Professional Paper No. 57

Series { B, Descriptive Geology, 113
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DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

GEOLOGY

OF THE

MARYSVILLE MINING DISTRICT, MONTANA

A STUDY OF IGNEOUS INTRUSION AND CONTACT METAMORPHISM

BY

JOSEPH BARRELL

WASHINGTON
GOVERNMENT PRINTING OFFICE
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GEOLOGY OF THE MARYSVILLE MINING DISTRICT, MONTANA: A STUDY OF IGNEOUS INTRUSION AND CONTACT METAMORPHISM.

By Joseph Barrell.

INTRODUCTION.

FIELD WORK AND ACKNOWLEDGMENTS.

The Marysville mining district had been for many years previous to 1899 one of the noted gold-producing centers of Montana. The mines are situated around the margins of an irregular batholith of quartz diorite, whose surface exposure is from half a mile to 1½ miles broad and 2½ miles long. This invasion of igneous rock, which as shown on later pages of this report was primarily the cause of the location of the mineral wealth in this district, is but 6 miles at its nearest point from the exposed surface of the far greater Boulder batholith, a granitic mass which is petrographically a quartz monzonite in normal composition. The Boulder batholith possesses a general rudely rectangular form, occupying about 60 miles in latitude by about 35 in longitude, and holds within its confines the mining city of Butte, from which for many years past has poured a flood of silver and a quarter of the world's copper. Other smaller mining centers also lie within this large granitic area, while such important ore deposits as those of Elkhorn and Unionville, south of Helena, have been found about its margin. Thus the Boulder batholith, with the outlying related areas at Marysville and at Granite, constitutes one of the more important centers of mining for the precious metals within the United States. The necessity of studying such regions from the scientific point of view is evident, not only in order to develop the phases of immediate economic bearing, such as the limits of occurrence of the ore deposits, the degree of their continuity in depth, and other similar questions, but also because of the broader bearing which such studies must have on theoretical and applied geology in general.

Mr. W. H. Weed, in charge of Montana field work for the United States Geological Survey, early perceived the importance of these problems, and in 1899, in furtherance of the work on the Butte and Helena region, had two special topographic maps made by Mr. R. H. Chapman, of the topographic corps of the Survey—one of the Elkhorn mining district, situated on the margin of the larger batholith, 20 miles southeast of Helena, the capital of the State; the other of the Marysville mining district, surrounding the small outlying batholith already mentioned, 17 miles northwest of Helena.

The writer, who had spent parts of two previous years as a mining engineer in the Butte district, was employed in 1899 by Mr. Weed as a field assistant and spent four months in mapping and studying the surface and mining geology in the vicinity of Boulder, Helena, Elkhorn, and Butte. The final report on the Elkhorn district, by Mr. Weed, with an appendix by the writer, was published in 1902. In 1900 the writer spent nearly two months in the same work at Deerlodge and Butte, chiefly on underground mining geology.

In 1901 the writer was further detailed, under Mr. Weed's direction, to make a survey of the geology and ore deposits of the Marysville mining district, the report on which constitutes the present work. About four weeks were spent in the mines and six in areal mapping and detailed study of the surface formations. Mr. R. W. Stone assisted, chiefly in the underground work, for about six weeks. Mr. Weed also had previously visited the region and spent several days in the field with the writer in 1901.

Since 1901 changes of post and the pressing requirements of other duties have repeatedly delayed the completion of the report. Although the economic importance of the district has been on the wane for some years, the theoretical importance of many of the facts presented and discussed in this report has been considered sufficient excuse for deferring its completion, so that time might be had for a somewhat full consideration of these details of more purely scientific interest.

It is with great pleasure that the writer acknowledges his indebtedness to Mr. Weed for the opportunity to study various portions of this geologic province, and more especially for the privilege of working out in detail the geology of the Marysville district. He has also had the advantage of conference with Mr. Weed, who has brought many details of the region to his attention and has critically read the manuscript of the report.

Thanks are due to Mr. Alexander Burrell, superintendent of the Montana Mining Company, Limited, for the privilege of using the company's office, maps, and engineering equipment and for free access to all parts of the Drumlummon mine; also to Mr. Longmaid, owner and manager of the Belmont mine, for similar privileges. Others have assisted in the work by supplying information and affording access to various mines and prospects.

The chemical analyses were made in the laboratory of the Survey by Mr. George Steiger. The thin sections necessary for the petrologic studies were also cut at Washington, but the entire preparation of the report has been done at Yale University during such spare time as the writer could command and without remuneration from the Survey.

The field season was cut short by the necessity of returning to college duties, and several problems that seemed of minor importance had to be left unsolved. Of these the only two worthy of note are, first, the details of the folded and faulted structures of certain localities remote from the igneous intrusions, this lack of detail showing in the structural plate; second, the question of magmatic variations within the batholith. At the time the two slightly different facies were supposed to shade into each other, but the observation by Dr. Whitman Cross in 1903 of an apparent contact between the two types raises the question whether the more central facies may not be a somewhat later intrusion instead of a contemporaneous variation.

GEOGRAPHIC POSITION.

The Marysville district is situated in Lewis and Clarke County, Marysville, the chief town within the limits of the district, lying 17 miles northwest of Helena, the capital of the State. The region whose detailed geology is brought within this report comprises an area approximately 5.5 miles in longitude by 8 miles in latitude, the limits being from 112° 14′ to 112° 21′ west and from 46° 43′ to 46° 50′ north.

Two railroads formerly gave access to Marysville through the gorge of Silver Creek. One, a branch from the Northern Pacific, ending some distance below the town, was abandoned years ago; the other, a branch from the main line of the Northern Pacific, by skirting the hill slopes outside of the gorge of Silver Creek enters it at a somewhat higher elevation and by making in addition a loop into Sawmill Gulch gains enough elevation to enter Marysville at the level of the town. The grade, however, averages more than 125 feet per mile for six miles. Although the district is mountainous, the somewhat mature and dissected character of the topography and the nature of the sedimentary formations permit wagon roads to be rather easily laid out, affording good communication between the various portions of the district as well as with Helena and other cities lying beyond its limits.

TOPOGRAPHY.

GENERAL TOPOGRAPHIC RELATIONS.

The mountainous region of Montana, within whose central-eastern portion the Marysville district lies, consists, first, of certain outlying eastern groups largely of igneous origin, the remains of volcanoes or laccoliths, which still stand some thousands of feet above the surrounding plains; second, of certain rather regular ranges, such as the Little Belt and Big Belt mountains, the Lewis and Livingston ranges, which rise up from the High Plains as the true front ranges of the northern Rockies; and third, back of these front ranges, of a mountainous plateau country which has been so thoroughly dissected and broken by later crustal movements that it now presents the appearance of highly irregular mountain groups separated by broad open valleys, but also comprising within its area certain regular ranges such as the Bitterroot Range.

As shown on the index map (fig. 1), the Marysville district lies on the eastern flanks of the central portion of the mountainous region, occupying a westward bow of about 8 miles in the Continental Divide, and drained by the headwaters of Little Prickly Pear Creek.

To the north the Continental Divide follows the Front Range of the Rockies' but at Marysville the watershed abandons the eastern margin and passes southward behind the Big Belt and Little Belt mountains into the deeply dissected plateau country, within which it does not follow any well-defined mountain axis. The Divide crosses the southwest corner of the Marysville district, as shown on the geologic map (Pl. I, pocket), but does not present here the usual conception of the backbone of a continent, the lowest point lying at an elevation of but 6,539 feet, and throughout the short distance shown on the map it is a somewhat broad, grassy, soil-clad axis less than 7,000 feet in elevation.

The highest point in the district is Mount Belmont, 7,329 feet above the sea, whose summit stands as an outlying buttress 1 mile northeast of the divide. From this highest portion the country descends in irregular hills to the valley of Little Prickly Pear Creek, which crosses the northern part of the district at levels of from 4,570 to 4,240 feet. Thus in a distance of 6 miles there is a range of 3,090 feet in elevation.

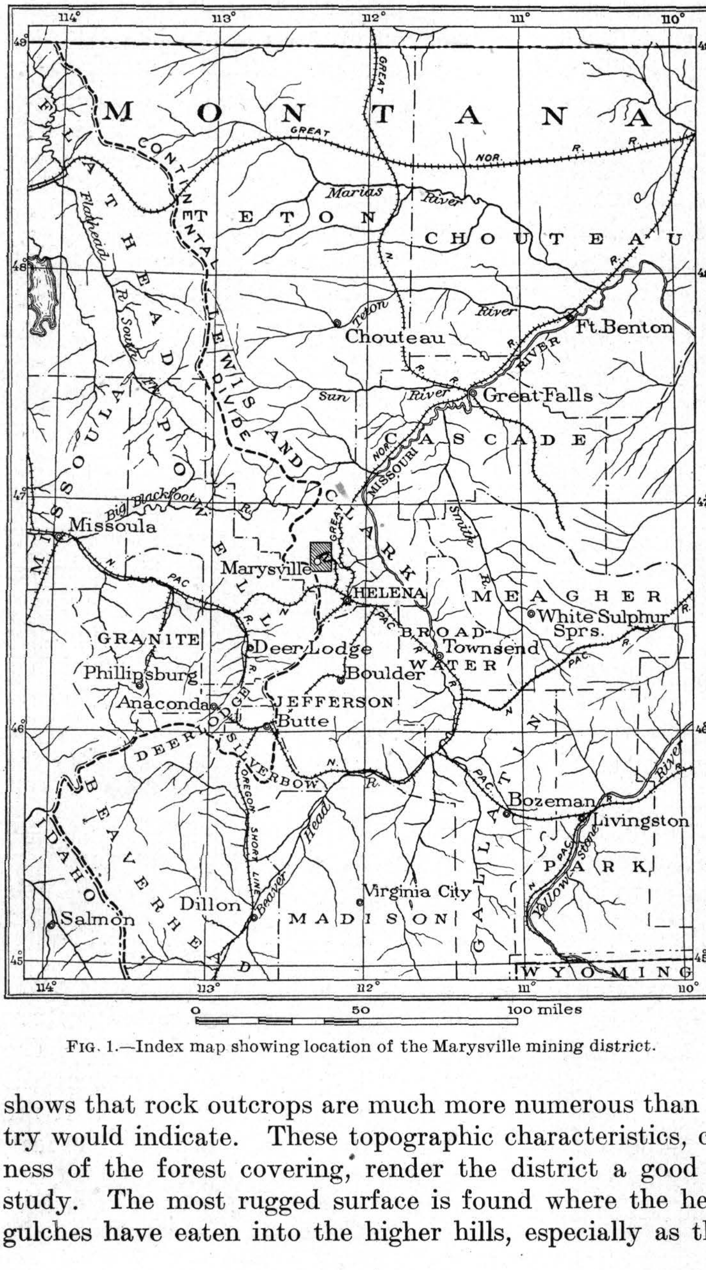
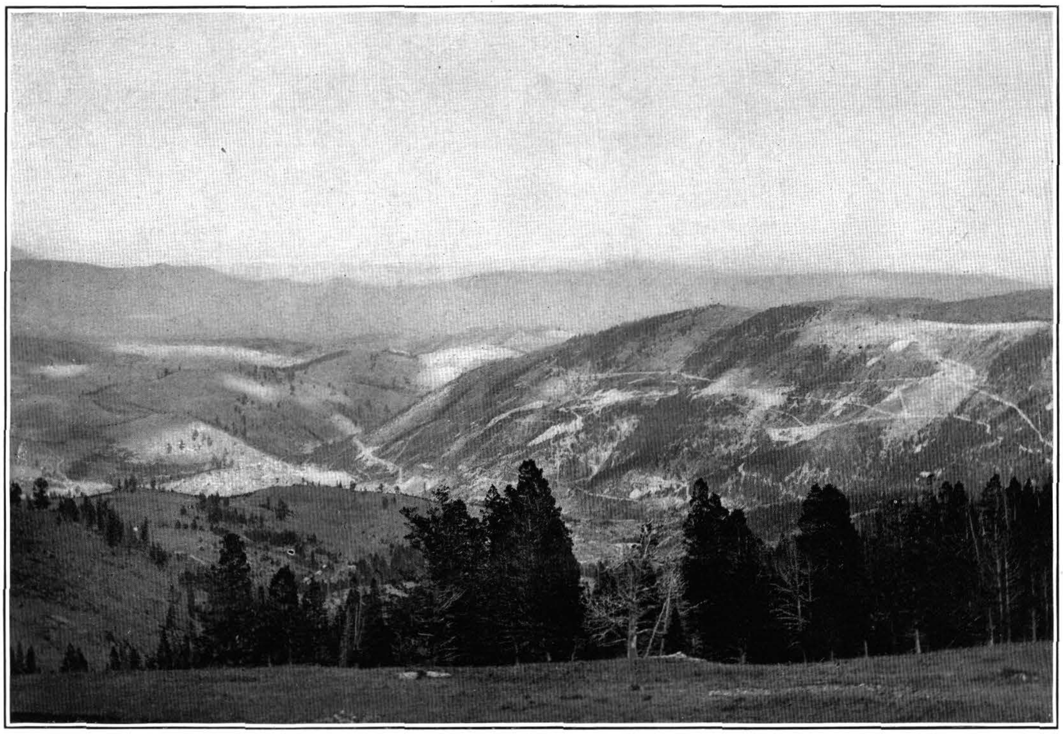


FIG. 1.—Index map showing location of the Marysville mining district.

On the northern side of this valley, but beyond the limits of the area shown in the map, rise irregular mountains to elevations of 6,000 to 7,000 feet above the sea, remnants spared by the general denudation, but cut through by Little Prickly Pear Creek on its way to join Missouri River.

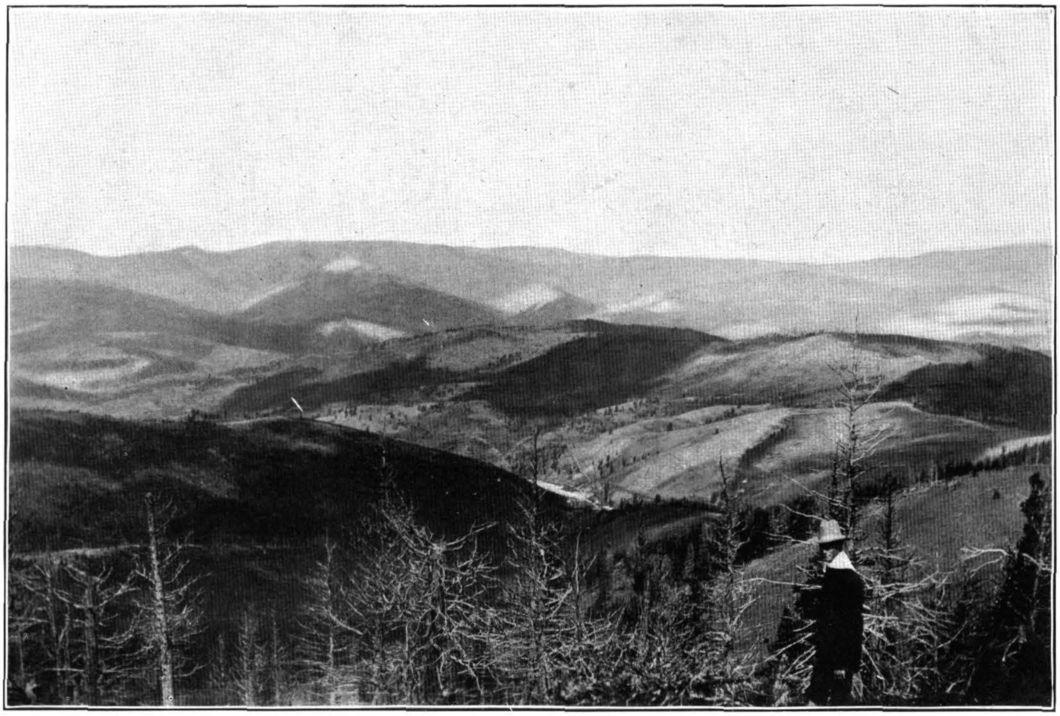
DETAILED TOPOGRAPHIC RELATIONS.

The region exhibits the character of a mature mountainous topography, being well dissected and as a result possessing an abundance of fairly steep slopes, rounded hill crests, and few cliff exposures. The soil, however, is in most places thin, and as the region did not suffer from Pleistocene glaciation this soil with its residual cobbles holds a fairly close relation to the rocks below. Careful observation further shows that rock outcrops are much more numerous than a first glance at the country would indicate. These topographic characteristics, combined with the sparseness of the forest covering, render the district a good one for detailed geologic study. The most rugged surface is found where the headwaters of the principal gulches have eaten into the higher hills, especially as these consist on the whole



A. DRUMLUMMON HILL AND AMPHITHEATER OF MARYSVILLE.

Looking southeast from slopes of Mount Belmont. Mountains flanking Missouri River in the distance. Prickly Pear trough in the middle distance. Helena limestone in the near distance. Drumlummon Hill on the right. Granite contact runs along the hill near the lines of roads and mine dumps. Marysville in basin on the left. Photograph by R. H. Chapman.



B. THE CONTINENTAL DIVIDE.

Looking northwest from Mount Belmont. The divide, lying at a distance of 10 miles, attains an elevation on the left of 8,400 feet, on the right of 7,100 feet. The front face is composed of rocks belonging to the Belt group and is deeply dissected by the tributaries of Little Prickly Pear Creek. This creek rises in the foreground and describes a complete semicircle in the middle distance. The mining camp of Empire is seen in the gulch bottom. The forested northeastern slopes contrast strongly with the grassy southwestern slopes. Note the similarity of topographic forms to those shown in *A*. Photograph by R. H. Chapman.

of the more resistant formations, but even on these slopes there is apt to be a scarcity of cliff faces, the angle of slope being below 30°. On the lower elevations the topography is more softened, the view showing successive tiers of well-dissected foothills with slopes of 10° to 20° rising above the almost flat floor of Little Prickly Pear Creek.

The topographic center of the district is the amphitheater shown in Pls. I and III, *A*, within which Marysville is situated. This consists of an almost circular basin a mile in diameter, surrounded by walls about 900 feet high. Above this level rise the more irregular and higher parts of the rim known as Edwards Mountain, Mount Belmont, and the Continental Divide.

The amphitheater has been cut out by Silver Creek, which has breached the walls by a gorge on the east side. It is to be noted that from the higher rim the drainage is radial outward in all directions, the only exception being Sawmill Gulch, which flows parallel to a lower portion of the rim until it joins Silver Creek. Little Prickly Pear Creek swings around this region in a well-marked arc, its headwaters, as shown in Towsley Gulch (see Pl. III, *B*), flowing 4 miles westward before turning to the north and finally to the east. The drainage system therefore resembles that which develops about an extinct volcano or upon the back of an uncovered laccolith. In confirmation of this statement it is found that the Marysville amphitheater consists of granite surrounded by a rim of metamorphic sedimentary rocks. In connection with the history of this igneous intrusion the drainage is discussed in considerable detail in the body of the work, since it contains the key to a knowledge of the rock structures now eroded.

Little Prickly Pear Creek flows in a flat-bottomed alluvial valley a mile and a half wide at the eastern limit of the area mapped, but narrowing to about half a mile on the western side. Its fall is 60 feet per mile, which, taken in connection with the form of the valley bottom, indicates an excessive load or meager water supply. This valley opens out to the southeast into the broad waste-filled plain of Prickly Pear Creek, 20 miles long by 10 miles wide, which slopes gently eastward to Missouri River. The waters of Little Prickly Pear Creek, however, instead of following down this natural basin, turn abruptly to the north 2 miles east of the border of the area shown in the map and break through the mountains in a canyon which is about 18 miles long and in places over 2,000 feet deep. The stream saves but little in length over the course that would be necessary to join the Missouri by way of the Prickly Pear Valley, entering the river about 25 miles farther downstream and possibly at a level 200 feet lower. It is probable, however, that the peculiar course of this stream, which thus abandons the open valley and cuts a canyon through the mountains, can not be wholly accounted for by the fact that it enters the Missouri at a lower level.

CLIMATE, SOIL, AND VEGETATION.

The eastern and central plains of Montana are arid and suited only for pasturage, but the western and northern mountain ranges receive an abundant precipitation, largely as snowfall. The Marysville district lies in a transition region, in consequence of which the higher slopes that possess a suitable soil support a dense coniferous vegetation and in the open spaces an abundant growth of grasses and herbs, the brilliant colors of the latter in their flowering season giving a garden-like aspect to these spaces. The trees are confined largely to the northern and eastern slopes, since these suffer least from the drying action of the summer sun on the thin soil and also in spring hold the snow longest around the roots. The prevailing winds are from the southwest, with the result that the southwestern slopes are swept more or less bare of snow, which accumulates on the leeward side of the hills. Here, protected by the evergreen trees, stray banks linger until about the first of July.

