyrometasomatic as well as to the tin deposits and other hydrothermal and following classes. Gas could not effect this enormous transfer.

In general, however, the trend in recent years among geologists has been to rely more and more upon the efficacy of gases in interpreting the origin of deposits such as are classed "contact-metamorphic." This trend perhaps began with the publication of the papers by Day and Allen (1925), and Zies (1929). Particular importance has been attached to Zies' discovery of several thousand pounds of magnetite, apparently introduced as a volatile chloride, among the fumarolic deposits of the Valley of Ten Thousand Smokes. The trend has continued and been given impetus by the more recent papers describing solubility of nonvolatile compounds in water vapor at high temperatures and pressures.

TIME OF CONTACT METAMORPHISM OF THE JUMBO BASIN

The geological evidence appears clear as to the time the contact-metamorphic deposits of the Jumbo basin were formed. These deposits were introduced not only after a shell around the intrusive mass had crystallized, but after the stock at the present level of exposure had essentially solidified. The evidence for this is threefold:

1. Skarn minerals have extensively replaced igneous rocks, which therefore must have been crystalline at the time of replacement.

2. All variants of the stock, ranging from gabbro to granite, are replaced alike. The skarn bodies are not disproportionately associated with any one variant of the stock, and structurally and mineralogically continuous skarn masses as at the Jumbo mine are in contact with widely variable intrusive rock types. Whatever may have been the cause of the diversity of rock types, at the time the intrusive rock of lowest solidifying temperature, granite or syenite, reached its final position and became crystalline, the remaining members of the stock must have been below their melting points. Contact metamorphism did not take place until after the last and presumably the lowest solidifying unit of the stock had formed, had been replaced, and had crystallized for at least tens of feet along its borders. Only by postulating very special conditions could one assume that more than a small fraction of the stock, if any, was fluid at this time.

3. Late-stage orthoclase has flooded the stock and has been at least locally introduced into almost all the variants of the stock. The orthoclase replaces earlier feldspars and consequently was formed after the stock was partly, and presumably largely, crystalline. The orthoclase is earlier than the contact metamorphism and unrelated to it, at least geographically.

These observations compel the view that contact metamorphism at the Jumbo basin was not an early-stage phenomenon, taking place soon after the introduction of the magma, but was a late-stage phenomenon, essentially the last step in the magmatic process. The time is thought to be equivalent to or somewhat later than Umpleby's stage 3. The evidence is strongly in support of the views of Umpleby, Spencer, and Spurr.

The sequence of events during contact metamorphism appears to have been as follows: The first event was marmorization of the original fine-grained limestone, followed by introduction of the silicate minerals of the skarn zone. This was followed by deposition of magnetite, deposition of sulfide minerals, and crystallization of residual calcite in the skarn zone. There is no evidence to indicate that one process was completed throughout the area before the next began. It is likely that marmorization, skarn introduction, and magnetite deposition were all taking place simultaneously in different parts of the contact zone.

The time of marmorization is not clearly established. Some or much of the recrystallized limestone, as discussed earlier, is certainly closely related to the introduction of skarn minerals and magnetite. Much more appears unrelated to skarn zones. The limestone may have recrystallized, as Umpleby (1917, p. 65) has suggested, in an early stage of metamorphism, of his stage 1 or 2 category. An alternative possibility is that solutions, after losing heat and solute in the reaction that formed skarn minerals, moved on, retaining only enough heat to aid in the recrystallization of the marble.

If this is the case, however, evidence of the passage of these solutions through the limestone would be expected in the form of introduced silicate or ore minerals, and such minerals are lacking. Carbon dioxide, released by the attack of hydrothermal solutions on the limestone in the replaced zone, may have been the agent involved in bleaching and recrystallization beyond the contact silicate zone. Difficulties appear here too, for calculations indicate that the CO_2 released by skarn replacement would be small in volume and highly soluble in the hydrothermal fluid.

SOURCE OF CONTACT-METAMORPHOSING SOLUTIONS

If most, though perhaps not all, of the Jumbo basin stock at the present surface of exposure was crystalline at the time of contact metamorphism, little choice remains but to postulate a deeper source for the contact-metamorphosing solutions. The solutions were most probably concentrated by partial crystallization in the still fluid, more deeply buried portions of the stock, from which they escaped and migrated, along channelways through crystalline igneous rock or along the margin of the stock, to the loci of the skarn bodies.

Abundant evidence from other districts suggests that many skarn masses have formed from solutions derived elsewhere than from the immediately adjacent igneous rock. For example, in the Mount Eielson district, Alaska [3], in Leadville, Colorado (Emmons, Irving, and Loughlin, 1927, pp. 209–210), and in many other districts, there are finely crystalline dikes whose volume and relations appear to preclude them as the sources of mineralizing solutions, but which are nevertheless surrounded by extensive contact-metamorphic aureoles. The author believes it highly probable that contact-metamorphic deposits associated with intrusive rocks, such as the gabbro and diorite sheets of the Nickel Plate mine, British Columbia (Camsell, 1910), and the magnetite deposits associated with the Triassic

[3] Wahrhaftig, Clyde, 1944, The Mount Eielson district, Alaska, U. S. Geol. Survey unpublished report.

diabases of Cornwall, Pennsylvania (Spencer, 1908, pp. 74–76), may have stemmed not from the adjacent igneous rock but from some deeper parent magma. There is abundant evidence that such rocks rarely yield ore-forming solutions in quantity.

Even better evidence that contact-metamorphosing solutions may have migrated far from their source before releasing their burden of mineral solute is seen in the class of deposits which Lindgren describes as "pyrometasomatic deposits not related to contact" (1933, pp. 735–743). He describes these as deposits "in which the mineral association points to the same mode of origin [contact-metamorphic] but which are not clearly related to any given contact." Among the more spectacular deposits of this type are the ores of the Granby Company in the Boundary District, British Columbia (LeRoy, 1912), and possibly those of Ducktown, Tennessee (Emmons and Laney, 1926). Deposits which may, with considerable hesitance, be assigned to this category are the zinc-manganese deposits of Franklin Furnace, New Jersey, and the analogous deposits at Långban, Sweden (Geijer and Magnusson, 1944, pp. 204–208).

STATE OF CONTACT-METAMORPHOSING SOLUTIONS

There is little doubt that contact-metamorphic deposits are formed from tenuous magma-derived fluids. The fluids must be capable of transporting iron, silica, calcium, magnesium, aluminum, and the many elements introduced in minor quantities in metamorphosed rocks. Three possible modes of transport which merit consideration have been proposed: (1) The materials are carried in liquid, alkaline, aqueous solutions; (2) the materials, particularly silica and iron, are introduced in the gaseous state as volatile halogen compounds; and (3) the materials, as nonvolatile compounds, are transported in solution in supercritical gas, principally H_2O.

Of these possibilities the first seems most nearly to satisfy conditions imposed by the deposits in the Jumbo basin. It seems unlikely that the introduced materials were transported as halogen compounds. No compounds of fluorine were found in any of the deposits studied. If the deposits had been introduced as fluorine compounds, in view of the calcium-rich environment, abundant fluorite would be expected. Fluorite is reported in quantity in only a few of the many contact-metamorphic deposits which have been studied throughout the world. Of chlorine compounds, only an insignificant amount of scapolite has been noted at the Jumbo basin. The calculations of Kistiakowsky and Anderson (Graton, 1940, pp. 282–285) probably constitute the most telling argument against assigning an important role to the halogens in contact metamorphism. They have computed the partial vapor pressures of various chlorine compounds at 925° C. and 330 atmospheres. Their calculations indicate that if a gas phase developed, by far the greater part of the halogen elements would depart as HCl and HF, and only an extremely small proportion of the Cl and F would be available to transport silica, iron, etc. This would necessitate an unreasonably large original fluorine and chlorine content in the magma.