The bottoms of the deeper gorges are especially picturesque, offering the contrast of dark, forested southern or western walls and grassy northern slopes, while cottonwoods and willows grow in clumps and lines along the courses of the streams.

On the northern hill slopes the trees continue down to elevations of about 5,000 feet, the limit varying considerably with the nature of the soil. Below this level the low hills of the northern half of the district are bare of trees and almost without grass, but in the gulches which trench them scattered pines have found enough moisture to give them a foothold. On the lowest levels the prickly pear and bunch grass hold sway. The most desolate portion of the district is north of Little Prickly Pear Creek, for here the sandy, porous nature of the surface renders it doubly difficult for vegetation to maintain a foothold, and large areas are covered with nothing but shaly shingle or ancient river cobbles. In contrast with the hopeless aridity of these lower slopes the larger part of the alluvial valley of Little Prickly Pear Creek is irrigated and raises abundant crops, the streams themselves being lined with willows and cottonwoods.

The climate thus varies considerably with the elevation and exposure, and marked contrasts may be found within a few miles. The following table shows the temperature and rainfall for Helena, for Marysville, and for the entire State, the averages covering periods of eight to nine years between 1895 and 1904, inclusive.

Temperature and rainfall at Marysville and Helena, Mont., and average for State, 1895–1904.

	Annual mean temperature.	Extreme temperature.[a]		Average annual precipitation.
		Maximum.	Minimum.	
	°F.	*°F.*	*°F.*	*Inches.*
Marysville	40.7	91	−22	17.87
Helena	44.2	95	−18	12.94
Average for State	42.6			14.09

[a] Average of the hottest and coldest days of each year.

On the average the rainfall of this region is rather equally distributed throughout the year, at Helena the amount being close to 1 inch per month except for May and June, when the mean is 2 inches. This average, however, is liable to be widely departed from during individual months, the precipitation frequently sinking to a fraction of an inch or becoming double the usual quantity.

CHAPTER I.

SUMMARY OF THE GENERAL GEOLOGY OF THE MARYSVILLE MINING DISTRICT.

INTRODUCTION.

The geology of the Marysville district involves a study of the phenomena of igneous intrusion and of contact metamorphism, and, as these are branches of the science which still hold much that is debatable, it is necessary in order to arrive at the conclusions that the facts shall be presented in great detail and the discussion as to their significance be made complete. Only by so doing can the conclusions be considered safe. In addition to the problems directly connected with the igneous intrusions and indirectly with the ore deposits, it is found that the structure of the sedimentary formations is far from simple, the strata being folded, warped, crushed, or faulted, and entirely without fossils. These structural complexities make it further necessary to give a full treatment to the subject. Yet many readers will not wish to follow the details, but will desire to get in a few pages the chief facts of the geology. For such this chapter is written, being condensed from the following chapters of the report.

SEDIMENTARY ROCKS.

ALGONKIAN SYSTEM.

GENERAL STATEMENT.

All the sedimentary formations of the district, with the exception of the recent alluvium and the older river gravels and conglomerate of the Tertiary, belong to the Belt group. This comprises an exceedingly ancient series of rock formations, which in recent years has been referred with increasing certainty to the late Algonkian. In view of the great age of this terrane, and its subsequent deep burial, the rocks exhibit a remarkable absence of regional metamorphism. Except in the vicinity of intrusives, the bedding planes are clearly preserved, and in general the degree of alteration is no greater than that to be noted in rocks of Paleozoic age in regions which have been but moderately disturbed.

The group consists of five major formations within the limits of the district, and a rather marked feature of it here, as elsewhere, is that the several formations are not sharply separated, but grade into each other, making the division lines difficult to locate accurately on a map with a scale as large as that of the geologic map of the district shown in Pl. I (pocket).

The oldest formations visible within the limits of the district are the gray sandstones and shales of the Greyson[a] and the red shales and sandstones of the Spokane, both occurring in the northern part of the area. Toward the south the overlying greenish Empire[a] shale is found, transitional into the buff to blue impure Helena limestone. Finally, in the extreme southeast corner, the deep-red Marsh shale overlies the Helena limestone, constituting the uppermost formation of the Belt group and lying unconformably beneath the middle Cambrian quartzite. The latter, however, outcrops beyond the limits of the district, and therefore is not shown on the map. A brief description of these formations is given in the succeeding paragraphs.

GREYSON FORMATION.[a]

The Greyson consists predominantly of dark-gray to nearly black siliceous and arenaceous shales, certain portions being almost fissile, others consisting of dark, hard, cherty strata cut by cubical joints. Deep dark-red or purplish beds are also occasionally found. The prominent strata stand out as low cliffs with vertical walls, cubical blocks strewing the ground immediately in front. In composition these are the more siliceous rocks, consisting of smooth dark-gray and bluish hornstones or quartzites. The best exposures of these rocks are found surrounding and underlying the large patch of extrusive andesites in the northwestern portion of the district.

On account of the warping, crushing, and faulting to which these beds have been subjected, as well as of the smallness of the area and the imperfect exposures, it was found impracticable to draw the boundary line between the Greyson and the Spokane, and accordingly the two are mapped together. The thickness of the Greyson has been estimated by Walcott as 3,000 feet, of which the upper 500 feet may be exposed in this district.

SPOKANE FORMATION.

The typical locality of the Spokane formation in this district lies in the northeast corner, where it appears as alternating well-bedded strata of red shales and sandstones. The shales in many places exhibit sun cracks and the sandstones cross-bedding and ripple marks. The numerous beds of gritty red sandstone offer considerable resistance to erosion and form the caps to the buttresslike projections of the main ridge. The thinner beds break down into loose slabs of all sizes which strew the surface and together with the dry meager soil give a deep-red cast to the entire formation, enabling it to be recognized from a long distance. The Spokane formation occupies considerable portions of the northwestern area between Little Prickly Pear and Canyon creeks and also fronts this valley on the south side. It is terminated on the south by a great fault, whose throw is from 1,000 to 2,000 feet, but which gives no topographic expression to the surface. A marked change of color, both in the soil and underlying rock, is, however, observed to occur along this line. The total thickness of the Spokane formation has been estimated as 1,500 feet.

[a] Owing to preoccupation, the use of the names "Greyson formation" and "Empire shale" is only temporary, and they will be abandoned as soon as additional field work in the region shall enable satisfactory substitutes for them to be found.

EMPIRE SHALE.[a]

The Empire shale is best seen in its original state in a narrow east-west belt forming the south or hanging-wall side of the great fault just mentioned. Here the formation consists of finely laminated, soft, limy shales, grayish green or buff colored, with a few reddish bands, weathering into smooth, flat slopes with thin soil and no prominent outcrops. From a distance the color of the soil is seen to be dominated by soft, pale grays, in contrast to the reddish tint of the Spokane areas. The bottom of the formation is apparently not exposed, but in the lower members a visible change is noticed into yellow and reddish sandstones, at some places of a shaly and at others of a calcareous nature. Above, the shale passes into the blue argillaceous Helena limestone, which, being more resistant, lies at higher elevations and gives rise to steeper slopes.

Near the batholith the Empire shale is transformed into hard brown or gray banded hornstones, so different in character from the unmetamorphosed portions that the boundary line separating the Empire and Helena formations is difficult to locate.

The thickness of the Empire has been estimated by Walcott as 600 feet, but may be considerably greater.

HELENA LIMESTONE.

The Helena limestone covers the greater part of the district. The appearance which it gives to the topography is shown in Pl. III, A, where the smooth curves of the smaller hills may be noted. This formation is composed of more or less impure bluish-gray and gray limestone, in thick layers, which weathers to a buff or pink and in many places to a light-gray color. Irregular bands of broken oolitic and concretionary limestone occur at various horizons. Bands of dark and gray siliceous shale and greenish and purplish argillaceous shale are interbedded in the limestones. These bands are from half an inch to several feet in thickness. There are also layers of thinner bedded limestones, especially toward the top of the formation.

The formation is so broken by obscure faults that it is difficult to estimate the thickness within the limits of the district, but it is probably as much as 4,000 feet.

MARSH SHALE.

The Marsh shale, the uppermost formation of the Belt group, outcrops in the extreme southeast corner of the district. The formation consists of smooth-bedded, uniform red shales, the lower beds calcareous in some places, quartzitic in others, strongly contrasting with the Helena limestone below and lying unconformably beneath the middle Cambrian quartzite above. The thickness shown within the limits of the district is about 1,000 feet, but the total thickness is somewhat greater.

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[a] Owing to preoccupation, the use of the names "Greyson formation" and "Empire shale" is only temporary, and they will be abandoned as soon as additional field work in the region shall enable satisfactory substitutes for them to be found.

TERTIARY FORMATIONS.

RIVER GRAVELS.

The Tertiary river gravels are found in patches on the north side of Little Prickly Pear Creek and in the northwest corner of the district, where they constitute the Gravel Range, a ridge a little over 4 miles long, of which the map shows the middle portion. The crest is 5,650 feet in elevation near its west end, and the gravels there are about 500 feet thick. At the eastern limit the elevation sinks to about 4,500 feet.

This is a superficial formation of sand, gravel, rolled cobbles, and bowlders, indicative of river rather than of lake origin. The material rests upon Spokane shale and extrusive andesite, the latter having been largely eroded before the deposition of the gravels. The bottom surface of both the andesite and gravels has a gradient at the present time of about 125 feet per mile toward the east. Since Little Prickly Pear Creek falls but 60 feet per mile, it follows that while at Canyon Creek the old and recent gravels are at the same level, at the western border of the district, on the contrary, there is a difference of several hundred feet.

West of the district border the surface material includes abundant bowlders of pink Cambrian quartzite 1 foot to 3 feet in diameter, the nearest outcrops of which are on the Continental Divide, about 10 miles farther west and southwest, at elevations of about 8,000 feet. The eastern patches of gravel are characterized by finer material, and there is some variation in coarseness in near-by places. The bowlders, smaller than a foot in diameter, are well rolled, being ellipsoidal in outline; the larger ones have a subangular but still waterworn character. Along with the predominant pink quartzite occur cobbles of sandstone, a little alaskite, and some andesite, but no granite. The surface of the Gravel Range is paved with these cobbles, the matrix being a sandy soil. The quartzite cobbles, being very resistant, are found scattered along all the stream beds leading from the range and down the hill slopes to considerable distances from the outcrop.

CONGLOMERATE.

Patches of hard, siliceous, resistant rock, conspicuously conglomeratic, are found in the northwestern portion of the district, and in the typical locality, a mile north of Procter's ranch, this rock forms the cap of a mesalike hill rising about 500 feet above the surrounding region. Although so unlike the incoherent Tertiary river gravels in superficial character, these patches are in reality silicified basal portions of the gravels, which, owing to their greater hardness, have resisted erosion in certain places where the unsilicified gravels have been removed. This conclusion as to similar origin is based on the fact that, like the river gravels, the conglomerate lies unconformably upon all the other formations, and in some places is closely associated with the gravels, differing from them only in color and in the detailed character of the cobbles. The formation is of a light-ocherous tint, but many of the included pebbles and cobbles when broken open are seen to be bleached to this color for only an inch or two in depth and within are a purplish red. Where the conglomerate is adjacent to the remaining patches of lava it embraces large, subangular, bleached and silicified blocks of the lava along with rolled river pebbles.

On the northern and eastern slopes of the mesa like hill north of Procter's ranch there is a large amount of residual material, consisting in part of bowlders 5 to 30 feet in diameter of the same silicified conglomerate which have settled from a former somewhat higher position, owing to the erosion of the softer shale upon which they rest. A detailed examination shows that there has been a considerable infiltration of quartz into the interstices between the individual pebbles, though the filling has not been completed, and small clusters of quartz prisms may be found projecting into the cavities. The infiltration is of the same character as that occurring at most of the lava localities in the neighborhood, but the originally loose and open texture of the conglomerate deposit has offered a greater chance for the deposition of silica.

The cause of the silification may be observed on the south slope of the hill, where conspicuous quartz veins cut through the shales, running in the direction of the crest line of the hill and passing into and under the conglomerate. Where the veins pass into the conglomerate they are largely lost, but small streams and gashes of quartz occur all through the rock. From these relations it is concluded that after the epoch of the gravel deposition ascending waters, probably heated, taking advantage of fractures, rose to the gravel stratum and then spread along its base. The fissures admitting the siliceous waters presumably did not extend upward into the incoherent gravels, but later movements, taking place after cementation of the gravels had begun, fractured the newly cemented rock. This relation between fractured and silicified underlying formations and superficial patches of silicified gravels may be noticed in several localities, indicating a similar origin for all of them.

AGE OF RIVER GRAVELS AND CONGLOMERATE.

The age of these superficial formations within the limits of the district can not be precisely determined, but from related formations in adjacent portions of the State the probable age limits may be set. The Bozeman lake beds of the Three Forks quadrangle correspond somewhat in their general nature to the gravels of the Marysville district. At one place within them Marsh found Pliocene fossils. Again, the Silverbow Valley south of Butte contains similar deposits, which farther west and south have been found to carry upper Miocene fossils. East of Helena, in the Smith River deposits, large vertebrate fossils referred to the middle Miocene have been found. It appears from these statements that in this part of Montana a period of valley filling existed during the greater part of the Miocene and Pliocene. As the deposits of separated districts are not closely correlated, it can be stated at present only that these ancient gravels are certainly Tertiary and probably not far from the end of the Miocene.

QUATERNARY DEPOSITS.

ALLUVIUM.

Little Prickly Pear and Canyon creeks do not flow at present upon rock bottoms, but have built up alluvial valleys of gravelly loam and clay suitable for agricultural purposes, the waters of the creeks being largely used for irrigation. Throughout the greater portion of these valleys rolled cobbles of Cambrian quartzite are common, but on the margins the material grades into the wash from the hillsides.

IGNEOUS ROCKS AND THEIR STRUCTURAL RELATIONS.

GENERAL STATEMENT.

The most striking feature of the Marysville district is the intrusive body of granite, 2½ miles long and of variable width, which occupies nearly the center of the district and around the borders of which is concentrated the mineral wealth that has given it prominence as a mining region. This central feature is known as the Marysville batholith, and may be considered also as the central point in the geologic history. One set of dikes and sheets—the microdiorite of Bald Butte—is of earlier origin than the invasion of the batholith and the formation of the zone of contact metamorphism. Another set of dikes—the Belmont diorite porphyry—is closely connected with the batholithic invasion in point of time, but whether immediately before or after it is not settled. The batholith itself possesses granitic dikes and sheets as outliers, mostly of more acidic composition. Later than the batholith are pegmatites cutting the granite, the Drumlummon porphyry, and a few rare basic dikes.

MICRODIORITE DIKES AND SHEETS OF BALD BUTTE.

Description.—The microdiorite of Bald Butte is, as the name implies, a fine-grained crystalline rock, in places porphyritic, of dark color, consisting chiefly of a lime-soda feldspar and one or more of the dark minerals, hornblende, biotite, and locally pyroxene. The appearance of these rocks under the microscope is shown in Pl. IV, p. 40. They occur as dikes and sheets sparingly scattered over the greater part of the district south of Little Prickly Pear Creek and perhaps corresponding to the sheets of coarsely granular pyroxene diorite or gabbro found north of that stream. Only the southeast corner of the district is entirely free from them, while the southwest corner, on the contrary, contains them in great abundance. They show a marked tendency to conform to the bedding planes of the Belt formations, with a dip usually of not more than 30°, and occur in outcrops, which are commonly from 300 to 1,000 feet long and from 10 to 50 feet thick, the thickness being, as a rule, from 2 to 5 per cent of the length. Much smaller intrusions may, however, be observed under favorable circumstances, while at Bald Butte the numerous sheets range upward to half a mile in length, with proportionate thickness.

Many of the occurrences are widely separated and vary somewhat in petrographic character owing partly to original differences, partly to later alterations. The alterations are due to contact metamorphism, hydrothermal action, or simple weathering. These changes are discussed in detail in a later portion of the report.

Age relations.—The age relations of the microdiorite dikes and sheets are evident in a number of localities. At Bald Butte a large dike of Belmont diorite-porphyry cuts a number of diorite sheets. The same relation may be observed on the eastern slopes of Mount Belmont, 500 feet west of the West Belmont mine. On Drumlummon Hill, at the granite contact east of the Cruse tunnel, a microdiorite dike 4 feet thick is cut off by granite and another is intersected by seams of aplite. Thus, whenever the age relations are made evident by intersection, the microdiorites are found to be older than all the other igneous rocks of the district. The sheets are widely scattered and the age relations of only a portion of them can be definitely determined, the possibility remaining that somewhat different varieties of the rock may not be closely related to the type occurrences.

There is nothing within the Marysville district to fix the absolute age of these earliest intrusions and recourse must be had to near-by regions to determine the time limits with a reasonable probability. The fact that the rocks are in many places unaltered, certain sheets even containing fresh augites, may be cited as an indication, though not a proof, against a Paleozoic or pre-Cambrian age, and they are naturally to be looked on as the first of the series of intrusions which inaugurated and accompanied the period of active growth of the cordilleran mountain ranges. In the Castle Mountain mining district, some distance to the east, this volcanic activity began during the Dakota epoch of Upper Cretaceous time. Further, volcanic materials occur in the Livingston formation, which is classified as transitional between the Cretaceous and Tertiary. From this time forward in this part of Montana igneous activity continued nearly to the close of the Tertiary. These first intrusions of the Marysville district may, therefore, be looked on with reasonable assurance as of late Cretaceous or more probably early Tertiary age.

GABBRO INTRUSIONS.

Description.—The gabbros are dark crystalline igneous rocks of granitic texture, whose chief minerals are pyroxene and a triclinic feldspar. Within the limits of the district they are confined to the Greyson-Spokane shales and sandstones on the northern side of Little Prickly Pear Creek. There are five large and a number of smaller patches, and a study of the soil is required for a determination of their limits. The forms of the outcrops are irregular, the larger areas averaging half a mile in length and 500 to 1,000 feet in breadth. At a number of places, notably in the large patch northeast of Procter's ranch, the contact is conformable to the stratigraphy, but as a thinly banded hornstone overlies the gabbro on each side neither contact can be regarded as the bottom surface of an intrusive sheet. It seems probable, on the contrary, from the number of small, irregular patches in the vicinity that they are various exposures of the outliers of a rather large and irregular intrusion whose depth is not known. At other places the elongation of the outcrops parallel to the bedding of the strata and especially their exposures on the side slopes of hills indicate that their form is that of sheets varying from a few feet to 100 feet is thickness. The appearance of the rock under the microscope is shown in Pl. V, *B* (p. 48).

Age relations.—Since the gabbros do not come into contact with any other intrusions, their relations to those south of Little Prickly Pear Creek can not be accurately determined. Although petrographically quite distinct from the microdiorites, certain of the latter found north and east of Trinity Hill show transition toward the gabbros. Thus they may be related to the earliest igneous intrusions of the district, or they may be later and more closely related in time to the batholith of granite, since such bodies in some places show markedly basic differentiations in outlying portions. On the other hand, andesite lava flows which preceded the formation of the Gravel Range rest in places upon the gabbros, indicating a long period of erosion between the coming to place of the two. The gabbros, therefore, belong to the early igneous history of the district and are probably more closely related to the microdiorites than to the batholith.

FELDSPAR-PORPHYRY DIKES.

TYPES.

The rocks of the feldspar-porphyry dikes are marked in all cases by the presence of phenocrysts of feldspar, as the name implies. These are acidic in composition, being nowhere more basic than an andesine. The groundmasses of different dikes vary in color from pale brown or greenish gray to dark gray, depending largely on the degree and kind of alteration, and in composition from those rich in quartz to those which apparently contain none. These dikes are restricted to the southern and western portions of the district and vary considerably in different localities. There is, therefore, a possibility that they do not all belong to the same period of igneous activity. They may be divided into three chief types—the Belmont porphyry dikes, which occur over Mount Belmont and to the south; the Drumlummon porphyry dikes, found in the Drumlummon mine and on the surface near by; and the porphyry sheets of Piegan Gulch, represented by three bodies 1 mile north of Gloucester.

BELMONT PORPHYRY DIKES.

Description.—The Belmont porphyry dikes, one of which is shown in Pl. IV, hold conspicuous phenocrysts of plagioclase feldspar from one-eighth to one-fourth inch in diameter and small amounts of biotite and hornblende, the whole embedded in a dark-gray microcrystalline groundmass which under the microscope is seen to consist of small tabular crystals of feldspar, in large part plagioclase; irregular and inconspicuous fillings of quartz; and shreds of pale-green biotite. The whole forms a rock of striking appearance, the white feldspar standing in contrast to the dark-gray groundmass. This is the appearance when fresh, but the rocks are commonly altered, the groundmass weathering to a light brown or gray, the feldspar phenocrysts becoming inconspicuous, and the dark minerals being more or less destroyed. The more conspicuous outcrops occur as reefs of rough light-gray bowlders or of rock in place which may be from 10 to more than 100 feet wide and can be traced in length for several hundred feet. They occur most abundantly on the south and west sides of the batholith.

In favorable localities they seem to grade down into dikelets which are but a fraction of an inch in width, while on the other hand the largest dike cuts across the entire southwest corner of the district. The commonest width is perhaps from 20 to 40 feet and, as shown on the map (Pl. I, pocket), the dikes are rather discontinuous, the average length of an individual outcrop being not over 500 feet.

Age relations.—The large porphyry dike passing through Bald Butte on the north side of the town, as previously stated, is clearly seen to cut the microdiorite sheets, a fact that shows it to be the younger rock. The relations to the granite are not directly exposed, but at no place is a transition found between the two. As they occur in places not more than 250 feet apart, there is no space for a transition between the two types. These considerations indicate that the dikes must not be looked on as continuations from the batholith in the covering rocks, and therefore do not represent the same stage of eruptive activity. They are, however, closely associated with the metamorphic zone, indicating a relationship to the batholithic invasion, but as to whether they are younger or older the evidence is not conclusive.

DRUMLUMMON PORPHYRY DIKES.

Description.—The Drumlummon porphyry dikes are found in one place at the surface, occurring within the margin of the batholith on the lower slopes of Drumlummon Hill, the principal dike bearing north with a nearly vertical dip and a thickness of about 10 feet. The other occurrences are within the Drumlummon mine in the southern workings of a number of levels.

The rock is spotted with numerous small phenocrysts of feldspar not over one-eighth inch in diameter. At the surface the matrix is pale brownish white, while in the mine specimen it is pale grayish white to greenish gray, the different colors being due to the greater oxidation of the surface rock. At places in the mine the phenocrysts are not visible, probably owing to the extreme alteration, and in such cases it is most difficult to distinguish the porphyry from the altered hornstone which forms its walls. The composition is predominantly of plagioclase feldspar, whose species it is not easy to determine.

Age relations.—The fact that the surface dike is found within the granite proves that the porphyry is the younger. The relation to the period of vein formation is shown in the Drumlummon mine, where the vein cuts the porphyry which appears on both walls, indicating that the porphyries, while younger than the granite, are older than the veins. The relations of the veins of this mine to the batholithic intrusion are discussed at length in the body of the report, and it is concluded from the detailed evidence that very probably the vein fissures and vein fillings are lingering after-effects of the igneous activity. If this conclusion is justified, the Drumlummon porphyry dikes, although younger than the batholith, are rather closely related to it in time.

PORPHYRY SHEETS OF PIEGAN GULCH.

A mile north of Gloucester, on the top of one of the buttresslike hills which face Piegan Gulch, are three similar intrusive sheets of feldspar porphyry, conformable to the bedding. The chief one is about 18 feet thick and holds feldspar phenocrysts up to 3 mm. in diameter, now largely altered to calcite. The microgranitic groundmass consists of quartz and feldspar. As these sheets are isolated, nothing is known of their age relations.

QUARTZ DIORITE OF MARYSVILLE BATHOLITH.

Quartz diorite is the rock of the Marysville batholith. It is commonly referred to as a granite, possessing the typical granitic texture and consisting of quartz, feldspar, and a moderate amount of dark minerals. The feldspar is, however, largely plagioclase, making the rock technically a quartz diorite. The mineral composition is indicated by the following statement, compiled from the microscopic measurement of a thin section from a rock specimen which was also analyzed:

Mineral composition of the quartz diorite.

Quartz	22.2	Apatite	.2
Orthoclase	15.6	Titanite	.1
Biotite	7.2	Magnetite	1.7
Andesine	47.5		
Hornblende	5.5		100.0

Within the area two types of the rock are to be noted, the normal being a fairly coarse-grained rock, very uniform in appearance and containing hornblende and biotite in about equal amounts. The mineral composition given above has been computed from a specimen of this type. The second phase is noted chiefly east and northeast of Mount Belmont, at points as a rule one-fourth of a mile or more from the margin of the batholith. It is characterized by a somewhat finer grain and a lesser proportion of hornblende and biotite, the latter having a shredded appearance and consisting of many minute flakes. The thin sections show no very marked difference in composition from the normal type, but mainly a difference in texture. Whether the rock of this type is a contemporaneous variation of the main mass or a somewhat later injection into it is not known.

The quartz diorite, or, as it will be usually termed, the granite, maintains its normal granularity and shows no chemical variation up to the immediate contact. In certain outlying tongues and wedges, however, the rock becomes markedly more porphyritic and somewhat more basic, a feature often found on batholithic margins elsewhere.

The igneous body of which this rock forms the type is extremely irregular in outline, as indicated on the geologic map. Beyond the main area, however, there exist but few outliers of the rock. These occur as dikes or sheets and sometimes as lenticular intrusions within the metamorphic zone. The more important of these are in the gorge of Silver Creek east of Marysville, and on the hilltop at the northern point of the batholith. Another outlier of still different shape is found on the northern slope of Mount Belmont closely adjacent to the main mass. Beside these near-by outliers there are, however, several more distant intrusions. One of these lies 1 mile southeast of the batholith, in Eldorado Gulch, and is shown in cross section D–D, Pl. II (pocket). Here the surface evidences are loose bowlders or "float" of quartz diorite, a few thin outcropping sheets and dikes of the rock, and a local area of contact metamorphism. Two miles north of the batholith, on the hill containing the Big Ox mine, there is a dike of quartz diorite, here somewhat porphyritic. As in Eldorado Gulch, it is associated with a local area of contact metamorphism much more extensive than could be accounted for by the dike alone.

APLITES AND PEGMATITES.

At certain places within the margins of the batholith, but more especially in the contact rocks of the border zone rather than in the quartz diorite, are found sheets and dikes of white, fine to coarse grained, igneous rock. In mineral composition these consist essentially of orthoclase and quartz and petrologically they are known as alaskites and pegmatites. Rocks of this character, however, where they occur associated with granitic masses, are commonly known by the term aplites, which signifies not only a certain petrologic type, but also a certain geologic association. Aplites do not necessarily differ in composition from pegmatites, but are typically of a fine, even grain, whereas pegmatites, popularly known as giant granites, are coarsely granular and apt to grade into highly siliceous fissure fillings.

As observed in many geologic provinces, the uniform finely granular texture of even the smallest dikes of aplite, the continuity in many places of crystallization of the quartz and feldspar with that of the wall rocks, and the commonly local character of the fissures have all led to the conclusion among the great body of geologists that the formation of dikes and sheets of this rock follows closely the crytallization of the main mass at a time when the wall rocks are still at a high temperature, and that the fissures are contraction cracks due to the shrinkage accompanying crystallization and cooling.

Pegmatites differ from aplites not only in the coarser grain and the more siliceous tendency, but in that they exhibit in places a ribbon structure and other gradations toward quartz fissure veins. Such transitions from what appears to be the result of true igneous injection to what is evidently the result of aqueous precipitation have led many geologists to the view that pegmatites are in fact produced by aqueo-igneous activity, quartz and feldspar crystallizing in the presence of water and other vapors concentrated from the cooling magma.

The observed geologic relations in the Marysville district are in conformity with these views. The aplites and pegmatites do not occur all around the margin of the batholith, however, but are distributed almost entirely along the eastern border, and especially on the northeast, as indicated on the geologic map. Here, they consist of numerous massive sheets of aplite intruded in the hornstone along the bedding planes. In places, as on the road leading up Silver Creek to Marysville, these sheets are observed to cut the granite as well as the wall rocks, but within short distances they fade out in the granite and are not noted very far from the border. The interior of the batholith, in fact, is unusually free from either small or large aplitic intrusions. As a rule these aplites are conspicuously free from biotite and hornblende, which gives them a notably white appearance. Locally, however, as seen in many places in the Drumlummon mine, a small amount of biotite exists scattered through the mass, giving the rock a pepper-and-salt appearance and causing it to be classed as biotite-granite-aplite. Such forms appear to be intermediate between typical alaskite-aplites and the typical quartz-diotite intrusions also found in the mine, but lean rather more toward the alaskites. The pepper-and-salt or biotitic granites were not noted cutting the quartz diorite of the batholith, but occur as dikes and irregular intrusions at some distance from the margin, so that there is a question if they may not be somewhat acidic outliers of the main intrusion rather than later injections such as the aplite sheets of Silver Creek.

Detailed study shows that the aplites may be classified under several heads. First, may be noted the aplitic segregations within the quartz diorite exposed near the contact on the southeastern slopes of Mount Belmont. Here a streaked effect is noted for several feet from the contact and parallel with it, part of the banding being due to a fine-grained biotitic aplite occurring with no definite walls within the normal quartz diorite. The lighter colored bands are contemporaneous in crystallization with the quartz diorite around them and suggest, as has been mentioned, that the rather common marginal dikes which closely resemble them in character, are of similar segregational origin, and belong to the same period of invasion as the main rock of the batholith.

A second class consists of contact bands on the walls of biotite-granite dikes, best observed near the batholithic contact on the roadside east of Marysville. These dikes themselves resemble the aplitic segregations noted within the batholith, being more acidic than the common quartz diorite, but within them are still further variations of a more marked alaskitic nature, especially along the walls, the biotite being restricted to the central portions of the dikes. Thus there may be said to be segregations within segregations. Similar occurrences were noted in the Drumlummon mine.

As a third class may be noted those aplitic injections which are clearly younger than the primary invasion of the batholith, since they cut across both the quartz diorite and the wall rocks. This separates them from the two previous classes, since in those the aplitic portions are segregations of the same age as the rock which holds them. These younger sheets are best observed at the granite contact on the roadside east of Marysville, where they are irregular in form and from 6 inches to a foot in thickness. In granularity they resemble the aplites of the other classes, and, although younger than the surrounding batholithic rock, they are probably not far removed in time from the aplites which are contemporaneous with the granite.

Aplite seams are also found in the lenticular intrusion on Silver Creek half a mile east of the batholith and in the dike of quartz diorite near the Big Ox mine 2 miles north of the batholith. The close association of the aplite with the margins of the batholithic rock, therefore, wherever it occurs, either in the main mass or in outliers, is one of the strongest evidences of the closely associated origin of the two rocks.

BASIC ROCKS OF POST-BATHOLITHIC AGE.

One thousand two hundred feet west of the railroad trestle over Silver Creek at Marysville are two vertical dikes about 50 feet apart. They are both dark basic intrusives containing solution cavities filled with a sky-blue secondary mineral. One dike is 3 inches in width, the other 15 feet. The narrower is observed to cut both granite and aplite, thus fixing their age as postbatholithic.

Under the microscope the rock appears to vary from a basalt to a diabase, the smaller dike having been originally largely of a glassy nature, while the large dike was once nearly or quite finely crystalline. The solution cavities show on fresh fracture a geodic lining of calcite succeeded by chalcedony, which has completed the filling. No indication of the original mineral remains.

These were the only two instances noted of basic dikes clearly younger than the batholith, but except in railroad or mine cuttings or similar favorable situations such intrusions would be easily overlooked, and if seen the younger dikes would not be separated on a superficial examination from the much older microdiorites. It is concluded, therefore, that there are probably other representatives of the postbatholithic dikes within the district.

LAVAS OF LITTLE PRICKLY PEAR CREEK.

Description.—In the northern part of the district are a number of patches, one more than a mile in length, consisting of the remains of lava streams which flowed down the Tertiary valleys after they had become well widened. The lava solidified in places as volcanic glasses, elsewhere as breccias or as microgranitic bases carrying phenocrysts of plagioclase, hornblende, and biotite. Nearly all are now extremely altered, usually purplish-violet or pinkish-brown rocks, though in places silicified and bleached to an ocherous color by vein waters from beneath, as discussed under the heading "River gravels." The original character has been largely masked by these alterations, but microscopic examination shows that in all cases the lavas have been of intermediate or basic nature. The patch which retains the original characters to the greatest extent lies on the eastern side of the district near Old Stage Station. This forms a low hill of fine-grained, almost black rock a quarter of a mile long and 100 feet high, whose base is mantled on all sides by the valley alluvium. Under the microscope the rock is found to be a glassy pyroxene andesite, consisting of about two-thirds small plagioclase-feldspar crystals, none of them more than 1 mm. long, and one-third brown glass, the pyroxene being in subordinate quantity.

Age relations.—The age relations of the andesite of Little Prickly Pear Creek may be determined from a study of its associations. It is noted that in places the outcrops lie between the Tertiary gravel and the rocks of the Belt group. The sheets are nowhere of great thickness and the gravel over most of the region lies directly upon the shale. This shows that after the lavas flowed down the valley they were largely removed by erosion before the deposition of the gravel and that the form of the ancient valley was nearly the same at the time of the lava flows as at the time when the filling in of the river bed began. It is concluded, therefore, that after the valley had become well widened out and the topography had reached a state of relative maturity these lava flows took place, accumulating to a moderate depth. This was followed by a period of erosion long enough to remove the lavas in great part, but not to alter radically the valley contours nor deeply trench its bottom. Finally came the great disturbances which destroyed the old topography and resulted in the accumulation of a great depth of gravel. The relation to the intrusive rocks is also clear, as in places the lavas lie directly upon the coarsely crystalline gabbros, and between the epochs of the two intrusions a long interval had evidently elapsed during which stream erosion had reached to some depth into the shale and planed off the gabbros which it contained. This fixes the period of andesitic outflow as a late, probably the latest, igneous invasion of the district.

STRUCTURAL GEOLOGY OF THE MARYSVILLE DISTRICT.

CONTACT SURFACES OF THE BATHOLITH.

OPPORTUNITIES FOR STUDY.

In the Marysville district the development of mines on the vein systems which are associated with the metamorphic zone of the sedimentary formations and the marginal portions of the batholith, has allowed unusual opportunities in a number of cases for studying the underground contact relations and comparing them with those of the adjacent surface. These opportunities, combined with the mountainous character of the region, have made it possible to work out to an exceptional detail the form and characteristics of the intrusion. The study of these contact relations is consequently a feature of this report, and will be found given in full in a later chapter. Here will be abstracted only certain general statements in regard to the character of the contact.

MINE CONTACTS.

The Belmont mine contact is shown in Pl. VII (p. 66) the section extending for about 2,000 feet. This section shows that the arm of hornstone projecting into the batholith from the slopes of Mount Belmont has no great downward extension, but that its bottom surface slopes gently away from the outcrop of the batholith. The fact that the contact line skirts around Mount Belmont almost on the same contour level as the bottom of this arm is strongly suggestive of the conclusion that the hornstone cover is not much deeper over this region, but rests with a flat surface upon the granite.

The Drumlummon mine, developed near the margin of the granite southeast of Marysville, shows contacts of another character. In the search for ore the workings have been carried to a depth of 1,600 feet from the outcrop, and as several veins intersect within the limits of the mine the exploration has extended in more than one direction. This has allowed the construction of the two cross sections shown in Pls. IX and X, the location of these cross sections on the workings being shown in Pl. VIII (p. 68). The detailed relations are exceedingly complex, but the main feature consists of a flat sedimentary cover projecting far out over the granite on the line of the main tunnel, terminating the more or less vertical walls which bound the granite below and run down to the greatest depth of the mine. These vertical walls however, are not simple in form, but show reentrant angles with a broad granite wedge entering from the side and granite dikes contained within the walls; the dikes, however, pinch out with depth and also appear to be lateral intrusions parallel to the main walls.

SURFACE CONTACT RELATIONS.

Besides the contacts observed underground by means of the mine workings, much detailed knowledge in regard to the form of the intrusion may be obtained by studying the surface relations. It is noted, for instance, that where streams cut across the granite boundary the granite has in places a greater areal expansion along the stream bed than on the hills which border it. At other places this is not true. In general this topographic relation gives some indication as to the slope of the contact surface, though in any individual case complexities of form may prevent a definite conclusion as to the relation of the contact surface to the outcrop. These relations, like the mine contacts, indicate that the batholith has both gently sloping and steep walls.

A valuable line of evidence is found in the dike and sheet extensions from the batholith. In certain cases, as on the hill at the northern point of the batholith, intruding sheets dip away from the main area, and on the principle that the injections are upward rather than downward this would indicate that at no great depth the batholith was more widely extended and that the sheets and dikes were intruded from these outlying portions.

Again, the metamorphic zone must be determined by the underground extent of the batholith as one of its principal factors, another factor being the permeability of the wall rocks, permitting penetration of magmatic emanations to varying distances.

To turn to the details of the geologic occurrence, it is found that around this batholith the narrowest portion of the metamorphic zone is along Drumlummon

Hill, where it varies from a quarter to half a mile in width, and it is to be noted that this is in the vicinity of the Drumlummon mine, where the contact slopes downward at an angle as steep as 70° for at least a quarter of a mile and possibly to a considerably greater depth. On the northern side of the batholith this zone is from half a mile to a mile in width, while on the southwestern side the metamorphism is marked to distances of at least 2 miles from the outcrop.

The considerable local zones of metamorphism around the small intrusive masses of quartz diorite in Eldorado Gulch and near the Big Ox mine have been previously noted and suggest considerable underlying portions of the magma at no great depth. This conclusion from the general but not detailed relation of metamorphism to igneous intrusion is in line with the conclusion already reached from the study of the contact surface and the outlying sheets and dikes.

As a further indication of the underground relations it may be pointed out that the great Boulder batholith, extending 60 miles in latitude by 32 miles in longitude, lies to the south of the Marysville batholith and is distant but 6 miles at its nearest approach. Not only does its composition strongly resemble that of the Marysville batholith, but its contact in those places studied by the writer is of the same general character as that described at Marysville, irregularly crossing the strata, in some places vertical, in others passing under the sedimentaries at a flat angle. Further, portions of the same rock break up at intervals around its borders to distances of several miles, the Marysville batholith being simply one of these.

Such are the grounds for believing that the Marysville batholith rapidly broadens downward in irregular pyramidal form and unites with the underground extension of the great Boulder batholith, of which its surface outcrop and the surrounding satellitic outliers are merely upward projections exposed by erosion.

FORMER COVER OF THE MARYSVILLE BATHOLITH.

It is shown in the detailed description of the batholith contacts that in many places the granite passes under the metamorphic rim at a slight angle and that consequently the size of the area exposed at the surface is determined by the depth of erosion, from which it is inferred that the surrounding border is a portion of a cover still remaining and once more extensive. The problem of this cover overlying the granite area is important in the consideration of the methods of intrusion, and a conclusion on the nature of the portion now removed by erosion can be reached only by a physiographic study of the features of the region. This is given in detail in the body of the work.

An inspection of Pl. II shows that the sedimentary structure around the granite indicates a doming of the strata to the extent of at least 1,000, and possibly nearer 3,000, feet. In spite of this feature, resembling the cover of a laccolith, the details of the intrusive form are seen to be widely different from those of a laccolith.

FOLDS AND FAULTS OF THE MARYSVILLE DISTRICT.

The movements which have affected the strata of the Marysville district have occurred at widely separated times with different effects, and it is necessary in discussing the structure to distinguish between the different events. First may be considered the initial warpings by which certain portions of the region sank downward more than others, a warping accompanied by the accumulation of the Belt sediments, thicker in certain places than in others. Such resulting bends in the lower strata have been named by Bailey Willis initial dips, and must have imparted the first gently warped character to the beds of the Belt group. These initial folds, however, can not be distinguished within the district, the feature of most general character being the development of the oldest formation in the northern part of the area and of the youngest in the southeast corner, the former an exposure due not to folding, but more largely to a great fault cutting across the district and resulting in an elevation of the northern side.