Greig, Merwin, and Sheperd (1933) have pointed out that silica may be transported as a nonvolatile compound in supercritical gas. Morey and Ingerson (1937, pp. 607–761) summarized the experimental evidence of supercritical transport up to the date of their publication. (See items 111, 113, 115, 116, 118, 129, 130, 136, 146, 147, and 149.) However, the work to date indicates from both theoretical (Smits, 1930, pp. 962–966) and experimental (Van Nieuwenburg and Van Zon, 1935, pp. 25–36) evidence that at constant pressure, solubility drops off markedly with temperature increasing beyond the critical temperature. Kennedy's data (1944) indicate that at a pressure of 300 atmospheres solubility of silica in water at 420° C. is less than half as great as solubility at 355° C. Further, supercritical solubility has been demonstrated for only a few elements.

Benedict (1939, pp. 252–276) and Keevil (1942, pp. 841–850), working largely with compounds of the alkali metals, inferred no significant amounts of dissolved salts in the gas phase even at temperatures of 500° and 600° C. However, their experiments have not been as conclusive as may be wished, for no measurements were made with under saturated solutions and vapor pressures of the order of many hundred atmospheres. At best, however, unless supercritical steam at pressures of the order of 1,000 atmospheres is postulated and properties as a solvent assigned to it, about which there are as yet no reliable data, gas cannot be considered as an efficient means of transport of the materials introduced in the Jumbo basin deposits.

REACTIONS WITH CARBONATE ROCKS

In the Lindgren genetic depth-zone classification of ore deposits, contact-metamorphic deposits are set apart from the hypothermal–mesothermal–epithermal group. (Lindgren has adopted the term "pyrometasomatic" in order to include the few deposits of contact-metamorphic mineralogy and character that are unrelated to visible contacts between igneous rocks and carbonate rocks.) The separation of contact-metamorphic deposits from the hydrothermal-depth-zone group is based primarily on the observed close relationship between bodies classed as contact-metamorphic to contacts between igneous rocks and carbonate rocks. Corroborating evidence is the presence of the calcium-silicate minerals which predominantly make up the skarn zone.

The special nature, and need for a special classification, of contact-metamorphic deposits at once disappears if contact-metamorphic deposits are considered the product of reaction between normal hypothermal solutions and calcium-carbonate rock. Such a reaction would explain the special mineralogy as well as the position of the deposits—along contacts between a relatively reactive rock (carbonate rock) and a relatively nonreactive rock (intrusive rock in most cases, but in some districts volcanic rocks or sedimentary beds free of carbonate).

Computations of the material added and subtracted during the metamorphism at the Jumbo basin (see pp. 17 and 19) indicate that the amount of calcium present in the original rock is adequate for formation of calcium-silicate minerals during metamorphism. Under appropriate conditions of temperature and pressure, calcium may be released and may combine with the silica and iron afforded in part by the metamorphosing solution and in part by the surrounding rocks.

Much geological evidence suggests that there is a certain minimum temperature below which rapid reaction between calcite and hydrothermal fluids, with resultant lime-silicate formation, cannot take place. Below the minimum temperature lime-silicate minerals do not form, though uncombined silica may form extensive replacement deposits in the limestone. Such replacement deposits and their associated ore deposits bear, both in texture and mineralogy, the earmarks of low-temperature deposits and have been classed as epithermal or shallow mesothermal. Graton (1933, p. 531) has pointed out that there are virtually no reported examples of silicified limestone or of vein quartz cutting limestone which have been classed as hypothermal. A few contact-metamorphic deposits show both types of limestone replacement—an early calcium-silicate type of reaction with the limestone and a late silicification type of limestone replacement. Among such are deposits at Bisbee, Arizona (Ransome, 1904) and Ely, Nevada (Spencer, 1917). At the Jumbo mine a transitional stage between lime-silicate type of replacement and silicification is indicated in which quartz is one of the last minerals to form.

Extensive magnetite deposits, other than those of the magmatic segregation type, are found only among those ore deposits associated with calcium-silicate skarn minerals, though magnetite is present as an accessory ore mineral in many hypothermal deposits. It cannot reasonably be postulated that only solutions or emanations destined to encounter limestone rocks were originally rich in iron. It is more probable that the extensive magnetite deposits noted in numerous contact-metamorphic deposits throughout the world are the result of the reaction between the limestone and a magma-derived solution only normally rich in iron. For the most part, magnetite does not replace limestone, or marble, but replaces a calcium-silicate mineral which had previously replaced the marble. Unfortunately the chemical system involved is of such complexity that no guess can be made as to the reactions causing the sudden precipitation of magnetite.

CHANNELWAYS OF THE CONTACT-METAMORPHOSING SOLUTIONS

The control of contact-metamorphic deposits by fractures that cut the igneous rocks as well as the adjacent marbles has been pointed out and emphasized by many students of contact-metamorphic deposits. In the Jumbo basin, this control is particularly evident at the Jumbo mine where fractures in the host rocks have been the loci of wall-rock alteration and are filled with skarn minerals. The copper deposits fill fractures which extend into the marble adjacent to the skarn zone, and many late fractures cutting the skarn zone contain chalcopyrite.

On a broader scale major fractures must have transsected the intrusive stock and carried the metamorphosing solutions up from their magmatic source. Such fractures would be localized along zones of weakness in the intrusive stock, as through inclusions, and along the margin of the intrusive body. Thus, the localization of contact deposits in inclusions within the stock and along the margins of the stock may be explained. Such an explanation is not altogether satisfactory for the tabular contact-metamorphic deposits, which typically occur flattened against the walls of the intrusive body, as are those of the Magnetite Cliff deposits (sections, pl. 5). Admittedly, the contact between an intrusive body and marble is a zone of weakness and fractures might logically follow such a zone. However, of the many hundreds of veins that extend from the intrusive rocks into surrounding sediments, as figured by Emmons in 1937, only an extremely small percentage follow the contacts between intrusive rocks and surrounding sediments. Contact-metamorphic deposits are, on the other hand, typically tabular bodies with their greatest extent, both vertical and horizontal, along contacts, though they may have been erratic offshoots into the surrounding limestone.

The following are two possible explanations, although neither is very satisfactory:

1. Limestone, particularly at moderate depths, is a more plastic rock than are the more siliceous schists and volcanics that generally surround the intrusive bodies in Emmons' illustrations. Fractures may more readily localize along a limestone contact with a buttressing intrusive igneous mass, whereas they would transsect a more brittle rock.

2. Limestone along its contact with an intrusive rock will be heated for a distance away from the contact. Hydrothermal solutions encountering the limestone might conceivably tend to react more rapidly in the preheated contact fringe than in the colder limestone more distant from the contact, where more heat must be furnished by the solutions to bring the limestone to the temperature required for reaction. Larsen's (1944, p. 403) curves show that the maximum temperature reached by a sediment adjacent to an intrusive mass

will be the original temperature of the bed plus one-half of the difference between its original temperature and the temperature of the intrusive mass. For example, if a limestone bed at 200° C. were cut by an intrusive at 800° C., the limestone adjacent to the intrusive would be raised to 500° C. However, the amount of heat supplied by the constantly renewed hydrothermal solution is probably much greater than that supplied by any possible preheating of the limestone.

The evidence of endomorphism strongly suggests that the solutions have risen vertically or traveled in the zone of the contact-metamorphic deposits and have not traveled outward from the intrusive mass through the endomorphosed rock. The extensive addition of calcium to endomorphosed rock could only have taken place from the marble zone, and the solutions from the marble zone could not have migrated inward against the flow of outward-moving solution.

Similarly the extensive zone of skarn minerals replacing schist on the northeast slope of Jumbo basin probably was developed by the action of rising solutions which became saturated with CaO by reaction with limestone, presumably below the schists. The solutions retained sufficient temperature to convert the schist beds to skarn minerals by reactions analogous to endomorphism.