This exposure of older rock on the northern limit of the Marysville district falls in line with its situation on the southwestern side of what has been called the Prickly Pear dome. The valley of Prickly Pear Creek, forming the central portion of this dome, is occupied by a broad oval exposure of the Belt group, while in the hills surrounding occur the outcrops of the Paleozoic and Mesozoic formations. The central portion now lies at a lower level than the borders, but from the occurrence of the older and once deeper formations on the surface it is seen that over the present valley of the creek a domal uplift has occurred to such a height that subsequent erosion has removed the entire Paleozoic and Mesozoic accumulation and extended far into the underlying pre-Cambrian, turning what was originally the structural summit of the dome into a wide basin. From the general relations of the Marysville district to the structure of the region it is seen that the uplift of the northern part of the district is due to marginal faulting rather than to simple domal warping. Superimposed upon this broader structure are local disturbances, which are best brought out in Pls. I, II (pocket), and XI, p. 74. The most conspicuous are, first, a synclinal depression running across the district, with an east-west trend just north of the batholith; second, the complicated faults bordering the batholith; and, third, the movement which has produced crescentic strike lines in various portions of the district.

Regional metamorphism is strikingly absent in view of the great age of the strata; but the movements which have affected the district have impressed a slight degree of cleavage and the fissility on the softer rocks, corresponding, doubtless, to a certain amount of fracturing and brecciation in the more resistant strata. This plane of cleavage, shown in Pl. XI, dips in general about 35°–45° SW. and is independent of the bedding. Around the batholith, within the metamorphic zone, occur numerous joint planes which are not found beyond its limits, and consequently can hardly be correlated with the cleavage and fissility already mentioned.

The movements on the fault planes must be of several different ages. One of the greater movements—the east-west fault near Little Prickly Pear Creek, shown in fig. 9 (p. 97)—was contributory to the formation of the Prickly Pear dome, which is thought to have been raised in late Cretaceous or early Tertiary time and which presumably antedated the intrusion of the batholith. Another great fault cuts across the southwestern part of the district, although it could not be precisely located within the area mapped, the evidence of its occurrence being beyond the boundary. Intrusions of the microdiorite of Bald Butte and of the Belmont porphyry occur with equal abundance on both sides of this fault plane, and it is presumed, therefore, that the two walls of the fault were in their present relations at the time of the earliest igneous injections.

Faults of the second order of age are the block faults of the metamorphic zone surrounding the batholith and presumed to be connected with its intrusion.

In the third place, the breaking up of the middle Tertiary drainage systems, as shown first by the formation and then the tilting and erosion of the Tertiary gravels must have occurred later than the last andesitic outflows, which seem to have closed the igneous history of the district. These movements must have taken place on fault planes, but to what extent they were within the limits of the district is not known. The silicification of the gravels from waters rising through brecciated zones would appear, however, to indicate movements of moderate extent within the area here discussed.

The opening of the vein fissures about the batholith and within the metamorphic zone appears not to be connected with these disturbances and to have been rather the result of local adjustments accompanying the cooling of the batholith. The detailed evidence in favor of these views is given in the body of the report.

SUMMARY OUTLINE OF THE GEOLOGIC HISTORY.[a]

The geologic record of the Marysville district opens with the late pre-Cambrian, when a basin of subsidence originated over this part of Montana, extending an unknown distance into Alberta and British Columbia, and probably terminating in southwestern Montana. Within this down-warping basin was deposited a great series of sediments, which from their occurrence in the Big Belt and Little Belt mountains have been named the Belt group. Where described by Walcott in the region adjacent to the Marysville district this terrane comprises about 12,000 feet of strata, while Dawson and Willis on the British boundary have measured thicknesses approximating 11,000 feet. In the region under discussion the sedimentation was initiated by the deposition of sandstone passing into shale, the whole slightly over 2,000 feet thick. Over this was laid down a great limestone member 2,000 feet thick, followed by about 5,000 feet of mechanical sediments, then another limestone formation over 2,000 and perhaps over 3,000 feet thick, and finally a layer of red shales of variable thickness, the greatest noted by Walcott being 300 feet. All the sedimentary rocks of the Marysville district, save the superficial deposits of the Tertiary and Quaternary, belong to this pre-Cambrian terrane.

The period of sedimentation was followed by warping, possibly immediately or after an unknown interval, which brought portions of the formations within the reach of erosion. This was sufficiently prolonged to reduce the region to an advanced stage of peneplanation before the transgression of the middle Cambrian sea. The length of the erosion interval and the absence from the Belt rocks of the characteristic Lower Cambrian fauna are considered by Walcott sufficient evidence for placing the entire series in the pre-Cambrian.

The Cambrian basal quartzite does not lie at highly discordant angles across the older rocks, but the magnitude of the unconformity is rendered evident by noting that at intervals of a few miles the quartzite rests on widely different formations of the Belt group.

[a] Under this head will be given a résumé of the geologic history as presented in detail in the following chapters, but without any attempt to weigh the evidence or the degree of certainty attaching to the conclusions, since this is properly the work of the later portions of the report.

In view of the fact that the Belt formations had not been metamorphosed nor even strongly folded before the middle Cambrian, and especially of the fact that Walcott found fossils within them nearly 7,000 feet below the upper beds, it may be assumed as probable, though by no means certain, that the group is rather late pre-Cambrian. The long Paleozoic and Mesozoic history following the Belt age may be passed over without considering the details, since such formations as were once deposited have been removed by erosion within the limits of the district, and during that long time no internal forces operated to any noticeable degree to change the character of the ancient Belt formations. In Paleozoic and most of Mesozoic time the region was in general subject to slight but widespread oscillations, which now carried it downward to form the bottom of a shallow sea, and now raised it into a low-lying land surface. Toward the close of the Cretaceous or the opening of the Tertiary, however, the geographic character of the region changed. Folded mountain structures arose, building great domes and arches. General uplift occurred, giving rise to plateaulike elevations. Volcanic forces awakened throughout the entire cordilleran region of America, producing eruptions, lava floods, and granitic intrusions on a scale which has not often been exceeded or equaled in the earth's history.

The first effect in the immediate region of this stirring into activity of the earth's internal forces was the elevation of a great dome over the region of the Prickly Pear Valley. This dome seems to have been in part made by marginal faulting, as two great faults cross the Marysville district, which is situated on what was its southwestern flank. Since then the erosion of the Tertiary has removed the dome and its place is now largely occupied by a plain of gravelly and sandy waste from the surrounding mountains, remnants of the original greater structures.

After the doming and marginal faulting the igneous activities of the Marysville district manifested themselves, first as a widespread, rather meager injection of basic and intermediate dikes and sheets. This was followed after an unknown interval, but while the erosion surface was still some thousands of feet above the present level, by a great granitic invasion, which gave rise to the Marysville batholith. This is apparently but an insignificant outlier, however, of the far larger Boulder batholith, which occupies over 2,000 square miles immediately to the south.

The invasion of the batholith was accompanied and succeeded by the formation of several sets of dikes. It also produced much fracturing of the surrounding rocks, resulting in many obscure faults bounding irregular crust blocks from a few hundred to a few thousand feet across, the general effect being to dome the cover upward at least 1,000 and probably 2,000 feet, and to metamorphose the limy sediments into hornstones, whose resistance to erosion is superior to that of granite. The domal form and resistant nature of the roof would be sufficient to account for the radial drainage away from the batholith previously noted, as well as for the craterlike amphitheater excavated in the granite after it became exposed to erosion.

There is no indication that the granite continued upward to the surface. On the contrary, while it is possible that dikes from it did so, it is reasonably certain, as shown in a later part of the report, that a hornstone roof formerly covered the larger portion of the granite at no great height above the present surface. The contact relations indicate an irregular granitic body, which can not be regarded as of a laccolithic nature. The facts presented in greatest detail in this report are those bearing on the nature of this invasion and the accompanying metamorphism.

After the solidification of the granite came first certain pegmatitic injections from still fluid portions of the magma at a greater depth, then the intrusion of certain porphyry dikes. At a still later stage, but while the country was yet heated from the large intrusions, open fissures originated around the periphery of the batholith, not along the immediate contact surfaces but either roughly parallel or at high angles to it. From the evidence presented later, these fissures seem to be of the nature of peripheral shrinkage cracks, rather than great fault fractures, a view which has already been expressed by Weed.[a] They served as channels for the escape of mineralized heated waters, which deposited in them auriferous quartz together with silver, copper and iron sulphides, fluorite, and calcite, forming the valuable ores which have given prosperity to the district.

The eruptive after effects of the batholith were followed by a period of prolonged erosion, during which some thousands of feet of strata were removed and this portion of Montana reduced to a mature topography, the mountains acquiring talus- and soil-covered slopes, the rivers flowing in wide valleys. At the present time, however, some of these valleys are filled with waste, as in Deerlodge Valley and, to a lesser extent, in the smaller valley of Little Prickly Pear Creek. In other places segments of such old valleys are found isolated in the mountains with no adequate stream flowing through them, in marked contrast to the near-by gorges. Such an example is seen in Elk Park, northeast of Butte. These facts point to new mountain-making movements, occurring at some time in the Miocene or Pliocene, by which profound faulting, tilting, and warping of the crust took place, breaking up the old drainage system, causing the streams in some places to build up their ancient valleys and in others to cut gorges across the newly raised barriers. Renewed volcanic outbreaks were also more or less closely associated with these crustal disturbances in this portion of the State.

In the Marysville region the detailed events of the Tertiary and Quaternary were as follows: First a broad, open valley was eroded along the course of Little Prickly Pear Creek. When the erosion was well advanced a flood of andesitic lava was poured forth, which must have widely covered the valley. This was in turn largely eroded, but before its complete obliteration crustal changes intervened which stopped the degradation and in its turn aggradation began, the stream burying its entire valley beneath some hundreds of feet of sand, gravel, and bowlders, giving rise to the deposits whose remnants are known as the Gravel Range. Slight movements with fracturing continued, and siliceous waters, doubtless hot, rose through the shattered zones and in places cemented the river gravel into a conglomerate whose resistance to erosion accounts for the prominence of the mesalike hill in the northern part of the district, which reaches an elevation of 5,013 feet. This stage of barren vein filling and siliceous cementation was succeeded by another crustal disturbance which strongly tilted the valley of Little Prickly Pear Creek, the western side being lifted so that the bottom of the old valley of erosion, as determined by the level of the lowest gravel, is now found at an elevation of about 5,000 feet in the northwest corner of the district. This old valley floor meets the present upper surface of the river alluvium at an elevation of about 4,350 feet where Canyon and Little Prickly Pear creeks become confluent. To

[a] Weed, W. H., Trans. Am. Inst. Min. Eng., vol. 33, 1903, p. 745.

the east the older valley floor dips beneath the present alluvium, which here partly fills the old valley. The discordance in grade is thus nearly 200 feet per mile—too much to be accounted for by other means than crustal dislocation and tilting. This last important disturbance took place so long ago that since then Little Prickly Pear Creek has not only cut through the old gravels but at the western limit of the area shown on the map has sunk 800 feet into the underlying rock. On the other hand, it has built up the wide trough to the east so that the present valley floor has been brought to a uniform grade. Within the limits of the district the creek does not flow on a rock bottom, a fact which indicates that at present it is not actively down cutting this part of its bed. This may be due partly to the completion of the grading by which the gravels and sands of the plain of aggradation to the east have extended upstream, or partly to a diminished water supply, and consequently decreased carrying power, since the close of the ice age. During all these periods of igneous activity and crustal disturbance, beginning with the Tertiary and continuing to the present day, the erosion of the uplands has gone uninterruptedly forward, though with varying pace.

Such has been the nature and succession of the principal geologic events which in the course of many million years have in the southern part of the district built up the girdle of mineral wealth around the border zone of the granite and excavated in the batholith itself the picturesque Marysville basin, and in the northern part given rise to the basic sheets intruded in the ancient sediments, the lavas and Tertiary river gravels laid down upon their eroded surfaces, and finally the fertile alluvium of the present stream bottoms.

CHAPTER II.

DETAILED DESCRIPTION AND RELATIONS OF THE ROCK FORMATIONS.

SEDIMENTARY FORMATIONS.

ALGONKIAN SYSTEM.[a]

BELT GROUP IN MONTANA.

All the sedimentary formations of the Marysville district, with the exception of the recent alluvium and the older river gravel and conglomerate of the Tertiary, belong to the Belt group. This comprises an extremely ancient series of rocks which in recent years has been referred with increasing certainty to the late Algonkian. Walcott[b] has reviewed the literature of the subject, showing that the entire series attains a thickness in the adjacent region of at least 12,000 feet and covers a known area of at least 6,000 square miles.

The formations consist at the base of quartzite and sandstone, overlain by shales, the succeeding portions of the terrane comprizing two great and rather siliceous limestone formations separated from each other and bounded both above and below by arenaceous and argillaceous members, also of great thickness. Weed[c] has cited the group in the region of the Little Belt Mountains as presenting an ideal example of a cycle of deposition. A marked feature of the formations is that the subdivisions grade into one another, rendering accurate division lines difficult to draw. In view of the great age of this terrane and its subsequent deep burial, the rocks exhibit a remarkable absence of regional metamorphism. Except in the vicinity of intrusives the bedding planes are clearly preserved, and in general the degree of alteration is no greater than that to be noted in rocks of Paleozoic age in regions which have been but moderately disturbed, as, for instance, in the Pennsylvanian Appalachians. So notable an absence of general metamorphism and the great thickness and varying character of the sediments make this a favorable region within which to expect traces of pre-Cambrian fossils. Careful search, however, has disclosed but one fossiliferous horizon, which is not far from the middle of the series. The remains in this have been described by Walcott in the paper cited as

[a] Since the above was written the two following further papers have been published on this system of rocks: Walcott, C. D., Algonkian formations of northwestern Montana: Bull. Geol. Soc America, vol. 17, 1906, pp. 1-28; Barrell, J., Studies for students; relative geological importance of continental, littoral, and marine sedimentation; section on pre-Cambrian formations: Jour. Geol., vol. 14, 1906, pp. 553-568.

[b] Walcott, C. D., Pre-Cambrian fossiliferous formations: Bull. Geol. Soc. America, vol. 10, 1899, p. 199.

[c] Little Belt Mountains folio: Geologic Atlas U. S., folio 56, U. S. Geol. Survey, 1899.

worm trails and fragments of the tests of a crustacean referred by him to the Merostomata.

Where the basal member has been observed, as by Weed[a] at Neihart, it is found to consist of quartzites and sandstones, rather massive and about 300 feet thick, resting upon Archean schists and gneisses. The entire series is overlain by the middle Cambrian quartzites, and although no sharp unconformity is found to exist between the two, yet on following the contact from place to place the Cambrian is found to cut across thousands of feet of the Belt groups, so that in many localities entire formations of the upper portion of the terrane are missing. In fact, south of the Three Forks of Missouri River and north of the forty-seventh parallel east of the Missouri the Belt group is entirely missing, the middle Cambrian resting directly upon the Archean gneisses. This gives the ancient geosynclinal basin a breadth of 90 miles in a north-south direction. To what degree this thinning out and disappearance is due to original limitations to the basin of deposition and to what degree it is the result of subsequent latest Algonkian and early Cambrian erosion and base-leveling can not be stated, but the great variations in thickness of the several formations in different localities indicate that this question can not be neglected.

About 150 miles to the north-northwest the same system of rocks has been more recently studied by Willis.[b] The rocks in that region, as at Marysville, form the Continental Divide, but overlie the Cretaceous of the Plains as the result of extensive overthrust faulting. Willis does not attempt to correlate closely the several formations of this northwestern region with those of the Prickly Pear basin, but the similarity of sequence is sufficiently striking to warrant placing the two lists in juxtaposition, as is done below:

Algonkian of the Prickly Pear basin and Little Belt Mountains.[c]

Formation.	Thickness.	Type locality.
	Feet.	
Marsh shales	300	Marysville district.
Helena limestone	2,400	Helena.
Empire shales	600	Empire.
Spokane shales	1,500	Whites Canyon.
Greyson shales	3,000	Greyson and Deep creeks.
Newland limestone	2,000	Newland and Sawmill creeks.
Chamberlain shales	1,500	Southeast of Neihart.
Neihart quartzite and sandstone	700	Neihart.
	12,000	

[a] Weed, W. H., Little Belt Mountains folio: Geologic Atlas U. S., folio 56, 1899; Geology of the Little Belt Mountains, Montana: Twentieth Ann. Rept. U. S. Geol. Survey, pt. 3, 1900, pp. 257-581.

[b] Willis, Bailey, Stratigraphy and structure, Lewis and Livingston ranges, Montana: Bull. Geol. Soc. America, vol. 13, 1902, pp. 305-352.

[c] Walcott, C. D., Pre-Cambrian fossiliferous formations: Bull. Geol. Soc. America, vol. 10, 1899, p. 199.

Algonkian of the Lewis and Livingston ranges, Montana.[a]

Formation.	Thickness.	Remarks.
	Feet.	
Kintla argillite	800	No upper limit seen.
Sheppard quartzite	±700	
Siyeh limestone	4,000	
Grinnell argillite	1,000-1,800	
Appekunny argillite	±2,000	
Altyn limestone	1,400	No stratigraphic lower limit seen.

[a] Willis, Bailey, Bull. Geol. Soc. America, vol. 13, 1902, pp. 316-317.

The general correspondence in sequence and in thickness can be seen at a glance, and the detailed description shows that it also extends to the lithologic character of the formations. In general the formations as far down as exposed are of greater thickness in the northwest than in the region measured by Walcott and Weed.

FORMATIONS OF THE BELT GROUP IN THE MARYSVILLE DISTRICT.

GENERAL STATEMENT.

Within the Marysville district the older formations, including the Newland limestone and the shale and basal quartzite below it, are not exposed. The oldest formations visible are the gray sandstone and shale of the Greyson and the red sandstone and shale of the Spokane, found in the northern part of the district. To the south are encountered successively the greenish Empire shale, the buff to blue Helena limestone, and finally in the extreme southeast corner the deep-red Marsh shale, lying unconformably below the middle Cambrian quartzite.

Ripple marks and sun cracks and other evidences of an unmetamorphosed character are abundant in the Spokane formation, but within the Helena limestone are many details of structure, such as local rolls, minute puckerings, and brecciated laminæ, similar to features noted by Willis in the Siyeh limestone.[a] It is probable that these originated largely through concretionary action or the breaking up of thin layers interbedded in limestone oozes at the time of deposition. But on the other hand the possibility must be entertained of a certain degree of massive compression of the formation, sufficient to show in the texture of the limestones, but not sufficient to become recognizable in the more readily yielding shales and sandstones. As a result of the freedom from regional metamorphism the local contact and hydrothermal metamorphism surrounding the larger igneous intrusions is very conspicuous.

The thickness of the formations occurring in the Marysville district can not be given with precision, owing to a number of circumstances. As noted by Weed, the subdivisions grade into one another and the area is so small that favorable places for measurement are not to be found. Further, the formations are dislocated by several great faults and many minor ones. The rocks in places have been crushed, and intrusives also break their continuity. A still further complication making it difficult to delimit the sedimentary horizons is the intense metamorphism adjacent to the batholith and over the entire southwest corner of the district, as a result of which the strata of mixed argillaceous-calcareous character have become the most resistant members,

[a] Op. cit., p. 323.

though in other places they are the least resistant, weathering to a shaly soil, while the purer calcareous or arenaceous beds form the more conspicuous outcrops. This makes it practically impossible to trace any bed from the unmetamorphic into the metamorphic zone.

The nomenclature given by Walcott will be used in describing the character of the formations as observed within the Marysville district.

GREYSON AND SPOKANE FORMATIONS.

The Greyson, as previously noted, is the lowest formation exposed within the area shown on the map. It consists predominantly of dark-gray to nearly black siliceous and arenaceous shales, certain portions being almost fissile, others consisting of hard, dark, cherty strata cut by cubical joints. Deep dark-red or purplish shaly beds are also occasionally found.

The Spokane, lying immediately above the Greyson, is lighter colored and consists of deep-red siliceous shale, portions being interbedded with thin layers of sandstone of the same color. The shale breaks down on exposure, but it is usually sufficiently firm to resist erosion and form strongly marked slopes and cliffs. The surface separating the two formations is too much broken by faulting and too obscure to justify mapping, and consequently the two, though elsewhere stratigraphically distinct, are here not separated.

The exposures of these formations are found on each side of Little Prickly Pear and Canyon creeks. As neither the top nor bottom members are shown within the limits of the area mapped, their position has not been exactly determined, but the bulk of the rocks belong to the Spokane formation, of which a thickness of at least a thousand feet is here exposed.