ORIGIN OF SHARP CONTACTS

Most replacement ores and their gangue minerals typically have gradational boundaries with the surrounding country rock. This is not true, however, of many skarn and associated ore mineral replacements in limestone. Locally those bodies may be gradational with the surrounding carbonate rock, as at the Jumbo mine; however, in a great many districts ore as well as skarn is in sharp contact with marble.

It has been pointed out that for each volume of calcite replaced by ore or skarn minerals, almost 1,000 volumes of CO_2 will be produced at 200° C. measured at 1 atmosphere pressure. Graton has suggested (oral communication, 1945) that the sharp contacts commonly found between the zone of contact-metamorphic minerals and the unreplaced carbonate rock might mark the position of a gas-liquid interface where attacking hydrothermal solutions were held at bay by CO_2 gas generated by the replacing solutions. The extremely erratic boundary of the typical contact-metamorphic deposit is readily explained by postulating varying rates of escape of CO_2 from point to point along the boundary; fluctuating rates of escape are called upon to explain gradational boundaries.

This suggestion is subject to a semiquantitative test. Each cubic meter of calcite replaced will yield 28,000 moles of CO_2 which, measured at standard conditions of 1 atmosphere pressure and 0° C., will have the enormous volume of 630 cubic meters. It is necessary, however, to reduce this figure to the terms of temperature and pressure prevailing during the replacement process. A temperature of 350° C. is postulated as being of the right magnitude, although, according to Knopf (1933, p. 593) many geologists believe that this is somewhat low. Estimation of the pressure attained during contact metamorphism is considerably more hazardous. At the postulated interface the pressure on the gas will be identical with that on the liquid phase, and minute supported openings in the marble away from the interface can have no effect on the pressure at the interface. A steady state phenomenon is postulated in which rate of gas escape is equal to rate of gas generation. Pressure on the solution will probably be greater than merely hydrostatic pressure at the depths at which the deposits are believed to form. If the solutions migrated upward along relatively unrestricted channels from their magma-chamber source, they would almost certainly be under greater pressure than that due to the weight of the overlying rock column. It seems certain, however, that the channels to the original magma chamber are not unrestricted, and high-pressure gradients probably exist along much of the pathway of the solution. The value should be somewhere between that of hydrostatic pressure and that of the dead weight of the overlying column of rock. Although some contact-metamorphic deposits may form relatively near the surface of the earth, as Barrell (1907, p. 167) deduced for the Marysville deposits, it appears likely that many of these deposits have formed at considerably greater depths, possibly one to two miles. From these inexact considerations a pressure of between 500 and 1,000 atmospheres is postulated.

The specific volume and solubility of CO_2 under these probable conditions of pressure and temperature can be approximated. Researches of Amagat (1892, p. 1093) have given us PV values at pressures of 1,000 atmospheres and temperatures up to 100° C. and values at 450 atmospheres up to 258° C. Amagat's PV data have been recalculated in terms of specific volume and the 1,000 and 450 atmosphere isobars are plotted in figure 38. The curves have been extrapolated to 350° C., guided by values computed for the high temperature range of the curves from the Beattie-Bridgeman equation of state (Beattie and Bridgeman, 1927, pp. 1665–1667). This equation, probably the most accurate of the equations of state proposed for CO_2 gas, is given in the form

$$P=\frac{RT}{v^2}\left[v+B_0\left(1-\frac{b}{v}\right)\right]\left[1-\frac{c}{vT^3}\right]-\frac{A_0}{v^2}\left(1-\frac{a}{v}\right).$$

The constants for carbon dioxide, when the specific volume is expressed in cubic centimeters per gram, $T=t°+273.13$, and pressure is in atmospheres, are as follows:

$R=1.865$; $B_0=2.381$; $b=1.6443$; $A_0=2.586$; $a=1.621$; and $c=15.0\times10^6$

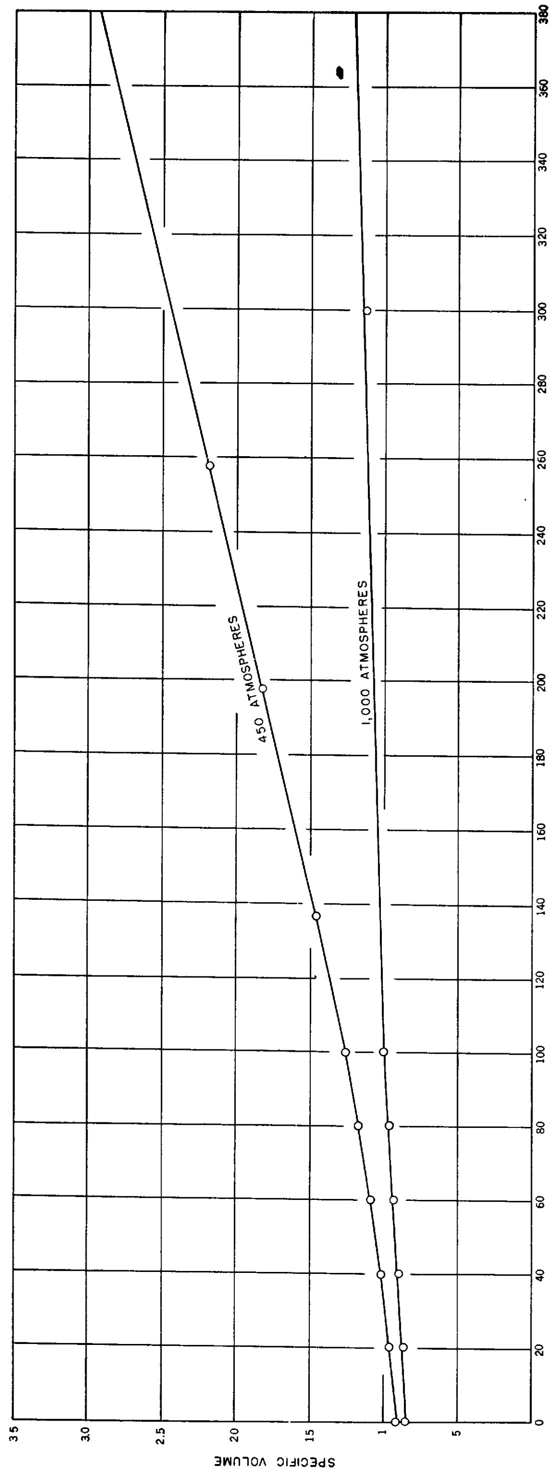

FIGURE 38.—Specific volume of CO_2 gas at 450 and 1,000 atmospheres pressure.

This equation has the disadvantage that evaluation of P or v is a laborious operation. In the range of Amagat's experimental data, Quinn and Jones (1936, p. 57) found that computed values deviated only 0.08 percent from the experimentally determined values. For a general discussion of this and related empirical equations of state see Beattie and Stockmayer (1941, pp. 195–229).

Calculations from this equation indicate that at a pressure of 1,159 atmospheres and temperature of 300° C., CO_2 gas has a specific volume of 1, which is the density of water at atmospheric pressure and 4° C. At a pressure of 1,000 atmospheres and a temperature of 350° C., CO_2 has a specific volume of approximately 1.2. Under these pressure and temperature conditions, the 630 cubic meters of gas yielded by replacement of one cubic meter of marble calculated at standard conditions will be reduced to approximately 1.25 cubic meters. At 450 atmospheres pressure the gas will have a specific volume of approximately 2.9, and 3.3 volumes of gas will be formed for every volume of calcite replaced. It appears, therefore, that no extremely large volume of CO_2 gas will be formed unless pressures are much less than even a few hundred atmospheres, which seems improbable to the author.

It is interesting to note that under 1,000 atmospheres of pressure and at a temperature of 350° C. liquid water has a specific volume of about 1.3, a value read from curves determined by plotting Goranson's data (1942, p. 209). If the assumption is made that the hydrothermal solution has density and compressibility properties similar to those of pure water, then the CO_2 gas phase formed by replacement of the limestone will actually be denser than that of the ore-bearing hydrothermal liquid.

Of more importance than the volume of CO_2 gas formed under the conditions of metamorphism is the solubility of that gas in the hydrothermal solution. Here again, the available physical data are inadequate, and major assumptions as to the composition and properties of the hydrothermal solution must be made.

The Bunsen absorption coefficient, from which the Henry's law constant can be calculated, was determined by Bohr (1899, p. 500) for CO_2 and water at one atmosphere pressure and at temperatures up to 60° C. The only data on solubility of CO_2 in water at high pressures and moderate temperatures are those of Sander (1911, pp. 513–549). His data have been plotted by Quinn and Jones (1936, p. 96) and smoothed curves drawn, from which a table of solubility of carbon dioxide in water at high pressures has been prepared. Data from this table have been replotted in figure 39. In this chart solubility in terms of cubic centimeters of CO_2 under standard conditions of 1 atmosphere pressure and 0° C. are plotted for given temperatures against pressure, measured in atmospheres. One cubic centimeter of CO_2 under standard conditions is equivalent to 0.001964 grams.

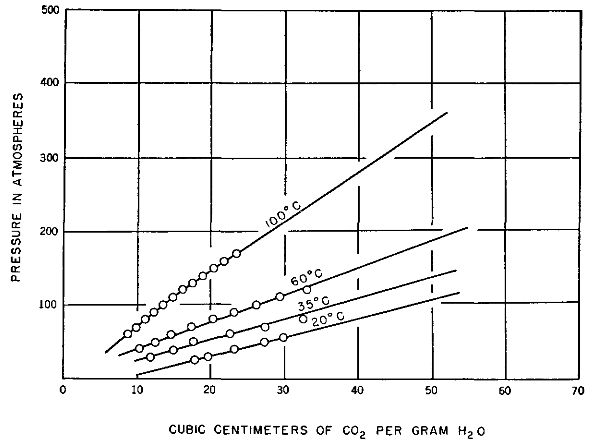

FIGURE 39.—Solubility isotherms of CO_2 in water.

The data from figure 39 have been replotted in figure 40, in which curves of equal solubility are plotted against temperature and pressure. The solubilities at 100° C., plotted in figure 40, have been extrapolated from figure 39. Straight lines have been drawn through the points of constant solubility in figure 39 and extrapolated to the temperature range under consideration, around 350° C. This is, of course, a far greater extrapolation than can be made with any assurance of accuracy. Solubilities read from the plot at 350° C. are to be considered as approximations which may be in error by a factor as great as 2.

These data indicate, however, that at a pressure of 1,000 atmospheres and a temperature of 350° C., approximately 45 cubic centimeters of CO_2, or 9 percent by weight, are soluble in one gram of water, whereas, at a pressure of 500 atmospheres, approximately 20 cubic centimeters of CO_2, or 4 percent by weight, will be soluble in one gram of water. The solubility of CO_2 gas in water is almost certainly considerably greater than is the solubility of silica in the hydrothermal solution which converted the marble beds to skarn (Kennedy, 1944, pp. 25–36), even assuming that the solubility of CO_2 in the solutions which formed the contact deposits is many times less than that indicated for pure

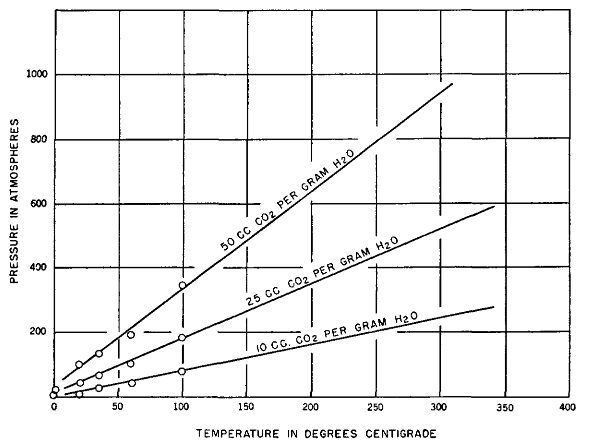

FIGURE 40.- Curves of solubility of CO_2 in H_2O at various temperatures and pressures

water by figure 40, and further assuming that the measured solubility of silica in the solutions is greater than the solubility in pure water. On page 17 it is shown that for each gram of silica introduced 0.74 grams of CO_2 are released. This could be carried away by 8 grams of water. Consequently, the attacking solution must carry silica in excess of 12.5 percent if more CO_2 is to be released than can be dissolved and carried away by the solutions.

It must be pointed out that any hydrothermal solution will not behave as pure water, and various factors will contribute to lower the solubility of CO_2 in it. Dissolved nonvolatile compounds, insofar as they hydrate, reduce the solubility of a gas in a solution. Similarly CO_2 solubility will be lowered in proportion to the mole fraction of other dissolved gases present. It does not seem likely, however, that these factors will reduce the solubility of CO_2 in a hydrothermal solution sufficiently to permit a separate gas phase to form, though the magnitude of these effects cannot be evaluated.

The alternative, that the hydrothermal solutions may have been saturated with CO_2 from their magma source, appears unlikely. Recorded analyses of volcanic gases indicate that the CO_2 content is highly variable, but, in most instances, low. The great majority of gases analyzed are predominantly H_2O and contain only a few tenths of a percent CO_2 (Clarke, 1924, pp. 266–288). Furthermore, there is little evidence that intrusive bodies which cut contact-metamorphosed limestone have dissolved much of the limestone and thereby become abnormally rich in CaO and CO_2. No systematic decrease in calcium in primary intrusive rock away from a limestone contact has been reported in any of the numerous contact-metamorphic deposits studied in recent years in the United States. It seems reasonable, therefore, to infer that the CO_2 content of the solutions before they reach the contact zone is no greater than that reported for typical gas fumaroles.

In summary, it is not likely that a gas–liquid interface would be created by the action of the hydrothermal solutions on limestone. Should any gas phase be generated, it would be of extremely small volume and very dense owing to the pressures prevailing. Furthermore, it is probable that no gas phase would be generated, for the hydrothermal solution traveling through the limestone would be sufficient in quantity to dissolve and carry away all CO_2 released.

The common experience of the geologist is to encounter gradational boundaries at the margin of the typical replacement body. In general, however, the replaced body is multi-mineralic rock, a granite or schist for example, and its constituent minerals vary greatly in ease of replacement. Outward from the center of the most intense alteration, minerals which are successively more resistant to replacement remain unattacked, and a typical gradational boundary results. In general, also, prior to the advent of the replacing solutions, temperature and pressure intensities are uniformly distributed throughout the zone of rock to be replaced. Neither of these two conditions holds in contact-metamorphic deposits developed in limestone or marble. Here the host rock is monomineralic, and there is no reason for the ore fluids to ignore one grain of carbonate and pass on to seek out and replace another. Likewise, prior to mineral introduction, temperature distribution throughout the zone is not uniform. The rocks have been preheated by contact with the intrusive mass; and a sharp temperature gradient through the limestone, outward from the walls of the intrusive mass, is to be expected. Solutions working outward from the locus marginal to the igneous rock encounter successively colder rocks, and the margins of the replaced rock are apt to be abrupt. In the Jumbo basin sharp contacts are characteristic of the deposits with the simplest mineralogy and with both the earliest skarn and the earliest ore minerals—diopside, garnet, and magnetite. These are interpreted as being the highest-temperature deposits of the group; they have formed in limestone near the intrusive mass where the preheating of the limestone had been greatest and where temperature gradients through the limestone were steepest.