The basal beds lie on the north side of Little Prickly Pear Creek, near Procter's ranch, and consist predominantly of smooth dark-gray and bluish hornstones and quartzites with blocky joints, underlain by deep-red or purplish shaly strata, a few black shales and dark limy beds being also seen. The prominent members, where lying nearly horizontal, stand out as low cliffs with vertical walls, and cubical blocks strew the ground immediately in front. The dark hornstones sometimes scratch easily with a knife, thus exhibiting a semblance to limestones, but a test with hydrochloric acid shows little or no calcite to be present. These beds may well be representatives of the Greyson formation described as consisting in the Little Belt Mountains of dark-colored, coarse, siliceous and arenaceous shales, but within the limits of the Marysville district the line of demarcation could not be traced well enough to warrant mapping.

The typical locality of the Spokane formation in this district lies in the northeast corner, where it appears as well-bedded shales and sandstones, in many places exhibiting sun cracks and ripple marks. The numerous beds of gritty red sandstone offer considerable resistance to erosion and form the caps to the buttresslike projections of the main ridge. The thinner beds break down into loose slabs of all sizes which strew the surface, and together with the dry, meager soil give a deep-red cast to the entire formation, enabling it to be recognized from a considerable distance. The colors vary from red to purple, depending on variations in the state of the iron oxide. Here and there this is seen to be gathered into spherical concretions.

EMPIRE SHALE.

The Empire shale has been described by Walcott[a] as "greenish-gray, massively bedded, banded siliceous shales, forming the basal part of the formation above the granite in the vicinity of Empire and at Marysville. They are finely exposed in the Drumlummon mine at Marysville[b] and along the ridge north of Empire, between Lost Horse Gulch and Prickly Pear Creek." Within the district this formation shows two entirely distinct facies due to the presence or absence of contact metamorphism.

In its unmetamorphosed condition the Empire is best seen immediately south of the east-west fault of the north-central part of the area, where it consists of finely laminated, soft limy shales, grayish green or buff colored, with a few reddish bands, weathering into smooth slopes with thin soil and no prominent outcrops. The bottom of the formation is apparently not exposed, but in the lower members a visible change is noticed into yellow and reddish sandstones at some places of a shaly and at others of a calcareous nature. Above, the shale passes into the blue argillaceous Helena limestone, which, being more resistant, lies at higher elevations. A section of the Empire shale just south of the fault showed a thickness of 520 feet, measured downward from the base of the Helena limestone, but as the section terminated against a fault the entire formation is doubtless thicker—Walcott estimated it at 600 feet. Adjacent to the batholith the shale is altered into hard banded light-green to light-gray and brown slaty hornstones, whose real thickness is indeterminable on account of numerous obscure faults. It seems probable, however, that the thickness here exposed is much greater than 600 feet.

As the Helena limestone has suffered considerable silicification adjacent to the batholith, and both formations are severely metamorphosed and faulted, the two are difficult to separate, and within the metamorphic limits the boundary lines are subject to much doubt.

HELENA LIMESTONE.

General character.—Walcott[c] describes the Helena limestone as follows:

> The Helena limestone formation is composed of more or less impure bluish-gray and gray limestone, in thick layers, which weather to a buff and in many places to a light-gray color. Irregular bands of broken oolitic and concretionary limestone occur at various horizons. Bands of dark and gray siliceous shale and greenish and purplish argillaceous shale are interbedded in the limestones. These bands are from half an inch to several feet in thickness. There are also beds of thinner bedded limestones, especially toward the top of the formation. The name Helena limestone is given on account of the occurrence of the limestone in the upper part of the city of Helena and on the hill slopes to the east, where the estimated thickness is 2,400 feet.

These same characters are to be noted at Marysville, the bluish-gray impure limestones weathering in many places buff or pink, as well as gray. Standing at a somewhat higher elevation than the other formations of the Belt group and possessing

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[a] Walcott, C. D., Pre-Cambrian fossiliferous formations: Bull. Geol. Soc. America, vol. 10, 1899, p. 207.

[b] The detailed stratigraphy makes it difficult to refer the strata exposed near the Drumlummon mine to the Empire proper. They may belong to a somewhat similar occurrence in the lower portion of the Helena limestone, silicified, indurated, and made prominent through contact metamorphism. Owing to the complicated structure this conclusion is, however, not certain.—J. B.

[c] Walcott, C. D., Pre-Cambrian fossiliferous formations: Bull. Geol. Soc. America, vol. 10, 1899, p. 207.

a somewhat better soil, it is largely covered with grass, and, especially on the northeastern slopes, by a scattered forest growth. The base has been taken as the lowest well-marked limestone horizon. The upper limit, more distinctly marked, is at the base of the red shale of the Marsh shale. The apparent great thickness as shown on the Marysville map on the southeast side of the batholith may be to a certain extent due to reduplication by faulting, but it seems difficult to escape the conclusion that the formation here comprises much more than the 2,400 feet estimated at Helena and would seem to equal the 4,000 feet of Siyeh limestone measured by Willis in the Lewis and Livingston ranges.

Adjacent to the batholith, where the contact metamorphism has been severe, and more or less silicification has taken place, it becomes difficult to distinguish the Helena limestone from the Empire shale, as has been mentioned. Both turn into hard light-gray or brown banded hornstone, but in the Helena the light colors prevail, and in many places some calcite remains. Cleavage on the bedding plane is locally missing, and a fresh fracture shows in many cases a splintery, subconchoidal appearance and a fine-grained stony texture. On a microscopic examination these deposits are found to have become transformed from carbonate rocks with varying degrees of siliceous or argillaceous impurities into rocks consisting of tremolite, actinolite, diopside, biotite, quartz, feldspar, and subordinate calcite, two or more of these minerals occurring in any one stratum. In the hornstone of the Empire little or no calcium carbonate remains, the siliceous and argillaceous impurities having been present in sufficient amount to combine with all of the lime present, forming calcic bisilicates and setting free the carbonic acid. In the limestone of the Helena, on the contrary, the silica and alumina have usually not been sufficient in amount to combine with all of the lime and magnesia present, and a balance of calcium and magnesium carbonates remains. This may be practically tested by the knife blade and by hydrochloric acid, those hornstones containing carbonates showing a greater softness and effervescing slightly, especially if the fresh rock is powdered. Occasional strata of marble are also observed, but toward the batholith, as shown under the heading, "Contact metamorphism," an infiltration of silica is apt to occur where but little was originally present in the rock, turning marble into hornstone and rendering the formation as a whole still more unlike the unmetamorphosed deposit.

Siliceous oolite.—Two occurrences were noted of siliceous oolite, which has resulted from a replacement of limestone.

At 1 mile and at 1.6 miles north of the cyanide mill on Silver Creek residual bowlders of siliceous oolite, dark gray, in places rusty, from 1 foot to 3 feet in diameter, are strewn in patches upon a limestone formation. The oolite is largely porous, the spaces between the individual spherules being unfilled. Under the microscope a nucleus of calcite not over 0.1 mm. in diameter, a certain per cent showing a rhombohedral form, appears in the center of many of the spherules which average 0.5 mm. in diameter. Since the plane of the thin section would cut only a part of the spherules near the center, and thereby expose the nucleus, it is probable that this is a universal feature of the grains. The quartz is built up around the nucleus in minute grains not over 0.005 mm. in diameter without a shelly nature. Scattered through the quartz is an exceedingly fine dust of calcite. The closing stage of growth has been a deposition of fine, drusy quartz on the surface of the spherules and finally a slight staining with limonite. These siliceous oolites would seem to be rather characteristic as occasional features of the limestones of the Belt group, since Mr. Weed has informed the writer that they occur in the Helena and Newland limestones as far north as the Canadian line, the siliceous globules weathering in relief.

Siliceous oolites were first noted in Pennsylvania.[a] They have been explained by some as the result of alteration from an originally calcareous oolite and by others as the direct result of deposition from hot siliceous springs. In line with this second theory Weed[b] has noted similar deposits now forming about the hot siliceous springs of the Yellowstone National Park.

In contrast to the Marysville occurrences a grain of quartz sand is the nucleus of each spherule and a siliceous cement fills up the interstices between the grains in the Pennsylvania oolite.

MARSH SHALE.

The uppermost formation of the Belt group consists of sharply delimited red shales, the lower beds calcareous in some places, quartzitic in others, strongly contrasting with the Helena limestone below and passing unconformably beneath the middle Cambrian quartzite above. This formation is known as the Marsh shale. It represents a recurrence of conditions favorable to the deposition of extremely muddy, ferruginous sediment.

The entire thickness was not measured, the upper beds being beyond the limits of the area mapped, but from section D-D, Pl. II, it is seen that 1,000 feet are exposed within the district, indicating a very marked thickening from Helena, 12 miles to the southeast, where about 250 feet are exposed, and in magnitude approaching more nearly the Sheppard quartzite and Kintla argillite in the Lewis and Livingston ranges, as described by Willis, which stratigraphically appear to correspond to the Marsh shale. Willis notes[c] in the Kintla argillite the casts of salt crystals "apparently significant of aridity, as the red character is of subaerial oxidation."

ABSENCE OF PALEOZOIC AND MESOZOIC FORMATIONS.

Within the limits of the district the sedimentary formations between the Algonkian and the Tertiary are missing, but the fact that their beveled edges outcrop on all sides not many miles away and usually show no indication of vicinity to ancient shores is proof that they were once deposited here and have since been removed by erosion. This erosion was induced by the elevation of the Prickly Pear Valley into a domal uplift. Marysville is situated in the western portion of the area formerly occupied by the dome, which has since been entirely planed away.

From the evidence afforded by the upturned outcrops of the surrounding later formations it can be roughly stated that there have been eroded from this region, besides the upper portions of the Belt group, several hundred feet of Cambrian quartzites, several thousand feet of Paleozoic limestones holding some argillaceous

[a] Bull. U. S. Geol. Survey No. 150 1898, p. 95.
[b] Oral communication.
[c] Willis, Bailey, Bull. Geol. Soc. America, vol. 13, 1902, p. 324.

and siliceous layers, and an unknown amount of Mesozoic strata, chiefly of argillaceous and arenaceous character. These facts bear on the depth to which the present surface was formerly buried. The time of the uplift was presumably latest Mesozoic or earliest Tertiary, being correlated with the crustal disturbances of the Laramide revolution and antedating the period of early Tertiary great igneous intrusions.

As lavas and river gravels which are older than the Pleistocene lie upon the present erosion surface, the bulk of the denudation of this domal uplift must be referred to the earlier Tertiary, comprising possibly much of Miocene as well as Eocene time.

TERTIARY DEPOSITS.

RIVER GRAVELS.

The Tertiary gravels constitute a superficial formation of sand, gravel, rolled cobbles, and bowlders, indicative of river rather than of lake origin. The upper limits are about 1,000 feet above the present near-by stream channels, and the deposit has a maximum present thickness of about 500 feet. The formation is found in patches on the north side of Little Prickly Pear Creek and in the northwest corner of the area. Certain of the outlying patches are cemented by silica into a resistant conglomerate. These are treated under a separate head. The main mass is only partly within the limits of the district and constitutes what is known from its character as the Gravel Range, a ridge a little over 4 miles long, of which the map shows the middle portion. This range runs in a direction northeast by east. The crest is 5,650 feet in elevation near its west end and sinks to about 4,500 feet at the eastern limit.

The formation rests upon shale and extrusive andesite, the latter having been largely eroded before the deposition of the gravel. The bottom surface of both the andesite and gravel has a gradient at the present time of about 125 feet per mile toward the east. Since Little Prickly Pear Creek falls but 60 feet per mile, it follows that while at Canyon Creek the old and recent gravels are at the same level, at the western border of the district, on the contrary, there is a difference of several hundred feet. The maximum thickness of the gravel is found at the west end of the ridge and is about 500 feet, though since the upper limit is an erosion surface the deposit may once have been much thicker. West of the area mapped the surface material includes abundant bowlders of pink Cambrian quartzite 1 foot to 3 feet in diameter, the nearest outcrops of which are on the Continental Divide about 10 miles farther west and southwest, at elevations of about 8,000 feet. The eastern patches of gravel are characterized by finer material and there is some variation in coarseness in near-by places. The material where smaller than a foot in diameter is well rolled, being ellipsoidal in outline; where larger it has a subangular but still waterworn character. Along with the predominant pink quartzite are cobbles of sandstone, a little alaskite, and some andesite, but no granite. The surface of the Gravel Range is paved with these cobbles, the matrix being a sandy soil. The quartzite cobbles, being very resistant, are found scattered along all the stream beds leading from the range and down the hill slopes to considerable distances from the outcrop. On the northern-central margin of the area mapped this residual mantle is very noteworthy, as the small, dry gulches cut through it, showing shale upon their side slopes and proving the cobbles to form a mere surface covering between the gulches. In locating the formation on the map this thin residual mantle has been disregarded and the boundary lines have been drawn where it was considered that the original underground surface would intersect the present surface of erosion.

CONGLOMERATE.

General statement.—Patches of hard, siliceous, resistant rock, conspicuously conglomeratic, are found in the northwestern portion of the district and in the typical locality, a mile north of Procter's ranch. This rock forms the cap of a mesalike hill rising about 500 feet above the surrounding region. From the following details it is seen that although so unlike in superficial character to the incoherent Tertiary river gravels these patches are in reality silicified basal portions of the gravels which, owing to their greater hardness, have escaped erosion.

These patches of conglomerate, like the river gravels, lie unconformably upon all the other formations, resting upon andesite, gabbro, or Greyson-Spokane shales and crossing bedding planes of the shales. The formation is of a light ocherous tint, but many of the included pebbles and cobbles when broken open are seen to be bleached to this color for only an inch or two in depth and within are purplish red. The cobbles are waterworn, range up to 6 inches or more in diameter, though predominantly the size of a hen's egg, and consist of quartzite, sandstone, and silicified andesite. Where the conglomerate is adjacent to the remaining patches of lava it embraces large, subangular bleached and silicified blocks of the lava along with rolled river pebbles. At other points many of the loose surface cobbles bleached on the outside and weathered from the conglomerate are larger than those seen in the matrix.

The conglomerate is found in various places north of Little Prickly Pear Creek, the most conspicuous and typical outcrop being, as noted, the mesalike cap to the hill 1 mile north of Procter's ranch, which consists of hard and massive beds dipping gently northeastward and presenting bold cliffs to the west. The other occurrences are mostly small and widely separated, though rather numerous, existing not only around this hill, but in smaller patches on the andesite area just north of Little Prickly Pear Creek and near the western limit of the area mapped. On the northern and eastern slopes of the hill referred to there is a large amount of residual material. Where this has obviously rolled from the higher outcrops its superficial character is evident, and it has not been noted on the map. In places, however, the surface is covered with large bowlders 5 to 30 feet in diameter, which, though separated and without common orientation, have evidently never moved far from their original location; these have been indicated on the map by dotting. The large residual blocks which have settled from a former somewhat higher outcrop may be distinguished from those still in place by means of the very rude and faintly marked stratification lines which can be observed in the larger bowlders. These lines are at highly different angles in adjacent residual blocks, showing rotation in settling from a former higher outcrop. The position of the larger and flatter cobbles within the bowlders is also indicative of the rotation in settling, as where the stratification is undisturbed these cobbles are horizontal, or nearly so. A detailed examination shows that there has been a considerable infiltration of quartz into the interstices between the individual pebbles, though the filling has not been completed, and small clusters of quartz prisms may be noted projecting into the cavities. The lava pebbles show extreme alteration, all the black bisilicates being completely destroyed and replaced by iron ore and quartz. The orthoclase feldspars are partially silicified, but beyond an infiltration of limonite the feldspathic groundmass appears to be but little altered. These changes are no more extensive than those occurring at most of the lava localities in the neighborhood, but the originally loose and open nature of the conglomerate deposit has offered a greater chance for the deposition of silica.

Relation of conglomerate to veins and brecciated zones.—On the south slope of the hill north of Procter's ranch conspicuous quartz veins may be seen cutting through the shale and running north-northwest in the direction of the crest line of the hill. The mineralizing action has been as much a silicification of the wall rocks as a deposition of quartz in fissures. The violet-brown to purple and gray shale and andesite which in many places show about the same colors are both along this zone bleached to the ocherous color of the conglomerate and are hardened so that they have a rough and resistant surface on weathering. Where the veins pass into the conglomerate they are largely lost, but small seams and gashes of quartz occur all through the rock. Again, nearly all of the area which lies north of Sanford's ranch, and on which the Woodchuck mine is situated, is cut by brecciated fault zones and minor faults, as indicated on the map, there being a great deal of silicified country rock, but comparatively little reef quartz. This is especially well seen in the Spokane formation. The andesite cap has been almost entirely silicified and bleached, and on it are found two patches of conglomerate large enough to map, besides loose residual cobbles weathered from the former matrix.

Relation of conglomerate to river gravels.—Both the Tertiary river gravels and conglomerate overlie the extrusive andesite and consist of similar material, except that the conglomerate is much silicified and contains a greater proportion of andesitic fragments similar to the patches of andesitic lava of the neighborhood. Furthermore, the conglomerate exists in small discontinuous patches, all of them thin compared to the outcrops of the gravels. Certain conglomerate bowlders large enough to be indicated on the map are found near the gravels and the conglomerate would seem to pass under the gravels, though no actual contact has been observed.

CONCLUSIONS REGARDING THE TERTIARY DEPOSITS.

From the preceding statements of fact the following conclusions are drawn: The relation between the siliceous infiltration into the cavities of the conglomerate and that throughout the subjacent fault zones in the two localities above mentioned is too close to be overlooked, and the natural explanation is that ascending waters, taking advantage of the fractures, rose to the gravel stratum and then spread. The fissures presumably did not extend upward at first into the incoherent gravels, but later movements taking place after cementation of the gravels had begun fractured the newly cemented rock. Patches of conglomerate where no underlying fractures have been noted may have been due to a lateral spread of siliceous waters, which more or less perfectly cemented the bottom stratum of the gravels. The great resistance of the cemented gravels accounts for their preservation long after the incoherent portions of the formation were washed away, and the greater proportion of lava fragments in the conglomerate is accounted for by the fact that andesite forms a considerable proportion of the underlying rock and would contribute a greater percentage to the bottom stratum of river gravel.

The pavement of quartzite bowlders and cobbles noted in the Gravel Range, which is distinguished in character from the material of the conglomerate by the coarseness and abundance of the bowlders, presumably does not extend in depth with the same abundance. In a formation holding large bowlders in a coarse sandy soil the surface wash, especially in a dry climate, removes the soil and leaves the bowlders, resulting in their progressive accumulation on the surface. Even if it be assumed that such bowlders existed to the same extent in the conglomerate, yet its surface would show no such accumulation, since the matrix is of equal hardness and consequently weathering and destruction of the two would go forward at the same rate.

Thus by viewing the conglomerate as the silicified lower beds of the gravel the differences between the two can be satisfactorily explained, while their many points of resemblance give warrant for believing that they are both remnants of the same formation rather than that there have been two widely separated periods of sedimentation, with silicification of the first deposits and then almost entire erosion before those of the second period were laid down.

The character of the gravels points to a fluviatile rather than a lacustrine origin, the evidence on this point consisting in the coarseness of the deposits and the absence of lake clays and silts. The increased coarseness and abundance of the quartzite toward the west and the fact that its outcrop is found in that direction is further evidence that the river flow was from west to east, as at present. The uneroded portions of the conglomerate and gravels still occupy a width of a mile and a half, indicating a rather wide and open valley. At a time when 500 feet or more of gravels filled the ancient valley it must have been comparable in size to the present valley of Little Prickly Pear Creek below its junction with Canyon Creek. In fact, as the bottom surface of the ancient gravel deposit slopes under the present valley alluvium at that place, the two valleys may be regarded there as one and the same.

AGE OF RIVER GRAVELS AND CONGLOMERATE.

To determine the age of the river gravels it is necessary to go beyond the limited area of the Marysville district. In the Three Forks quadrangle is an extensive deposit of sand, conglomerate, limestone, clay, and volcanic dust filling the valleys above the present river levels. These beds, named the Bozeman lake beds, correspond in general nature to the valley filling of the Marysville district. At one place within them Marsh found Pliocene fossils. Again, the Silverbow Valley south of Butte contains similar deposits which farther west and south have been found to carry upper Miocene fossils. In the Smith River deposits east of Helena have been found river and lake beds of sand, conglomerate, clay, and volcanic ash which contain large vertebrate fossils of both the John Day and Deep River formations of the middle Miocene.

It appears from these statements that in this part of Montana a period of valley filling existed during the greater part of the Miocene and Pliocene, followed by a period of crustal disturbances which in many cases remodeled the drainage systems and disturbed the gradients so that now the older deposits are usually trenched by the present streams. The two periods of filling and disturbance were doubtless more or less associated, and therefore no close correlation can be made between adjacent districts. It can be stated at present only that these ancient gravels are certainly Tertiary and probably not far from the end of the Miocene.

QUATERNARY DEPOSITS.

Little Prickly Pear and Canyon creeks do not flow at present upon rock bottoms, but have built up alluvial valleys of sand and clay suitable for agricultural purposes, the waters of the creeks being largely used for irrigation. Throughout the greater portion of these valleys rolled cobbles of Cambrian quartzite are common, but on the margins the material grades into the wash from the hillsides.

IGNEOUS ROCKS AND THEIR STRUCTURAL RELATIONS.

INTRODUCTION.

The chief geologic interest of the Marysville district centers in the igneous rocks and the deposits of precious metals. The igneous rocks are however viewed from two different standpoints, that of the general reader or mining engineer, who wishes information in regard to the chief types and their geologic relations, and that of the geologic specialist, for whom they should be completely, accurately, and quantitatively described. In the present advanced state of petrography it is well to make this distinction and separate the detailed petrographic description from the general geology. This report follows in the main the suggestions laid down in the recent publication entitled "Quantitative Classification of Igneous Rocks," by Cross, Iddings, Pirsson, and Washington, and the terminology they employ for field purposes on the one hand and for exact petrographic description on the other will be used to a considerable extent. In the descriptions the order of age will be followed so far as it is determinable.

MICRODIORITE DIKES AND SHEETS OF BALD BUTTE.

DEFINITION.

Diorite is a crystalline granular rock consisting chiefly of lime-soda feldspar and one or more of the dark minerals, hornblende, biotite, or, more rarely, pyroxene. Small amounts of quartz, orthoclase, magnetite, and other minerals are present in many specimens. The appearance of such a rock is on the whole darker than that of a granite, and as the texture becomes finer the color deepens to a dark gray. Where the rock is so fine grained that the individual crystals can barely be distinguished an appropriate name is microdiorite, which according to the dominant dark mineral may be a hornblende, biotite, or pyroxene microdiorite. Where one mineral crystallizes markedly coarser than the others the rock is a porphyrite qualified in the same manner by the name of the dominant mineral.

CHARACTER AND DISTRIBUTION.

The microdiorites occur as dikes and sheets, sparingly scattered over the greater part of the area south of Little Prickly Pear Creek, and perhaps corresponding to the sheets of coarsely granular pyroxene diorite or gabbro found north of that stream. Only the southeast corner of the district is entirely free from them, while the southwest corner, on the contrary, contains them in great abundance. They show a marked tendency to conform to the bedding planes of the Belt formations, with a dip usually of not more than 30°, and occur in outcrops which are commonly from 300 to 1,000 feet long and from 10 to 50 feet thick, the thickness being normally from 2 to 5 per cent of the length. Much smaller intrusions may, however, be observed under favorable circumstances, while at Bald Butte the numerous sheets range upward to half a mile in length, with proportionate thickness.

DETAILS OF OCCURRENCE.

Bald Butte.—The flat in front of the town of Bald Butte lacks rock exposures, but the surface material consists largely of small decomposed fragments and soil from the microdiorites, indicating that they are extremely abundant beneath. On the hill slopes they are seen to outcrop as numerous sheets, averaging 10 to 15 feet in thickness, separated by layers of hornstone and dipping to the northeast conformable to the strata at angles of 15° to 30°. These rocks are commonly altered from the original shades of gray and black to greenish gray, many of them being difficult to distinguish from the hornstones of similar color. Under the microscope this is found to be due in some specimens to a recrystallization by which the original hornblende crystals have become replaced by a matted mass of pale green hornblende fibers, or in others to the fact that the whole mass of the rock has become sifted through with brownish-green flaky aggregates of mica, probably biotite.

A large dike of Belmont diorite porphyry, dipping steeply to the southwest, cuts across these sheets, and these alterations in the microdiorites are doubtless in large part to be connected with this intrusion and the channel which it formed for the escape of heated waters. As evidence of this action, adjacent to this large dike the hornstones are shattered and mineralized, and the microdiorites show a parting parallel to the dike. Within the planes of this parting occurs an infiltration of quartz and fluorite, these same minerals being found in both the hornstones and microdiorites and having largely replaced the dike of Belmont porphyry itself.

A type specimen of the fresh rock was collected for analysis from a point just north of the houses of the mining camp of Bald Butte and is described in detail under the heading of "Petrography." It consists of a gray feldspathic groundmass holding needlelike prisms of hornblende, whence the name of hornblende porphyrite under which it is described. Photomicrographs of this rock are shown in Pl. IV.

Drinkwater Gulch.—Another occurrence studied in detail, and of somewhat different appearance is on Drinkwater Gulch, 3 miles north of Bald Butte. In the chapter on "Contact actions" it is shown that the Bald Butte rock has been affected by extensive hydrothermal metamorphism, while the Drinkwater Gulch sheets are close to the granite and have suffered from a more direct form of contact metamorphism. In this place, however, the mineralogical and textural differences will be described only so far as they affect the appearance of the rock in the hand specimen.

In appearance the Drinkwater Gulch rock differs somewhat from those of Bald Butte in that the microcrystalline groundmass on fresh fracture shows a deep reddish-brown color due to minute flakes of biotite scattered through the rock. Within the groundmass are dark-green areas up to an eighth of an inch in diameter, poorly defined in outline and separated from the reddish-brown groundmass by a narrow white zone. Under the microscope the green spots are found to consist of fibrous aggregates of hornblende crystals filling polygonal areas occupied by former phenocrysts, the appearance of both the spots and groundmass indicating a secondary recrystallization of the rock related to the contact metamorphism in the neighboring strata. The narrow white zones surrounding the hornblende nuclei indicate that during the recrystallization the hornblende has withdrawn to itself the iron from the immediately surrounding groundmass.

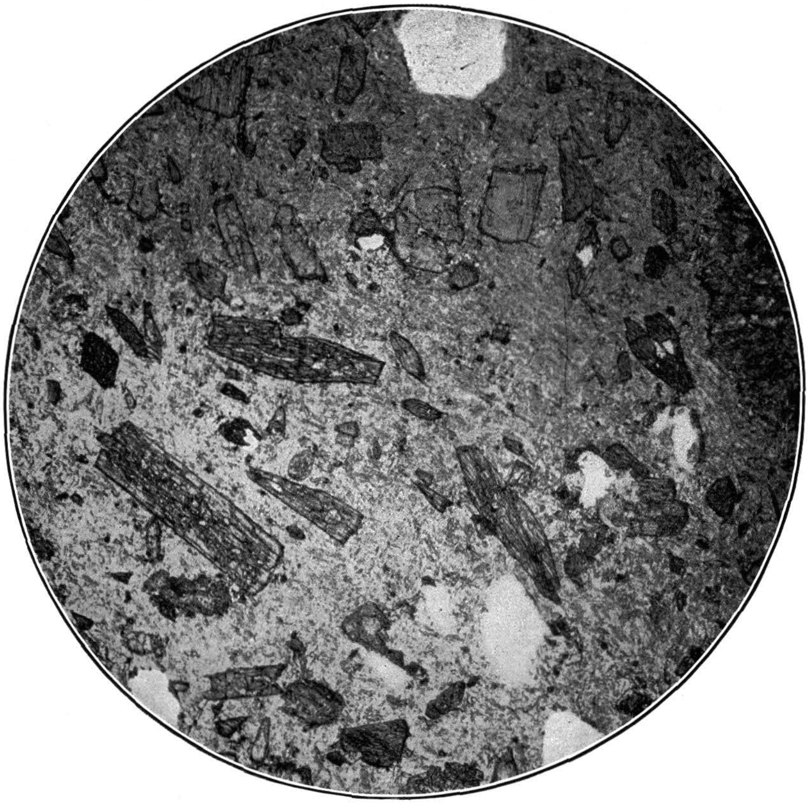
Both the sheets and the inclosing hornstones are broken up by the intersection of several systems of joint planes into rude tetrahedral blocks from several inches to a foot or more across. Along certain of these seams the rock is bleached to a grayish-white.

Sawmill Gulch.—Sheets of microdiorite of still another variety are exposed in the railroad cut, one on Silver Creek near Sawmill Gulch, the other in Sawmill Gulch near the large trestle. These are biotite diorites, the first 3 to 4 feet thick, the second 10 to 15 feet thick. In the hand specimen they are seen to be gray-black rocks of a gabbroic appearance, showing an abundance of biotite scales. Under the microscope the biotite is seen to be of two natures—first, idiomorphic crystals up to 0.5 mm. in length with the appearance of original crystals; second, flaky aggregates scattered more or less freely over the section. A considerable amount of calcite is present, occurring with orthoclase and in places flaky biotite, more rarely pyrite and ilmenite, the whole aggregate forming sharply bounded polygonal patches, some of which are a quarter of an inch in diameter, and bearing witness to the extensive replacement and recrystallization of the rock by which the original minerals have locally been destroyed and this mosaic formed in their places.

The distinctive features of these sheets are the originally coarser grain and the petrographic evidence which indicates hydrothermal alteration at a distance of a mile to the east of any large outcrop of igneous rock. The latter feature is discussed in the section on "Petrography."

Trinity Hill region.—Northeast of the metamorphic zone surrounding the batholith scattered sheets of microdiorite are found, a typical example lying upon the ridge north of Trinity Gulch. This sheet is double, each layer being from 6 to 10 feet thick.

The sheets of this northern portion are inclosed in rocks which do not show the intense contact metamorphism of the occurrences previously described and themselves present a somewhat different appearance. On weathered surfaces they show brown or gray and on fresh fracture a whitish gray. Under the microscope they are seen to have suffered a great deal of alteration, but of a different kind from that of the metamorphic zone. Instead of a recrystallization of biotite and hornblende, the former chiefly over the groundmass and the latter in place of previous phenocrysts of hornblende, the feldspar is found to be largely sericitized and stained with limonite, the dark minerals being to a considerable extent replaced by calcite, chlorite, and magnetite. Yet the degree of alteration varies much in different occurrences, one sheet



A

B

PHOTOMICROGRAPHS OF MICRODIORITE OF BALD BUTTE.

A. Without analyzer. The light-gray mottled background consists of interfelted feldspar laths. The hornblende phenocrysts show small inclusions of feldspar. On the right-hand margin is an aggregate of calcite, hornblende needles, and feldspar, presumably occupying the place of some former mineral. The white spots are holes in the thin section. Magnified 21 diameters.
B. Same slide under crossed nicols.

1.4 miles north of Trinity Hill, and another 1.75 miles N. 80° E. of the same hill showing as fairly fresh augite diorite, the augite being only slightly and locally altered to calcite, uralitic hornblende, and iron ore.

Summary.—It may be seen from this detailed description of localities that not only did the original character and distribution of the microdiorites vary throughout the district, but the subsequent alterations supply data from which inferences may be drawn as to the presence of concealed igneous bodies of later origin and the manner in which they have affected the microdiorites. This discussion is, however, left for its appropriate place at the end of the descriptive geology.

PHYSICAL CHARACTER OF THE MICRODIORITE MAGMA.

A close study of the details of intrusion may allow many inferences of varying degrees of certainty to be made in regard to the physical condition of the magma at the time of intrusion and the mechanics of the intrusion, depending upon the magma, the invaded formation, and the forces operative at the time. In any such discussion, however, the facts as observed should be presented by themselves and the conclusions sharply separated, since it is always possible that in the light of fuller and later knowledge these facts may receive another interpretation. Therefore, the most essential facts bearing on this subject are first presented.

Observed relations to the country rocks.—The sheets are widely scattered, the outcrops of many adjacent sheets being half a mile apart over a region where the thin soil would hardly be able to obscure any occurrence large enough to be indicated on the map, yet the texture is everywhere crystalline and in some places is coarse enough to be distinguished by the naked eye, the rocks grading from more or less porphyritic microdiorites to diorites.

Within the metamorphic zone surrounding the batholith are numerous sets of closely spaced joint planes and the bedding is usually not the plane of readiest cleavage, yet the microdiorites are nearly always in the form of sheets and show no tendency to penetrate along the joint planes. Neither sedimentary inclusions within the microdiorites nor the microdiorites themselves possess the closely jointed structure of the walls. It is further noted that the microdiorites are intruded along many planes in the Empire shale and Helena limestone and are in the form of flat, discontinuous lenses, whose thickness is usually from 2 to 5 per cent of the length of the outcrop, and these sheets tend to be segregated in certain localities.

Again, it is observed in places that the intrusion of the sheets has resulted in very little contact reaction with the wall rocks, since in no place where the sheets cut marbles is the resulting garnetiferous contact zone more than an inch in width and usually no mineralogical contact effect whatever is to be noted.

Another feature worthy of being stated in detail as bearing on the physical state of the dike and its walls at the time of intrusion and the manner of penetration is to be noted on the northern slopes of Drinkwater Gulch. Here a sheet of microdiorite about 8 feet thick has followed the bedding plane of the grayish-white, green, and brown banded hornstones dipping 25° N. At one place it is seen to be double, a band of hornstone 4 inches thick containing calcite passing somewhat below the middle of the dike. Above this another slab 6 inches thick, exposed for several feet, has become separated from the roof and tilted at an angle of 30° to the walls of the sheet. The upper end has dropped at one place 2 feet, at another 3 feet, so that it rests obliquely along both the dip and the strike of the sheet. The upper end has moved forward a few inches and the lower end probably rests upon the thin central partition, with which it may be continuous downward.

A very similar occurrence is to be noted 400 feet east of the railroad trestle at Marysville, where a slab of hornstone stands obliquely in a dike 4 feet thick, which dips 60° E., conformable to the hornstone. The slab is tilted at an angle of about 15° to the walls of the dike, having a dip of about 75°, and has apparently been lifted about 4 feet; but as there are a couple of offsets on the hanging wall of the dike the evidence is not perfectly conclusive as to whether the slab has risen or sunk from its original position.

Inferences as to character of magma.—From the preceding statements in regard to character and occurrence the following inferences may be drawn. The small number but wide distribution of these dikes and sheets, taken in connection with their slight thickness wherever found, indicate that they have penetrated to considerable distances from the parent magma and have maintained during the intrusion a considerable degree of fluidity. The latter statement is based on the well-known laws of viscous flow. With the least motion of imperfectly fluid particles upon each other work is done and there remains less capacity for intrusion at a distance. Consequently a viscous magma will tend to open for itself a chamber locally, while a more fluid one will tend to split the strata and penetrate to great distances. This principle has been applied by Pirsson[a] to the explanation of the form of laccoliths, the same author pointing out that such internal work would tend to maintain the heat of the liquid. Corroborative evidence in regard to the comparative liquidity of the microdiorite magma at the time of the dike and sheet injections is found in the unbent and unbrecciated character of the partition mentioned in the preceding section and the slabs standing at angles to the wall rocks. For such a partition only 4 inches thick to have remained intact and parallel to the main walls, the walls must have been quietly forced apart by equal pressures on all parts of the surface, in a manner analogous to the action of a hydrostatic press. As to the tilted slabs the exposures are not sufficiently complete to reveal all the relations, but if they had been pried free by a viscous magma they would doubtless have been transported farther and become more broken, while on the other hand, if the magma had been perfectly fluid they would possibly not have remained permanently in their present tilted position.

Inferences as to depth and manner of intrusion.—The consideration of the age relations in the next section shows that the microdiorites were intruded as far back as the early Tertiary and very probably no earlier than the later Cretaceous. They antedated the batholithic invasion and were certainly intruded at a depth of as great as 1 mile and possibly 2 miles from the surface of the time, the evidence for this conclusion resting partly on considerations treated at length under the heading, "Former cover of the Marysville batholith."

[a] Weed, W. H., and Pirsson, L. V., Geology of the Judith Mountains: Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1898, p. 584.

They were intruded, therefore, into a country rock which was considerably warmer than the surface, owing to its depth, and which may have been still further heated by magmatic bodies lying at a greater depth in the neighborhood. It is seen, however, that there was no general metamorphism and that, therefore, the temperature of the walls must have been very much less than that of the magma, since metamorphism takes place at temperatures far below that of fusion. Yet the microdiorites were intruded to considerable distances from a parent reservoir, with the maintenance of magmatic fluidity.

The conclusion, therefore, is that the individual acts of penetration were done quickly, chilling before coming to rest being thereby avoided, and that these intrusions resembled volcanic eruptions in their intermittent and paroxysmal nature. Whether or not there was more than one act in the process can not be stated, as the intersection of dikes and sheets has not been noted.

AGE RELATIONS.

The age relations of the microdiorite dikes and sheets are evident in a number of localities. At Bald Butte, as noted on a previous page, a large dike of the Belmont diorite porphyry cuts the microdiorite sheets. The same relation may be observed on the eastern slopes of Mount Belmont, 500 feet west of the West Belmont mine. On Drumlummon Hill, at the granite contact east of the Cruse tunnel, a microdiorite dike 4 feet thick is cut off by granite and another is intersected by seams of aplite. In the railroad cuts 400 feet east of the trestle a number of microdiorite dikes conformable to the stratification are cut at various angles by aplite seams. Thus wherever the age relations are made evident by intersection the microdiorites are found to be older than all the other igneous rocks of the district.

Another confirmatory line of evidence leads to the same belief. The intrusion of the granite has produced an aureole of intense contact metamorphism of varying width which has converted the rather soft and well-bedded Empire shale and Helena limestone into gray and reddish-brown hornstones of great hardness, cut by several planes of fissility and in many places showing no particular aptitude for splitting on the bedding planes. Yet the greater number of microdiorite intrusions are conformable to the bedding planes and show no tendency to follow the joint planes associated with the metamorphic zone, standing in this respect in contrast to the dikes of Belmont diorite porphyry, which are always steeply inclined.

The sheets are widely scattered, and the age relations of only a portion of them can be definitely determined, the possibility remaining that somewhat different varieties of the rock, such as the pyroxene diorite north of Trinity Hill and the mica diorite of Sawmill Gulch, may not be closely related to the type occurrences; but in the absence of more positive evidence the general similarity of geologic relations and magmatic character is justification for including them under one category.

There is nothing within the Marysville district to fix the absolute age of these earliest intrusives, and recourse must be had to near-by regions to determine the time limits with reasonable probability. The fact that the rocks are in many places unaltered, certain sheets even containing fresh augites, may be cited as an indication, though not a proof, against a Paleozoic or Algonkian age, and they are naturally to be looked on as the first of the series of intrusions which inaugurated and accompanied the period of active growth of the cordilleran mountain ranges. In this connection may be noted the Dakota formation (Upper Cretaceous) in the Castle Mountain district,[a] in which a bed of volcanic ash is found, "thus proving the occurrence of volcanic activity during the Dakota epoch." Further, in the Livingston formation, which is classified as transitional between the Cretaceous and Tertiary, volcanic agglomerates occur.[b] From this time forward in this part of Montana igneous activity continued nearly to the close of the Tertiary. These oldest intrusives of the Marysville district may therefore be looked on with reasonable assurance as of latest Cretaceous or more probably early Tertiary age.

PETROGRAPHY.

Introduction.—Under the head of "Character and distribution" have been mentioned such details of a petrographic nature as seemed necessary for an understanding of the megascopic appearance and field relations of these rocks, the features of more purely petrographic interest being left for discussion under the present heading. Among such features are the microscopic fabric of the rock, or the character of its crystallization, especially the ways in which this may differ from the usual or simplest mode of crystallization of such a magma and its connection with the physical conditions attending the consolidation. Again, the chemical composition and its variability within the limits of the rock are of extreme importance from the petrographic standpoint, as on an exact knowledge of these are based any conclusions as to differentiation within the magmatic reservoir and the consanguinity of one intrusion with others coming either before or after in that region. For these reasons it is necessary to enter into details which have but little interest or bearing on the general geology of the district.