CLASSIFICATION OF JUMBO BASIN CONTACT-METAMORPHIC DEPOSITS

In the preceding pages evidence has been cited which indicates that in source and composition the solutions which formed the deposits of the Jumbo basin differed little from normal hydrothermal solutions, and that the mineralogy and structural position of the deposits is probably largely a reflection of their marble environment. This view is strengthened by the observation that deposits classed as mesothermal and hypothermal have not been reported from marble or limestone environment; perhaps when they do form in marble or limestone environment they are by convention called "contact-metamorphic." Published descriptions of contact-metamorphic deposits indicate that all types of hypothermal deposits, ranging from the gold-arsenopyrite type (Camsell, 1910) to that of cassiterite (Knopf, 1908) have their analogues in contact-metamorphic deposits.

The Magnetite Cliff bodies of the Jumbo basin are believed to have formed under conditions equivalent to hypothermal. The deposits of the Jumbo mine are believed to have been formed under deep or intermediate mesothermal conditions. The last stage in these deposits, during which zeolites formed on the walls of cavities, probably represents conditions of still lower temperature and pressure—shallow mesothermal or leptothermal. The upper magnetite deposits presumably occupy a genetic position between the Jumbo deposits and those of the Magnetite Cliff area.

MINERAL DEPOSITS OF THE JUMBO BASIN

MAGNETIC SURVEY

APPLICABILITY

The results of magnetic surveys made of the magnetite deposits on Kasaan Peninsula by the Geological Survey during the summers of 1942, 1943, and 1944 proved conclusively the value of a magnetic survey conducted in conjunction with detailed geologic and topographic mapping. Consequently, a magnetic survey of the Jumbo basin was included in the present investigation. Because of limited time and manpower, a dip needle and Brunton compass were selected as the only practicable magnetic instruments for use in the steep, heavily forested terrain of Prince of Wales Island where magnetic anomalies are large and a great number of closely spaced readings are required.

A Lake Superior-type dip needle (Clements and Smyth, 1899, pp. 342–343; Hotchkiss, 1915, pp. 97–107) was used in these surveys. The needle was counterbalanced by a weight on the south-seeking pole so that this pole was depressed about 9° below the horizontal in the normal magnetic field of the earth. The needle is at an angle of about 81° to the normal earth's field which dips about 72° N. in the vicinity of the Jumbo basin. In this position the dip needle has higher sensitivity to variation in magnetic intensity than if the needle were counterbalanced, as is sometimes recommended, to give a positive reading of a few degrees. Dip-needle observations are taken in the plane of the magnetic meridian and deflections of the needle are roughly proportional to small changes in vertical intensity of the earth's magnetic field. Anomalies in horizontal deflection are measured with a Brunton compass where a backsight can be taken along a line of known orientation.

FIELD METHODS

The close control required by the geologic and magnetic work was provided by a plane-table and telescopic-alidade topographic survey. Because of prevalent rain and fog, mapping by means of a solar compass is not practicable.

A number of points on an initial net were located by tape and transit. Because of the extreme slope of the terrain and the heavy cover of brush and timber over much of the area mapped, plane-table triangulation was not practical. Plane-table traverses were made from the points on the original survey net with orientation carried by backsight. Numerous rod shots were taken from each station occupied along the lines of traverse. No attempt was made to occupy corners of a grid or systematize the taking of magnetic data. Points of geologic interest were located by rod shots from the plane table. The dip-needle man then occupied the point and backsighted on the plane table with a Brunton compass corrected only for the regional magnetic declination. The local variation from the regional declination is thus the difference between the correct backsight bearing from the plane table and the bearing actually obtained by the magnetic observer. The dip needle was then oriented in the plane of the magnetic meridian and the reading recorded with that of the horizontal anomaly. In general, points of interest selected by the geologist were no more than 40–50 feet apart and were sufficient for topographic control and the magnetic survey. However, in regions of great variation in magnetic anomaly, additional stations as close together as 10 feet were occupied by the magnetic observer. This method is preferable to the grid method, in that the great amount of work in locating and occupying the corners of a grid is obviated, and only the number of points needed completely to work out the pattern of magnetic anomalies need be occupied by the magnetic observer.

At least three people are required for the efficient functioning of a party, and where brush is heavy it is desirable to have an additional member to clear brush along lines for plane-table shots and to locate outcrops.

MAGNETIC DATA AND INTERPRETATION

GENERAL FEATURES

Both geologic and magnetic data indicate that the larger magnetite deposits in the Jumbo basin area are tabular; they strike approximately east and dip steeply to the south.[4] In detail they pinch and swell and their magnetic patterns are locally superimposed. The topography is irregular but, in general, slopes steeply southward, approximately parallel to the dip of the major ore concentrations. These complexities are reflected in the magnetic anomalies, which, locally, are high and variable. However, certain inferences may be drawn from the magnetic data which are of considerable aid in interpreting the probable subsurface extent of the magnetic bodies.

Dip-needle anomalies recorded throughout the mapped areas have been contoured on a 10° interval. Solid contours on the accompanying maps (see pls. 2, 3) indicate lines of equal positive dip-needle deflection (lines of equal deflection below the horizontal of the north-seeking pole of the dip needle), and dashed contours indicate lines of equal negative deflection (equal deflection below the horizontal of the south-seeking pole of the dip needle). The dip needle was counterbalanced so that the normal reading for the area was $-9°$, and thus the points of true zero deflection are actually nearer the first dashed contour than nearer the zero contour.

Horizontal anomalies were measured throughout the mapped areas but they have not been shown on the accompanying maps of isomagnetic lines because these anomalies are very small and erratic. Hotchkiss (1915,

[4] All directions in this report dealing with dip-needle interpretations are referred to magnetic north.

p. 111) has shown that when the magnetic formations strike normal to magnetic north, as at the Jumbo basin, there is no regional or consistent horizontal anomaly.

ANOMALIES IN THE VICINITY OF THE MAGNETITE CLIFF BODIES

Magnetite Cliff is characterized by moderate to large dip-needle anomalies (pl. 2). Anomalies were not determined over part of the large Magnetite Cliff deposit because of the 60° slope of the terrain.

Geological evidence indicates that these masses are tabular, that they strike essentially normal to the regional magnetic meridian, and that they dip steeply to the south. The characteristic anomaly profile for bodies of this shape and attitude has been determined experimentally by Hotchkiss (1915, p. 121). In areas of little relief strong positive anomalies are to be expected, localized with peak intensity somewhat north of the outcrop of the east-striking mass; much weaker negative anomalies are to be expected in a belt parallel to the trend of the mass and lying somewhat to the south. This, in general, is the distribution of the anomalies in the Magnetite Cliff area. However, because the land surface slopes steeply in the direction of the dip (average slope of terrain is more than 45°) the effect of the buried south pole of the magnetite plates is great, and consequently negative anomalies cover broader areas and are much stronger than would otherwise be the case.

The small deposit which crops out in the upper right corner of the Magnetite Cliff mapped area (ore body *C*, pl. 4) is marked by low positive anomalies over the major part of the outcrop. Negative anomalies of moderate intensity occupy a considerable area to the south. These anomalies are interpreted as consistent with the structural data which indicate that the dip is steeply southward (sections C–C′ and D–D′ of pl. 5) and that the south pole of this mass is relatively near the surface. A few feet south of this area of negative dips is a small area of limited extent characterized by high north dips with negative anomalies to the south. This may indicate that the magnetite shown in cross section D–D′ (pl. 5) may actually consist of two masses, the lower unit of which may lie somewhat nearer the surface than the lower termination of the outcropping body. However, insufficient evidence is at hand to explain adequately this and many other complexities in the pattern of anomalies.