Detailed petrography.—In many of these dikes the feldspar grades downward from phenocrysts into groundmass, making the quantitative classification of the rock difficult, and in others, especially those where there is evidence of recrystallization within the metamorphic zone, many of the feldspars are without crystal form, cleavage, or twinning. As there is little or no quartz, even Becke's method can not be employed. Consequently at first it was supposed that two types—a syenitic and a dioritic—might be present, and representatives of each were therefore chosen for analysis, the age relations in both being clearly defined. The analyses are compared with those of the two rocks most nearly resembling them as given by Washington.[c]

[a] Weed, W. H., and Pirsson, L. V., Geology of the Castle Mountain mining district: Bull. U. S. Geol. Survey No. 139, 1896, p. 45.

[b] Geologic Atlas U. S., folio 1, U. S. Geol. Survey, 1894.

[c] Washington, H. S., Chemical analyses of igneous rocks: Prof. Paper U. S. Geol. Survey No. 14, 1903.

Analyses of microdiorite of Bald Butte and of two similar rocks.

	A.	2.	B.	22.		A.	2.	B.	22.
SiO_2	52.07	52.12	56.88	56.47	H_2O+	1.60	0.88	3.03	1.65
Al_2O_3	15.99	16.35	15.61	15.33	TiO_2	1.08	2.10	.49	.99
Fe_2O_3	4.77	3.68	2.95	2.54	CO_2	None.	.07	None.	....
FeO	5.59	6.02	2.34	4.53	P_2O_5	.40	.89	.13	.54
MgO	4.54	4.14	6.35	5.08	MnO	....	.17	....	.18
CaO	7.50	7.25	5.23	6.93	BaO	....	.04	....	....
Na_2O	2.97	3.65	3.59	3.81					
K_2O	2.79	2.34	2.39	1.66		99.64	100.33	99.66	99.71
H_2O-	.34	.25	.67	....					

A. Hornblende microdiorite, near West Belmont mine, east slope of Mount Belmont, Marysville, Mont. Older than the batholith. Field No. 133. (Andose-shoshonose.) George Steiger, analyst. (Bull. U. S. Geol. Survey No. 228, 1904, p. 155, where by a typographical error this rock is given as hornblende-mica diorite.)

2. Diorite (andose), Mount Ascutney, Vt. L. G. Eakins, analyst. (Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 272.)

B. Hornblende porphyrite, north slope of the town of Bald Butte, Marysville, Mont. Older than the Belmont porphyry. (Andose.) George Steiger, analyst. (Bull. U. S. Geol. Survey No. 228, 1904, p. 155.)

22. Pyroxene andesite (andose), near Dunraven Peak, Yellowstone National Park. F. A. Gooch, analyst. (Prof. Paper U. S. Geol. Survey No. 14, 1903, p. 274.)

From these analyses the norms have been computed as follows:

Norms of the microdiorite of Bald Butte and related rocks.

	A.	2.	B.	22.		A.	2.	B.	22.
Quartz	3	2.4	7.1	6.8	Hypersthene	11	11.5	14.7	14
Orthoclase	16.7	13.9	14.5	10	Magnetite	7	5.3	4.4	3.5
Albite	25.2	30.9	30.4	32	Ilmenite	2.1	3.9	.9	1.8
Anorthite	22	21.1	19.2	22.5	Apatite	1	2	.3	1.2
Diopside	10	7.4	4.6	6.8					

Daly[a] notes the tolerably high percentage of potash in the Ascutney Mountain rock and concludes that besides that present in the biotite there must be a notable amount occurring as an orthoclase molecule in the lime-soda feldspar. In specimen A the potash is seen to be even higher, and yet no orthoclase can be identified within the rock. An apparently wide departure between the norm and the mode is therefore to be noted, which is explained partly by the presence of the hornblende and partly by the lack of individuality in the orthoclase feldspar, as noted below. In rock A the hornblende occurs in small, chunky, rounded green prisms, averaging 0.1 mm. in length, with a tendency toward segregation, which is largely due to the crowding among the larger feldspar crystals. It has preceded the feldspar in crystallization, and here and there the feldspar has incorporated the hornblende in its growth. The feldspars exhibit a tabular development, with sparse albite, but common Carlsbad twins. The central parts have usually a well-defined tabular development and but little zonal extinction, the extinction angles in the zone perpendicular to the brachypinacoid indicating the composition of andesine, Ab_5An_4. Some of these well-defined tabular crystals have been greatly extended by an irregular and allotriomorphic growth of the boundaries, with a mottled extinction at a slightly different angle and inclosing small hornblende crystals. Within these outer portions, as well as in the separate anhedral crystals filling interstices between the other minerals, the larger part of the albite and orthoclase molecules are doubtless contained.

The rock of analysis B is shown in the photomicrograph, Pl. IV. The feldspar is much more definitely crystallized, the andesine crystals averaging 0.2 mm. in length,

[a] Daly, R. A., Geology of Ascutney Mountain, Vermont: Bull. U. S. Geol. Survey No. 209, 1903, pp. 38, 39.

with a normal tabular development giving a trachytic texture and shading off into the interstitial orthoclase. The hornblende exists as well-formed idiomorphic phenocrysts 1 to 1.5 mm. long, locally skeletal, the irregular cavities having been filled with feldspar. A few rounded cavities 1 to 2 mm. in diameter, now filled with hornblende, calcite, some feldspar, and chlorite, may possibly have once contained augite. One of these is shown on the right-hand margin of the photomicrograph.

The petrography of the altered microdiorites is treated under the subject of metamorphism in Chapter IV (pp. 137–138).

GABBRO INTRUSIONS.

DEFINITION.

Under the class of gabbros are included those dark crystalline igneous rocks of granitic texture whose chief minerals are pyroxene and a triclinic feldspar. As pyroxene very commonly alters into hornblende, or either may crystallize from the same magma, the line between the gabbros and diorites is poorly defined. Any granular rock composed to a considerable degree of dark minerals, even if largely or completely hornblende, should be classed with the gabbros and not with the diorites, while if it be possible to determine the mineral as pyroxene, even a lesser amount would indicate that the rock belonged to the gabbro group. They are distinctly basic rocks, possessing normally not over 50 per cent of silica, and are especially liable to alteration.

CHARACTER AND DISTRIBUTION.

Within the limits of the district the gabbros are confined to the Greyson-Spokane shales and sandstones on the northern side of Little Prickly Pear Creek. There are five large and a number of smaller patches, usually showing no topographic distinction, and requiring a study of the soil for the determination of their limits. The ease of alteration in these rocks is doubtless the cause of their offering less resistance to the weather than the rather soft shales and sandstones of the Belt group. The forms of the outcrops are irregular, the larger areas averaging half a mile in length and from 500 to 1,000 feet in breadth. At a number of places, notably in the large patch northeast of Procter's ranch, the contact is conformable to the stratigraphy, but as a thinly banded hornstone overlies the gabbro on each side, neither contact can be regarded as the bottom surface of an intrusive sheet. It seems probable, on the contrary, from the number of small irregular patches in the vicinity, that they are various exposures of a rather large and irregular flat intrusion, whose depth is not known. At other places the elongation of the outcrops parallel to the bedding of the strata, and especially their exposures on side slopes, indicate that their form is that of sheets varying from a few feet to 100 feet in thickness.

The well-defined and angular character of the margins of the area northeast of Procter's ranch suggests that fault planes form part of the boundaries, and as the whole mass is not offset by these faults it would appear that they are not younger than the intrusions, but originated presumably at the same time, assisted by the forces producing the intrusions.

The surface rocks are apt to be extensively altered, but uniformly exhibit the granitic texture, even close to the margins. They are dark gray or rust colored on the exposed surfaces and on fresh fracture are a gray black, resembling strongly the microdiorites, save in their coarser crystallization. The microscope serves to point out both the resemblances and differences. It shows that they possess a simple mineral composition, consisting of about 50 per cent labradorite, 45 per cent augite, and 5 per cent magnetite, thus being considerably more basic than the typical microdiorites. A photomicrograph of this rock is shown in Pl. V, *B*.

AGE RELATIONS.

Since the gabbros do not come into contact with any other intrusions their relations to those south of Little Prickly Pear Creek can not be accurately determined. Although petrographically quite distinct from the microdiorites, certain of the latter found north and east of Trinity Hill show transitions toward the gabbros. These are the augite microdiorites, which contain as much as 20 per cent of idiomorphic augite crystals embedded in feldspar that grades downward into a groundmass, carrying probably a considerable proportion of albite and orthoclase. The fact that the only microdiorites carrying augite were found in the region nearest the gabbros is significant, but is not sufficient evidence on which to found a positive relationship in age. The andesite lava flows which preceded the formation of the Gravel Range rest in places upon the gabbros, indicating a long period of erosion between the coming to place of the two. The gabbros therefore belong to the earlier igneous history of the district.

PETROGRAPHY.

Normal form.—Under the microscope, as shown in Pl. V, *B*, the texture of the gabbros is seen to show a diabasic tendency, the feldspars having dominated the crystallization and the augite and magnetite having been completed later, but the augite also has a considerable degree of crystal outline. The coarseness of grain differs in the several localities, the feldspar crystals varying from 0.5 to 2 mm. in length. All the minerals assume the same degree of granularity. The measurement of a thin section from the northeastern locality by Rosiwal's method gave the following results:

Measurement of gabbro (section No. 170-B).

Mineral.	Number of measurements.	Average intersection (mm.).	Total distance (mm.).	Specific gravity.	Per cent by weight.
Labradorite (Ab_7An_8)	95	0.17	16.40	2.7	36
Pyroxene	101	.21	21.14	3.4	58.4
Magnetite	11	.13	1.23	5.2	5.2
Biotite	5	.03	.17	3	.4
	212	....	38.94	....	100

The labradorite is extremely uniform in character, different crystals giving precisely the same specific determination and showing no zonal structure.

The augite is a pale, clear brown, with cleavage somewhat irregular, angle between 𝕮 and c 48°–49°, and birefringence 0.028–0.029. These determinations confirm the microscopic appearance in placing the augite as a diopside with a moderate amount of Tschermak's molecule. By multiplying the percentages of the minerals present by their content of silica the entire rock is found to contain about 48 per cent silica.

One thin section of the rock in a highly altered condition, such as is common to these areas, showed the plagioclases completely transformed into muscovite and zoisite, with a little of the epidote molecule. The black bisilicates possess well-preserved hornblende rims with varying degrees of pleochroism and kernels of colorless to pale-yellow serpentinous products.

Contact form.—At a place 1.05 miles N. 20° E. of Procter's ranch the gabbro was studied in immediate contact with the overlying hornstone. The two are of very much the same color and many small, sharp chips of the hornstone are included in the marginal portion of the igneous rock. Under the microscope the gabbro is found to have a character markedly different from the normal, being, in fact, a muscovite micrograpite. The mineral composition of this rock is, roughly, quartz, 40 per cent; alkaline feldspar, 40 per cent; muscovite, 10 per cent; magnetite, 10 per cent. Many of the quartz crystals show a dotted interior and clearer margins, pointing to a final growth under different conditions from the first. The feldspar is badly sericitized and is nowhere more basic than an oligoclase. The magnetite occurs in isometric granules arranged in an open mesh, which incloses all the other minerals. The prismatic, hexagonal, and diamond-shaped forms of many of these skeletal heaps, from 0.5 to 0.7 mm. long, suggest an alteration from some earlier iron-bearing mineral, probably hornblende. The muscovite not only occurs within the feldspars as sericite but exists also throughout the rock in well-defined allotriomorphic crystals of equal size with the quartz. The bordering hornstone, as seen by the naked eye, is cleanly and sharply separated from the igneous rock, but under the microscope the distinction is not so clearly made. The hornstone is seen to consist of fine-grained quartz and muscovite with scattered granules of magnetite, but near the immediate contact it becomes coarser and the muscovite flakes are segregated into areas which suggest an alteration from previous feldspars. These contact effects are, however, extremely local and to be observed only on careful examination. From this description of the contact phenomena it is inferred that there was probably considerable hydrothermal alteration along the contact plane after the primary crystallization had been completed, with a probable enrichment in silica.

Associated pegmatites.—In the gabbro area in the northwestern part of the district a pegmatite dike was noted showing a thoroughly welded contact, formed by intercrystallization along the walls. On microscopic examination of one thin section, it was found to consist of the following minerals:

Composition of pegmatite from northwestern part of Marysville district.

Albite	70
Quartz	15
Epidote	8
Chlorite	5
Serpentine group	2
Magnetite	0.5

The amounts are stated roughly, since in a rock of pegmatitic structure a single thin section does not suffice to give an accurate idea of the mineral composition. The serpentinous products, embracing two species, besides associated magnetite, have clearly been altered from original biotite. The albite probably contains a little of the anorthite molecule, but possesses no perthitic orthoclase, and, though much twinned, gives a very clear-cut extinction. Thus there are no indications of orthoclase, though some doubtless enters isomorphously into the albite. The albite occurs in crystals averaging a quarter of an inch in diameter and contains the quartz pegmatitically intergrown.

Although, as stated previously, too broad a generalization should not be based on a single thin section, it is seen that in composition this is a very unusual pegmatite, containing more than the usual amount of soda, lime, magnesia, and iron, and less potash and silica than such rocks usually carry. The explanation is doubtless to be found in the basic character of the rock which it cuts, and from which, on the usual theories of the origin of pegmatites, it has been derived. Such acidic segregation dikes related to syenites and gabbros have been noted elsewhere, especially by Brögger in Norway.

FELDSPAR-PORPHYRY DIKES.

GENERAL CHARACTER.

The rocks of the feldspar-porphyry dikes are marked in all cases by the presence of phenocrysts of feldspar, as the name implies. These are acidic in composition, being nowhere more basic than an andesine. The groundmass varies in color from pale brownish or greenish gray to dark gray, depending largely on the degree and kind of alteration, and in composition from those rich in quartz to those which apparently contain none. These dikes are restricted to the southern and western portions of the district, and vary considerably in different localities. There is, therefore, a possibility that they do not all belong to the same stage of igneous activity and it will be well to discuss them with this fact in mind. They may be divided into three chief types—the Belmont type, which occurs over Mount Belmont and to the south; the Drumlummon type, found in the Drumlummon mine and on the surface near by, and the Piegan Gulch type, represented by three sheets 1 mile north of Gloucester.

BELMONT PORPHYRY DIKES.

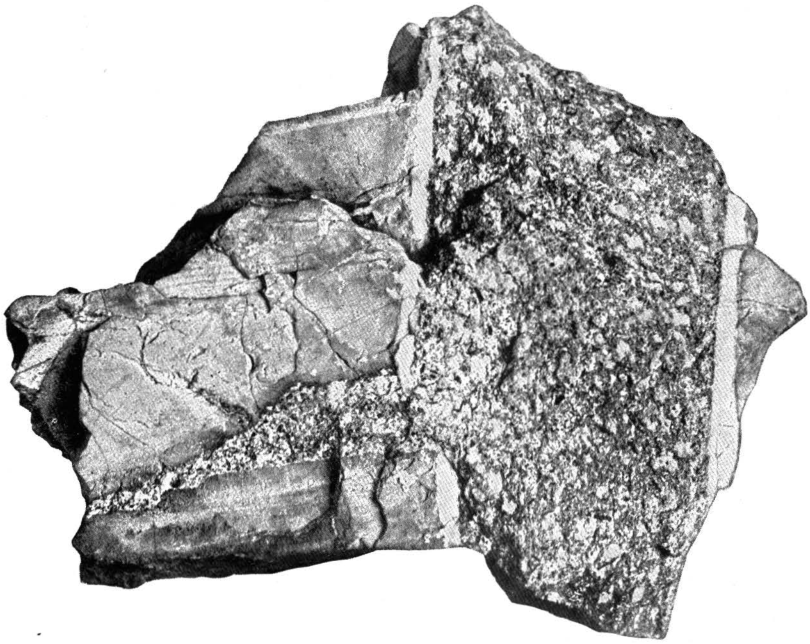
Description.—The Belmont porphyry dikes, one of which is shown in Pl. V, A, hold conspicuous phenocrysts of plagioclase feldspar from an eighth to a quarter of an inch in diameter and smaller amounts of biotite and hornblende, the whole embedded in a dark-gray microcrystalline groundmass, which under the microscope is seen to consist of small tabular crystals of feldspar, in large part plagioclase; irregular and inconspicuous fillings of quartz; and shreds of pale-green biotite. The whole forms a rock of striking appearance, the white feldspars standing in contrast to the dark-gray groundmass. This is the appearance when fresh, but the rocks are commonly altered, the groundmass turning to a light gray, the feldspar phenocrysts becoming inconspicuous, and the dark minerals being more or less destroyed.

Geologic relations.—The more conspicuous outcrops occur as reefs of rough light-gray bowlders or of rock in place, which may be from 10 to more than 100 feet wide, and can be traced in length for several hundred feet. Their occurrence is restricted to the south and west sides of the batholith, and they are noticeably abundant upon the slopes of Mount Belmont.

In favorable locations they grade down into dikelets which are but a fraction of an inch in width, while on the other hand the largest dike cuts across the entire southwest corner of the district. The commonest width is perhaps from 20 to 40 feet, and, as shown on the map, the dikes are rather discontinuous, the average length of an individual outcrop being not over 500 feet. There may be several successive dikes, however, following in the same line, and in many places two or more lines run parallel for some distance.

In a few instances the dip of the dike may be observed, but usually it must be inferred from the topographic relations. Over the region of Mount Belmont and to the south of the batholith, where the dike or its successive members extend down the slopes, there is either a bend in the outcrop or a progressive stepping off to the northeast, indicating that the dike system dips to the northeast at an angle not far from 50°. East of Bald Butte the dikes for the same reason are judged to be vertical. The great dike of Bald Butte, however, as shown in section C–C, Pl. II, dips in the opposite direction, being parallel to the most conspicuous joint system of that locality. From these statements it is seen that in contradistinction to the earlier set of microdiorite intrusives, these dikes in few places, if anywhere, follow the bedding planes of the sedimentary rocks, but on the contrary rise at steep angles through the strata. It is also important to note that the dips of the outcrops show no tendency to convergence downward.

Microscopic petrography.—The more essential petrographic features have been noted in the general description. Here are to be mentioned such further details as are of more purely petrographic interest. The feldspar phenocrysts, which constitute about one-fourth of the volume of the rock, are completely idiomorphic and stand in marked contrast to the much finer groundmass. They are locally isolated, but are more commonly in clusters, which are intergrown. Both Carlsbad twinning and twinning according to the albite law are very irregularly developed. A number of measurements indicate that the composition is that of an andesine, $Ab_5\ An_2$ to $Ab_5\ An_3$, the rock being slightly more acidic than the plagioclase of the batholith. A noticeable feature is that on being turned approximately to the extinction angle between crossed nicols the majority of the crystals show a network of a slightly different composition and extinction angle. This does not have the appearance of the normal perthitic intergrowth, but suggests that possibly the crystals have been brecciated and then cemented by a redeposit of feldspar of slightly different composition, though in crystallographic continuity. This lace work is especially noticeable in the outer zone of many crystals. The groundmass, which is trachytoid, consists of plagioclase ranging from andesine to albite, with a certain amount of presumable orthoclase and a little quartz. The chief dark component is biotite, amounting to perhaps 5 per cent, hornblende being usually present in



A. DIKE OF BELMONT PORPHYRY.

From southwestern slopes of Mount Belmont. Natural scale. Dark-gray groundmass, weathering to light brown and holding small crystals of hornblende and biotite (black), with larger crystals of feldspar (white). Quartz seams 3 mm. wide on the walls. (See p. 51.)

B. PHOTOMICROGRAPH OF GABBRO.

From north of Little Prickly Pear Creek. With analyzer. For mineral analysis according to Rosiwal's method see page 47. Black mineral, magnetite; dark, rough mineral, diopsidic pyroxene; light mineral, labradorite feldspar, dominating the crystallization. Magnified 28 diameters.

more sparing amount. This description makes it evident that the rock can not differ greatly in composition from that of the batholith, though no chemical analysis is available for comparison.

Contact relations.—Besides those relationships connected with the time of intrusion, and noted under the heading "Age relations," the only feature to be described is the local accompaniment of quartz veinlets. This was noted in the dikes between Penobscot and Towsley gulches. The hornstone shows partings in a number of directions, and of these the parting planes parallel to the dikelets, bearing to the northeast, show numerous quartz seams, in places against the dikelets, in places parallel and within the hornstone. This would not be noteworthy were it not for the fact that in the specimen illustrated in Pl. V, *A*, a small lateral tongue of porphyry is given off from a dikelet 1½ inches wide, and this breaks the continuity of the quartz seam one-eighth inch wide which lies between the dikelet and its walls. The difficulty of explaining this feature as due to a mere infiltration into joint planes and the probability that it has something to do with the physical condition of the magma and its walls at the time of intrusion justify its mention.