In the Magnetite Cliff area a broad region of low positive anomalies covers the northernmost portion of the deposit. These anomalies are much weaker than is to be expected and cover regions near the upper limit of this ore deposit, where the ore is believed to be relatively thin (cross sections C-C′ and D–D′, pl. 5). The major part of the mass is characterized by strong south dip-needle deflections. It is difficult to interpret these deflections but they probably indicate that the plate has little continuation down the dip below the lowermost exposures of magnetite. Thus, the south pole of the lower mass would lie near the surface of the ground.

A patch, with outcrop dimensions of about 70 by 40 feet, is exposed in a small canyon about 25 feet north of the principal Magnetite Cliff body (ore body *B*, pl. 4 and sections B–B′, C–C′, pl. 5). Large negative magnetic anomalies appear to be associated with this body. They are believed to indicate a considerable thickness of ore of limited lateral extent; however, local irregularities in topography complicate the observed magnetic field and it cannot be clearly interpreted.

ANOMALIES IN THE VICINITY OF THE UPPER MAGNETITE BODIES

Four areas of magnetic anomalies have been mapped in the vicinity of the upper magnetite deposits. These are related to three exposures of magnetite-bearing rock and a postulated small buried magnetite mass (pl. 3). Little is known concerning the shape and attitude of the magnetic bodies. For the most part they appear to be elongated in a direction normal to the magnetic meridian and to dip steeply southward, though the evidence is not conclusive and some information indicates that the patch in the southeast corner of plate 4 dips steeply to the north.

The pattern of dip-needle deflections around these masses is extremely simple. For the most part the masses apparently have acted as single magnets with a near-surface north pole and a buried south pole.

The body shown in the northwest corner of plate 6 is characterized by weak positive anomalies over the northern portion of its outcrop and by a faint negative disturbance a few feet to the south of it. The weakness of these magnetic effects indicates that the magnetite is present as a thin tabular sheet of small tonnage; the general distribution of anomalies suggests a southward dip.

Southeast of this area several anomalies have been mapped that are unrelated to any exposed magnetite masses. Weak positive anomalies are here bordered on the south by a region of strong negative anomalies. These anomalies are interpreted to indicate a small buried tabular lens of magnetite essentially parallel to the present land surface, which slopes steeply to the south. Because the magnetic distrubance does not extend over a very great area, and yet is relatively intense, the lens is presumed to lie at a depth of a few tens of feet.

A small patch of high-grade magnetite crops out on a steep south-dipping slope about 200 feet south of the buried magnetite lens. Moderate positive dip-needle deflections mark the major portion of outcrop and extend somewhat north of its limits. These deflections are bounded on the south by a region of strong negative deflections. The anomalies suggest a southward dip, at only a slightly higher angle than the present steep hillside. The effect of the buried south pole of the ore patch is marked.

The largest mass of magnetite, actually a group of several bodies of extremely irregular shape, crops out in the southeast corner of the mapped area. This group acts as a single magnet and has a surprisingly simple magnetic field. An area of moderate positive anomalies covers most of the outcrop. The magnetite bodies are flanked on both the north and the south by small areas of negative anomaly. The pattern of anomalies is not comparable to that shown by any other magnetite deposits in the Jumbo basin. Hotchkiss's diagrams (1915, p. 121) suggest that a magnetite mass striking normal to the magnetic meridian and dipping north would be characterized by a zone of negative anomalies north of a zone of positive anomalies. The negative anomalies lying south of the zone of positive anomalies may be due to the steep south slope of the terrain, which would tend to increase the observable effect of the buried south pole of the ore. Some independent geological evidence from the northwestern limit of this ore deposit tends to confirm the implication of the magnetic pattern that the ore is dipping to the north.

THE DEPOSITS

MAGNETITE CLIFF BODIES AND VICINITY

The deposits of Magnetite Cliff crop out on the north slope of the Jumbo basin at altitudes ranging from 1,500 to 1,900 feet (pl. 1). They can be reached by trail from the beach opposite Jumbo Island.

Four short adits have been driven to explore the deposits (pl. 4) but no ore has been mined.

GEOLOGY

A variety of rocks is exposed in the vicinity of Magnetite Cliff (pl. 4). Parts of the Jumbo basin stock, here largely granodiorite, intrude marble and calcareous schist. Apophyses of granodiorite cut marble and locally both intrusive rock and marble have been converted to massive skarn rock, composed predominantly of diopside and garnet. Massive plates of magnetite lie within and adjacent to the skarn zone.

STRUCTURE

The major structural features of the deposits are shown on the cross sections on plate 5. The contact between the rocks of the intrusive stock and the overlying marbles dips about 50° southwest. Marble and schist overlie the stock and are, in general, concordant, though gentle folds and flexures in the marble are present. The bedding of the marbles indicated in the sections and plate 4 is somewhat schematic as much of the marble retains no trace of the original bedding and locally outcrops are sparse.

The dominant structural feature of the deposits is an intrusive sheet of granodiorite which extends from the stock through the overlying marble beds. The sheet, averaging about 25 feet in thickness, is locally a dike and locally a sill. A slice of marble, ranging in thickness to more than 50 feet, is included between the sheet and the underlying stock and is partly replaced by skarn minerals and magnetite.

ORE DEPOSITS

Three tabular magnetite deposits and one chalcopyrite deposit crop out in the Magnetite Cliff area. They have formed by replacement of marble adjacent or very close to the intrusive stock. They may be bounded on one side by igneous rock, and on the other by marble, or they may be partly or completely enveloped in garnet-diopside skarn rocks. Zones of skarn minerals are contained within the magnetite. The dip of the deposits ranges from 30° to more than 60° southeast; they strike about N. 25° W. A few small fractures, in general parallel to the dip and strike of the deposits, cut the ore.

Most of the ore is massive magnetite containing some disseminated chalcopyrite. The gangue minerals are predominantly diopside with smaller amounts of garnet. Calcite is present in only a few small lenses. The average grain size of magnetite ranges from 0.1 millimeter to 3 millimeters in different specimens. Magnetite generally replaces diopside and no specimen examined was completely free of residual diopside (pls. 11, 12). Similarly garnet has been extensively replaced by magnetite. Chalcopyrite is later and, in general, replaces magnetite. Chalcopyrite constitutes an average of 2–3 percent of the deposit, though locally it may be very sparse or may constitute as much as 10–15 percent of the ore. No correlation was noted between the total amount of chalcopyrite and that of magnetite. Likewise, no particular part of the deposit appeared to be systematically richer in chalcopyrite. Goddard (1943) has noted increased copper content near the margins of magnetite deposits on Kasaan Peninsula, southeastern Alaska. These conditions do not hold in the Jumbo basin.

RESERVES

Three magnetite deposits are believed to constitute the major reserves of the Magnetite Cliff area. Another small patch is present, consisting predominantly of garnet but containing some chalcopyrite. Five cross sections have been constructed normal to the strike of the tabular magnetite, and two vertical cross sections have been constructed on lines parallel to the strike (pl. 5). Geologic information obtained from surface outcrops, from three short adits, and from study of magnetic anomalies has been used in the construction of the cross sections. At best, however, these data are inadequate, and estimates of reserves are to be considered only as approximations.

TONNAGE

The tonnage in these deposits has been computed by planimetric measurement of the area of ore shown in each of the cross sections normal to the strike. The average cross section has been multiplied by the average distance between the planes of the cross sections. The volume per ton of ore is assumed to be 8.5 cubic feet.

Estimated tonnage of iron ore reserves, Magnetite Cliff area, Prince of Wales Island, southeastern Alaska

1. Magnetite ore body *A*:				
Area of ore exposed:				
Cross section A–A′ [1]	sq ft	340		
Cross section B–B′	do	1,650		
Average distance between planes of sections	ft	47		
Volume of block	cu ft		46,700	
Area of ore exposed:				
Cross section B–B′	sq ft	1,650		
Cross section C–C′	do	8,300		
Average distance between planes of sections	ft	95		
Volume of block	cu ft		472,600	
Area of ore exposed:				
Cross section C–C′	sq ft	8,300		
Cross section D–D′	do	13,760		
Average distance between planes of sections	ft	116		
Volume of block	cu ft		1,279,500	
Area of rock exposed:				
Cross section D–D′	sq ft	13,760		
Average distance section extends eastward [2]	ft	40		
Volume of block	cu ft		550,400	
Total	cu ft		2,349,200	
Long tons				276,400
2. Magnetite ore body *B*: [3]				
Area of ore exposed:				
Cross section B–B′	sq ft	980		
Cross section C–C′	do	3,400		
Average distance between sections	ft	95		
Volume of block	cu ft		208,000	
Volume of block east of C–C′ [3]	do		192,000	
Total	do		400,000	
Long tons				47,000
3. Magnetite ore body *C*: [4]				
Area of ore exposed:				
Cross section B–B′	sq ft	1,020		
Cross section C–C′	do	1,650		
Average distance between sections	ft	93		
Volume of block	cu ft		124,200	
Area of ore exposed:				
Cross section C–C′	sq ft	1,650		
Cross section D–D′	do	2,470		
Average distance between sections	ft	96		
Volume of block	cu ft		197,700	
Area of ore exposed:				
Cross section D–D′	sq ft	2,470		
Average extent eastward [5]	ft	30		
Volume of block	cu ft		74,100	
Total	do		396,000	
Long tons				46,600
Grand total	long tons			370,000

[1] An insignificant tonnage of ore, which has not been computed, lies west of the plane of cross section A–A′, plate 23.

[2] The area of ore in cross section D–D′ is assumed to extend an average distance of 40 feet east of the plane of this section. Little ore is shown in section E–E′, and the tonnage lying east of the plane of that section is insignificant.

[3] The intermediate ore body is exposed in a gully at an altitude of about 1,700 feet. Its extent and thickness is largely inferred from magnetic anomaly data. About one-half of this ore is assumed to lie between the planes of sections B–B′ and C′–C′.

[4] The uppermost of the Magnetic Cliff ore bodies crops out at an altitude of about 1,900 feet. On the basis of magnetic data it is inferred that this body extends to the plane of section B–B′, but only a little to the west of it.

[5] Estimated.

Of this tonnage little is sufficiently well known to be classed as measured ore. Somewhat less than half is considered indicated ore, and the remainder is classed as inferred ore.

The tonnage of the small patch of chalcopyrite-bearing skarn associated with ore body *C* has not been measured but is estimated to be no more than 25,000 tons.

GRADE

Channel samples 2 inches by 6 inches in cross section have been cut from the magnetite deposits by the U. S. Bureau of Mines. The samples have been taken both from the outcrops and from the three drifts that cut the ore. A total of 97 channel samples have been cut with average length of slightly more than 6 feet, aggregating 637.5 feet of sample. Because of lack of adequate exposures these samples have not been taken systematically from the deposit, but their average iron and copper content is believed to be representative of that of the three deposits.

Analyses of these samples have been kindly furnished by the U. S. Bureau of Mines. Iron ranges in amount from 13 to 65.2 percent and copper ranges from 0.02 to 4.27 percent. The samples contain a weighted average of 45.2 percent iron and 0.73 percent copper.

The analyses of ten composite samples, made up of parts of the channel samples, have been furnished by the U. S. Bureau of Mines. The analyses of these samples have been arithmetically averaged and indicate:

Average assay of channel samples, Magnetite Cliff deposits, Prince of Wales Island, southeastern Alaska

[Analyses by U. S. Bureau of Mines]

		Oz. fine	*Value*
Gold	per ton	0.01	$0.35
Silver	do	.08	.567
Total			.917
Cu	percent	.77	
Fe	do	46.4	
S	do	2.05	
P		Tr.	
TiO_2		Tr.	
Insol	percent	23.4	

No samples of the small patch of chalcopyrite-bearing skarn have been cut. Inspection of this deposit suggests that it contains about four times as much chalcopyrite as the average magnetite ore. This would indicate a grade of 2½–3 percent copper.

UPPER MAGNETITE BODIES

The upper magnetite deposits crop out about 2,000 feet southwest of the peak of Mount Jumbo at altitudes ranging from 2,150 to 2,500 feet. They can be reached by trail from Magnetite Cliff although the route is circuitous and difficult.

No artificial openings have been driven to explore the deposits and no ore has been mined.

GEOLOGY

The deposits are principally in marble inclusions in the Jumbo basin stock, here largely granodiorite (pl. 6). The marble inclusions have been completely recrystallized and little trace of the original bedding remains. Parts of the inclusions have been replaced by skarn minerals, and locally the granodiorite is intensely altered. Dikes of granodiorite and latite cut the marble in the vicinity of the magnetite. Some of these dikes, principally the earlier latites, have been altered and impregnated with pyrite.

ORE DEPOSITS

Ore bodies crop out at five localities a few hundred feet apart in the upper magnetite area. For the most part they are in inclusions of marble in the Jumbo basin stock, though one small patch at an altitude of about 2,150 feet (pl. 6) is surrounded by granodiorite, and may have replaced the granodiorite. Other masses are surrounded by limestone, surrounded by skarn minerals, or in contact with marble, skarn minerals, and granodiorite. Although the deposits are, in general, associated with skarn minerals, no systematic relationship to the skarn zone was observed. The major skarn zone, possibly largely a replacement of granodiorite, contains no magnetite deposits.

Most of the magnetite deposits are highly irregular lenses and pods. Few data on their structure have been obtainable. The two bodies that crop out near the western portion of the mapped area (pl. 6) appear to be tabular and to dip about 45° S. Some evidence indicates that the deposits that crop out in the southern portion of the mapped area plunge steeply to the north, although their attitude of contact ranges widely.

The deposits are made up predominantly of magnetite but contain a few percent of chalcopyrite. Locally garnet, diopside, quartz, and calcite are abundant gangue minerals. The proportion of gangue to ore ranges widely.

RESERVES

These smaller deposits have not been adequately sampled and no systematic attempt has been made to estimate the tonnage they contain. Their small outcrop dimensions, coupled with the weak magnetic anomalies observed nearby, indicate that they are small and have little vertical extent. At best, no single deposit is estimated to contain more than a few thousand tons and collectively they probably contain less than 50,000 tons.

The iron and copper content of the ore is believed comparable to that at Magnetite Cliff.

JUMBO MINE

The workings of the Jumbo mine are located at altitudes ranging from 1,570 to 1,900 feet in the center of the large cirque at the head of the Jumbo basin. The deposits are about 2 miles west from the beach opposite Jumbo Island and can be reached by a good corduroy trail.

MINE WORKINGS

The principal workings of the Jumbo mine consist of a large open stope, three tunnels, several winzes and raises, and a sublevel. The total length of workings accessible for mapping was about 2,300 feet (pl. 7). Most of the ore has come from a large stope, opened by a short adit at a 1,750-foot altitude. The stope has, in part, been driven or caved through to the surface. Reportedly, ore from this stope was put through a raise from the 1,700-foot level and thence lowered to the 1,570-foot level, from which it was transported to tidewater by an aerial tram 8,250 feet long. Some workings are reported to extend from a winze, put down at a point about 300 feet from the mouth of the 1,570-foot level. At the time of the writer's visit these workings were flooded and inaccessible. Numerous other short adits and open-cuts have been driven near the principal workings of the Jumbo mine. These were not mapped.

GEOLOGY

The geology in the vicinity of the Jumbo deposits is shown in figure 41. The detailed geology and principal workings are shown in plate 7. The rocks in the vicinity of the Jumbo mine consist largely of rocks of the intrusive stock, which range in composition from granodiorite to gabbro. Also are included marble, andesite dike rocks, and skarn. The coarsely crystalline intrusive rocks have been altered locally to scapolite and sericitized and albitized. The andesite dikes, likewise, have been intensely altered; their exact original composition is obscure. A few scattered lenses of marble are present within the skarn zone, and tongues of skarn cut through the marble.

STRUCTURE

The Jumbo mine deposits are in the nose of a large inclusion or roof pendant of marble and schist surrounded by intrusive rocks. A skarn zone about 250 feet in width has formed along the contact between marble and intrusive rocks near the nose of the inclusion. Numerous altered andesite dikes and apophyses of the intrusive stock are present within the skarn zone. Chalcopyrite-bearing fractures which cut the skarn zone belong predominantly to two sets. One of these strikes about N. 20° W. and dips at low angles to the east. The other strikes about N. 70° W. and dips steeply to the north. Andesite dikes, for the most part, strike northwest.

ORE DEPOSITS

The major ore deposit of the Jumbo mine is irregular in shape, comprised largely of chalcopyrite, epidote, calcite, quartz, and garnet, and crops out near the contact between skarn and unreplaced marble. Lenses of chalcopyrite and skarn minerals and some massive veins of chalcopyrite extend into the marble. The ore strikes about N. 45° W. and plunges 30° NW. In addition, chalcopyrite veinlets cut the main skarn zone and, locally, gabbro of the intrusive stock. Finely disseminated chalcopyrite is present in some of the altered andesitic dikes.

An appreciable amount of molybdenite is present in some parts of the skarn zone. Molybdenite is associated with quartz and epidote and is present in greatest concentration in a zone adjacent to and on the skarn side of the chalcopyrite-bearing zone. Molybdenite concentrations are, however, very spotty.

Subordinate pyrite, pyrrhotite, and sphalerite are associated with chalcopyrite but nowhere abundantly. A few masses of specularite were also noted. No magnetite was found within the Jumbo mine.

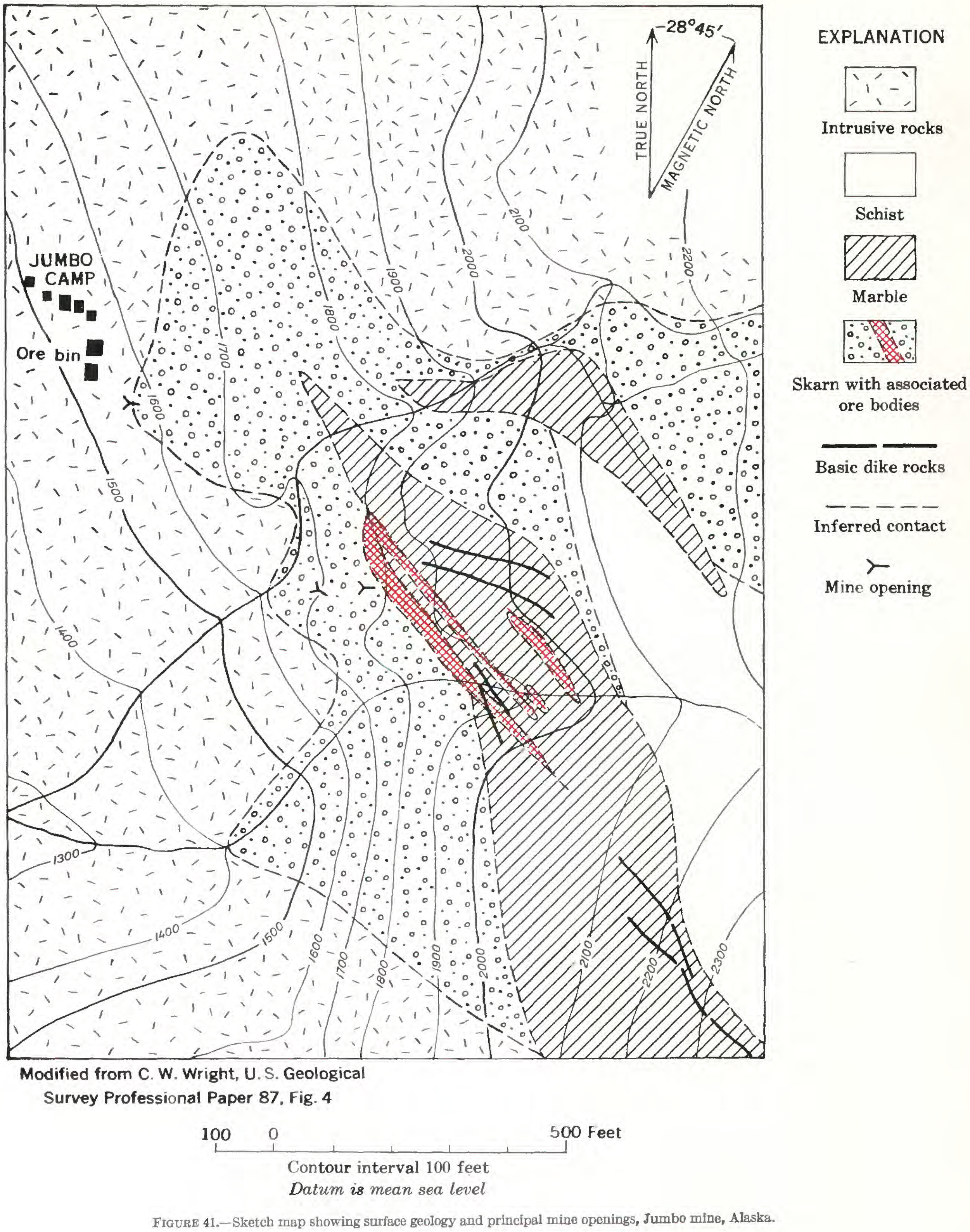

FIGURE 41.—Sketch map showing surface geology and principal mine openings, Jumbo mine, Alaska.

RESERVES

No patches of chalcopyrite of sufficient grade to be classed as ore remain exposed in the accessible workings of the Jumbo mine. A few thousand tons of material estimated to contain 0.5-1 percent of chalcopyrite are present, principally in altered andesite dikes. Ore of good grade is reportedly present in the workings below the 1,570-foot level, but these were flooded and inaccessible at the time of the writer's investigation.

SUGGESTIONS FOR PROSPECTING

In conclusion, the field and office investigations related in this report make it possible for the author to submit suggestions for further work in the Jumbo basin. Further prospecting in this district may be on a regional scale or may be limited to more thorough exploration of the known deposits.

For work on a regional scale the following recommendations are offered:

1. In view of the known deposits at Kasaan Peninsula and the Jumbo basin, particular attention should be given to the margins of intrusive rocks exceptionally rich in orthoclase.
2. Ore may most likely be found where alkaline stocks cut limestone or marble.
3. Inclusions in igneous stocks appear to be particularly favorable loci of ore deposition.
4. Sharp reentrants along the margins of stock and the acute angles of the noses of inclusions should be well examined.
5. Apophyses of the stock into surrounding marble appear to be favorable loci of ore deposition.
6. A threefold locus is demonstrated by the deposits of the Jumbo basin in which deposits form where marble-schist-stock or marble-dike-stock meet.
7. The mineralogy of the skarn rock may be a guide to the type of ore: high-iron garnet suggests nearby magnetite.
8. Skarn zones formed by replacement of igneous rock or schist are likely to be barren of ore deposits.

For prospecting further the known deposits, the courses below are indicated:

1. Exploration may reveal extension of the Magnetite Cliff deposits down the dip below an altitude of 1,400 feet.
2. At the Jumbo mine the most favorable zone for further exploration is believed to be below the 1,570-foot level, along the direction of plunge of the stoped ore body.

The prospects of finding any major deposit of copper ore at the Jumbo mine do not appear good. Deposits of copper of the type classed as contact-metamorphic are, as a rule, erratic and not of the type upon which a large-scale mining industry may be founded. Exploration and development costs of such deposits are high, and the returns over a long period of time are not great.

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