Degree and kinds of alteration.—In degree of alteration there is much variation. It was noted that in a specimen collected on the Continental Divide between American and Sawmill gulches, and showing considerable alteration, the biotite had turned to chlorite, calcite, and muscovite, while the plagioclase was filled with calcite and sericite. These alteration products are such as might be formed by weathering. Southeast of Bald Butte some epidote and pale-green shredded biotite are present, while in the Bald Butte mine, where hydrothermal mineralizing action, as shown later, has been most intense, the entire rock has become recrystallized, the biotite changing into a light-green secondary mica accompanied by the separation of iron. Minute flakes of this mica approaching sericite are also dusted over the groundmass. In the more completely altered portions the feldspar is completely destroyed, the phenocrysts being replaced by a matting of sericite and the groundmass by quartz. Muscovite and fluorite replace the biotite, and fluorite and quartz are extensively deposited in fissures through the brecciated rock mass.

Age relations.—The large prophyry dike passing through Bald Butte is continuous throughout its length, not discontinuous or offsetting like many of the others, and on the north side of the town is clearly seen to cut the microdiorite sheets, a fact that shows it to be the younger rock. The relations to the granite are not directly exposed, but a number of indications may be pointed out. First, where the granite of the batholith passes out into sheets or dikes or chimneylike intrusions the habit becomes in a few places somewhat porphyritic, the andesine or labradorite crystals being of normal size, 2 to 4 mm. in diameter, and well formed, and the other minerals occurring as a holocrystalline matrix of some coarseness. At other places granitic, aplitic, and pegmatitic facies are noted, but nowhere is a transition found toward the Belmont porphyry. On the southeastern slope of Mount Belmont the porphyritic arm from the batholith is more basic than either the batholith of the porphyry dikes, while on the northern slopes a porphyry dike occurs not more than 250 feet from the chimneylike outcrop of granite of normal coarseness. These considerations indicate that the dikes must not be looked on as continuations from the batholith into a cover and therefore do not represent the same stage of eruptive activity.

On the contrary, they are either older or younger. A fact pointing to their greater antiquity is that they have not been found within the batholith, but only within the adjacent hornstone. The strength of this argument is weakened, however, when it is considered that certain formations are much more favorable for the development of igneous intrusions than others. As an instance may be cited the Newark rocks of the eastern United States, which are characterized by prominent intrusive and extrusive diabase and basalt sheets, while within the adjacent gneisses, through which doubtless considerable material was also forced, there are but few and comparatively thin dikes.

The fact, already mentioned, that the Belmont porphyry dikes in few places or nowhere occupy the bedding planes of the rocks, as do the microdiorites, may be taken as an indication that at the time of their intrusion the sediments had already been so metamorphosed and broken with joint planes that the bedding planes were no longer the surfaces of readiest separation.

On the other hand, the possibility that these dikes are younger than the batholith may be suggested by the certain degree of resemblance which they bear to the porphyries of the Drumlummon mine, which are clearly younger than the granite.

The extensive hydrothermal mineralization (discussed under the subject of metamorphism) which has taken place at Bald Butte affords proof that the porphyry dikes are older than that epoch of mineralization, which was doubtless associated with the intrusion and cooling of considerable masses of igneous rock beneath. As shown on page 80, the batholith probably underlies this region at no great depth and would naturally be considered the igneous rock in question.

The relation of these porphyry dikes to the metamorphic zone and the region of the batholith may be taken as evidence that their origin was not far removed from that of the granite.

To sum up the preceding statements, the Belmont porphyry dikes are clearly younger than the microdiorite sheets and dikes and older than the period of mineralization at Bald Butte. They are closely related to the batholith, but not simultaneous in origin with it, and as to whether they are younger or older the evidence is not conclusive.

DRUMLUMMON PORPHYRY DIKES.

Occurrence.—The Drumlummon porphyry dikes are found in one place at the surface within the granite and near its margin on the lower slopes of Drumlummon Hill, the principal dike being of nearly vertical dip and 10 feet thick. The other occurrences are within the Drumlummon mine, in the southern workings of a number of the levels.

The principal mass occurs immediately south of No. 3 shaft in the Drumlummon mine and has been mapped from the eighth to the twelfth levels, inclusive. As shown by the general geologic map, this is not far from the St. Louis workings and is therefore near the granite contact and about a quarter of a mile from the surface occurrences. It is a highly irregular mass, averaging from 20 to 50 feet in thickness, with a general dip to the south of 40° to 80°, cutting the bedding planes at a high angle. On the eighth level it has a general east-west trend, on the twelfth running more nearly north and south. In places it has a rolling boundary, here and there giving off branches, and is associated with smaller isolated occurrences within 200 to 300 feet.

Petrography.—The rock is spotted with numerous small phenocrysts of feldspar not over an eighth of an inch in diameter. At the surface the matrix is pale brownish white, while in the mine specimens it is pale grayish white to greenish gray, the difference doubtless being due to the greater oxidation of the surface rock. At some places the phenocrysts are not visible, probably owing to the extreme alteration, and in such cases it is most difficult to distinguish the porphyry from the altered hornstone which forms its walls. The composition is predominantly of plagioclase feldspar whose species it is not easy to determine, though as the maximum extinction angle in the zone perpendicular to the clinopinacoid is as high as 17° to 18°, it must be either albite or andesine. The twinnings are poorly developed and in numerous specimens examined entirely absent, giving the crystals the appearance of orthoclase. It is doubtful, however, if orthoclase is present anywhere in this rock as phenocrysts, but it is believed to exist in considerable amount in the groundmass.

A small amount of hornblende and biotite were originally present, but both are now completely replaced by calcite, pyrite, kaolinite, chlorite, quartz, sericite, and epidote, not more than three of these minerals occurring ordinarily at one point. The feldspars show a considerable degree of mottling, and where brecciated the fragments have grown together again by the secretion of feldspar.

Care must be used to distinguish fine-grained and somewhat porphyritic facies of the granite from these porphyries, especially when both are highly altered and smeared with the dirt of the mine.

Age relations.—The fact that the surface dike is found within the granite proves that the porphyry is the younger. Within the mine the two rocks have not been found intersecting, but occur locally 10 to 20 feet apart without showing any gradation of the one toward the other.

The relation to the period of vein formation is best seen on the ninth and tenth levels of the Drumlummon mine, where the vein cuts the porphyry which appears on both walls. On the fourth level the relations are not so simple, as the strike faults cut the porphyry, but the vein branches and largely pinches out. At other places on a number of levels porphyry is observed on one wall only, indicating, as in the case of the granite intrusions, that the vein fissures, while younger than both the granite and the porphyry, have been influenced somewhat by them in location and in character.

PORPHYRY SHEETS OF PIEGAN GULCH.

A mile north of Gloucester, on the top of one of the buttresslike hills which face Piegan Gulch, are three similar intrusive sheets of feldspar porphyry, conformable to the bedding. The chief one is about 18 feet thick. It holds abundant feldspar phenocrysts up to 3 mm. in diameter, whose species were undetermined, the mineral being now largely altered to calcite and originally deficient in twinning. The biotite which was once present is completely altered to muscovite and chlorite, and there are a few smooth, gibbous quartz crystals 0.5 mm. in diameter. The whole is set in a micrograntic groundmass of quartz and feldspar. The rock is more acidic than the previous types. As these sheets are isolated from all the other igneous rocks, nothing is known of their age relations.

QUARTZ DIORITE OF MARYSVILLE BATHOLITH.

DEFINITION.

Under the division of diorites are classed those rocks more than two-thirds of whose feldspar is plagioclase and whose dark components, subordinate in quantity to the feldspar, are typically either biotite or hornblende. Quartz diorites are those which in addition carry more than about 10 per cent of quartz. As the species of the feldspar can seldom be distinguished in the field, for general geologic descriptions it is well to refer to all quartz-feldspar-bearing granular rocks as granites, while for exact petrographic description the quantitative system is far superior to the older qualitative divisions. Thus such terms as quartz diorite have largely lost their usefulness, though this is retained in the present instance as being more precise than the term granite and more familiar to the large body of general readers than the new quantitative names. In the general descriptions, however, throughout the paper this rock of the batholith will be referred to as simply the "granite."

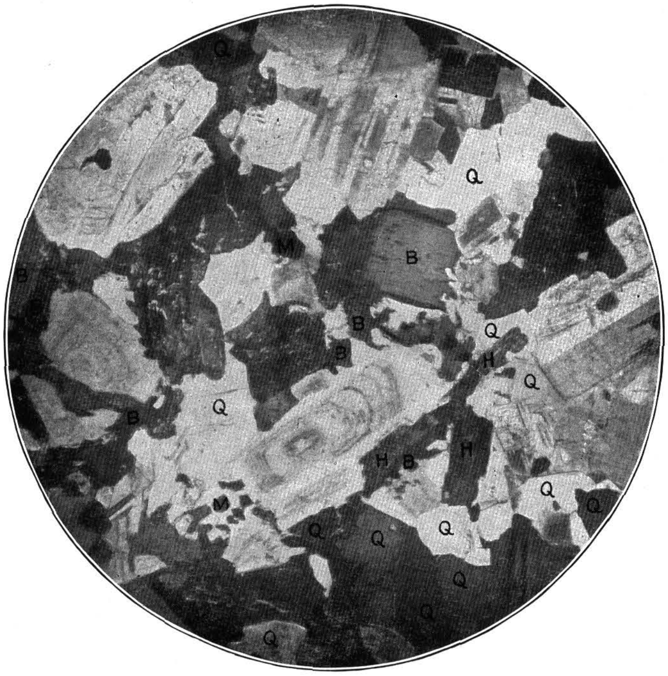
CHARACTER AND DISTRIBUTION.

Quartz diorite is the rock of the Marysville batholith, an irregular intrusion somewhat pear-shaped in surface outline, 3 miles long and from one-half mile to 1¾ miles wide, around borders of which are located the mines whose outputs of gold have made Marysville in the past one of the most productive mining centers of Montana. The rock has the normal granitic texture, though showing two phases whose relations are discussed under the heading "Petrography." At the border more acidic and basic facies are sometimes found, but these are extremely local in occurrence and not strongly marked, so that except in a critical study they might be readily overlooked. A few outliers of the typical rock occur in dikes and sheets as far away as the Big Ox mine, 2 miles north of the nearest exposure of the batholith. Besides the two internal phases and the acidic and basic marginal facies previously mentioned, distinct intrusions of aplite and pegmatite are closely associated with the margin, being found neither in the interior of the batholith nor at a distance within the sedimentary walls.

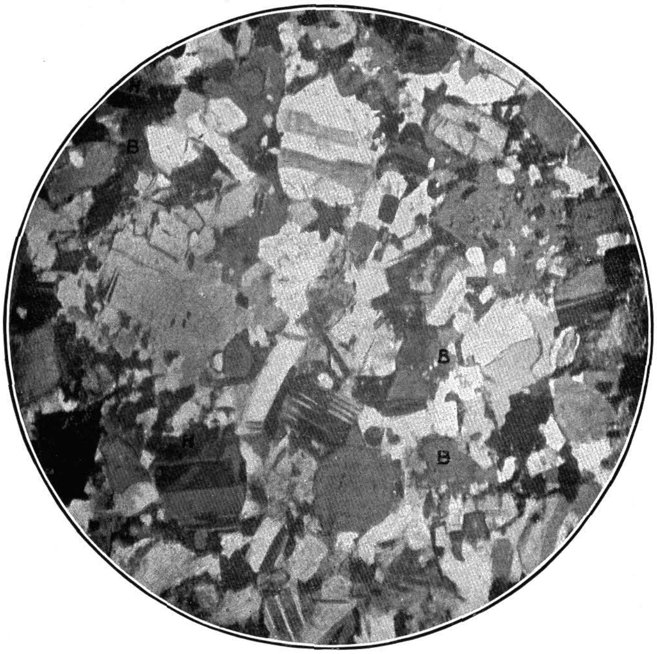
PETROGRAPHY.

As previously noted, the quartz diorite of the batholith exhibits two phases. The normal rock is fairly coarse and even grained, very uniform in appearance, and contains hornblende and biotite in about equal amounts. A photomicrograph of a thin section of this rock is shown in Pl. VI, *A*. The second phase shown in thin section in Pl. VI, *B*, is noted chiefly east and northeast of Mount Belmont, at points, as a rule, a quarter of a mile or more from the margin of the batholith, but probably not so far from a former roof. It is characterized by a somewhat finer grain and a lesser proportion of hornblende, the biotite having a shredded appearance and existing in many minute flakes. The plagioclase of this finer grained rock is apt to show a slight dominance in size and in priority of crystallization. The thin sections showed no very marked difference in composition from the normal type, but mainly a difference in texture.

On account of the shortness of the field season the writer did not have time to study the field relation of these two types, as it would have involved a detailed tra-



A



B

PHOTOMICROGRAPHS OF QUARTZ DIORITE OF MARYSVILLE BATHOLITH.

A. Normal type, yellowstonose; with analyzer. See Analysis A, page 55. Field No. 164. Feldspar (plagioclase and orthoclase) unmarked; Q, quartz; B, biotite; H, hornblende; M, magnetite. Magnified 11 diameters.

B. Fine-grained type; with analyzer. From spur northeast of Belmont. Field No. 7. Principal minerals, plagioclase, orthoclase, quartz, biotite, and hornblende. The latter two minerals in small scattered crystals, only the larger being marked B and H. Magnified 11 diameters.

verse of the granite area; but the appearance of the whole mass gave the impression that the magma had been slightly variable and the absence of noted contacts suggested that it was probably due to one continued period of invasion. Dr. Whitman Cross, however, in a reconnaissance trip through this region in the summer of 1904, noted a contact of the fine-grained against the coarse-grained variety on the road from the Crüse mine down Jennies Fork, and states that the finer grained rock appears to him like a distinct intrusion filling a considerable channel through the coarser grained rock. The question of the relationship of these two phases must therefore be left open until more detailed study can be given. It is to be noted, however, that the coarser or normal type forms nearly everywhere the outer portions of the batholith and shows no tendency to fineness of grain on approaching the contacts.

The normal type was selected for analysis, the specimen being taken on Ottawa Gulch along the roadside at an elevation of 5,950 feet. The following table gives the composition of this and related rocks:

Analyses of Marysville quartz diorite and related rocks.

	A.	B.	C.		A.	B.	C.
SiO_2	63.55	63.76	63.88	ZrO_2	None.		
Al_2O_3	16.57	16.01	15.84	CO_2	0.69	0.23	
Fe_2O_3	2.36	2.22	2.11	P_2O_5	.21	.25	0.21
FeO	1.98	1.96	2.59	SO_3	.06		.34
MgO	1.53	2.43	2.13	Cl			Trace.
CaO	4.69	4.55	3.97	MnO	.13	.09	.07
Na_2O	3.78	3.98	2.81	BaO	.15	.17	.09
K_2O	2.78	2.84	4.23	SrO	.04		.02
H_2O at 105°	.31	.28	.22	LiO_2			Trace.
H_2O above 105°	1.11	.57	.66				
TiO_2	.42	.52	.65		100.36	99.95	99.82

A. Quartz diorite, road up Ottawa Gulch, Marysville, Mont. Elevation, 5,950 feet. (Yellowstonose. In Bull. U. S. Geol. Survey No. 228, 1904, p. 155, this rock is erroneously stated as a tonalose. The computations in that case were not checked by the present writer.) Typical of the Marysville batholith. Field No. 164. Analyst, George Steiger.

B. Diorite (Yellowstonose near tonalose), Needle Mountain, Yellowstone National Park. Hague and Jaggar, Bull. U. S. Geol. Survey No. 168, 1900, p. 96.

C. Butte granite (amiatose), Walkerville station, Butte, Mont. Weed, W. H., Jour. Geol., vol. 7, 1899, p. 739, Bull. U. S. Geol. Survey No. 228, 1904, p. 132; Quantitative Classification of Igneous Rocks, p. 223. Analyst, H. N. Stokes.

Although the thin section showed but little weathering, the part used for analysis unfortunately contained considerable carbon dioxide. As this is evidently secondary in the form of calcite, its presence has been neglected in the computation of the norm. By considering it as original, however, the name of the rock is not changed. Analysis B is the one in Washington's tables (Prof. Paper U. S. Geol. Survey No. 14) which approaches nearest to this analysis of the Marysville rock. Analysis C is of a typical granite from Butte, Mont., representing the type of the Boulder batholith in that region. The very close correspondence of these rocks should be noted, the Marysville specimen being characterized by the rather low magnesia. The analyses of the granites from Butte as given in Bulletin No. 228, U. S. Geological Survey, pages 132–136, inclusive, being taken as a whole, the Marysville rock is seen to be marked by higher lime and soda, lower magnesia and potash. The norms and modes of these rocks are as follows, the latter being determined by Rosiwal's method:

Mineral composition of quartz diorite of Marysville batholith and related rocks.

NORMS.

	A.	B.	C.
Quartz	18.7	16.6	19.4
Orthoclase	16.7	16.7	25
Albite	32	33.5	23.6
Anorthite	[a] 20	20.3	18.1
Diopside	2.5	1.8	.7
Hypersthene	4.1	6.2	6.8
Magnetite	3.5	3.2	3
Ilmenite	.8	.9	1.2
Pyrite	.04	....	.24
Apatite	.34	....	.31
Others	....	....	.99
	98.5	99.2	99.3

[a] CaO for CO_2 not deducted.

MODES.

	A.[a]			C.[b]	
	Per cent by weight.	Probable error in per cents.	Number of measurements.	Per cent by weight.	Number of measurements.
Quartz	22.2	1	72	22.55	....
Orthoclase	15.6	1.7	69	17.57	....
Plagioclase	[c] 47.5	2.8	82	[d] 42.47	171
Biotite	7.2	1.2	25	9.77	....
Hornblende	5.5	.9	27	4.44	....
Pyroxene	....	....	....	2.37	....
Apatite	.2	.05	7	....	....
Titanite	.1	.05	3	....	....
Magnetite	1.7	.2	12	.76	....
Pyrite	....	....	....	.07	....
	100.0	....	297	99.98	604

[a] Total measurements=145 mm. on one slide; area of measurements=290 sq. mm.
[b] Quantitative Classification of Igneous Rocks, p. 226.
[c] Ab_5An_4.
[d] Ab_3An_2.

In the Marysville specimen the probable error was determined by dividing the measurements into ten sets of thirty each and noting the divergence of the individual means from the general mean, the probable error being computed from these data by the method of least squares. The rather large values for these errors are due almost entirely to the unequal distribution of the minerals within the thin section. The measurement of a couple of thin sections from the same specimen should give more accurate results, but in view of the general variation of the rock mass the present results would seem sufficiently close for most purposes. It is to be noted that the modes agree more closely than the norms; this is in large part due to the fact that the thin section measured for the mode of the granite from Butte was not from the same specimen as that which was analyzed and from which the norm was derived.

APLITES AND PEGMATITES.

INTRODUCTORY OUTLINE.

Granitic masses are commonly intersected by more or less numerous thin dikes and sheets of a white granular rock consisting essentially of quartz and alkaline feldspar, in some places fine grained with a sugary texture, in others in wider dikes having the appearance of a white acidic granite. These are commonly known as *aplites*.

The word aplite has come from the connection to signify a certain geologic relationship to other igneous bodies that renders it objectionable from the standpoint of petrography, which deals only with the composition and mineral features of the rock. Petrographically there may be considerable variation in the composition of these dikes, many holding considerable quantities of biotite, while others consist essentially of quartz and orthoclase. Spurr,[a] in order to express this variation of composition, has called the former biotite-granite-aplite and the latter alaskite-aplite, alaskite being the name proposed by him for all acidic rocks consisting essentially of quartz and orthoclase. To conform strictly to the petrologic definition of aplite the rock must be fine grained and all the crystals about equally developed.[a] As it is the geologic relationships which have been used here for grouping the occurrences, aplites is used as the most preferable group name, including both fine-grained biotite granites and alaskites.

The evenly granular texture of even the smallest dikes, the continuity in many places of crystallization of the quartz and feldspar with that of the wall rocks, and the commonly local character of the fissures have all led to the conclusion among the great body of geologists that the formation of dikes and sheets of this rock followed closely the primal crystallization, at a time when the wall rocks were still at a high temperature and when possibly the final crystallization of quartz and feldspar was still incomplete, a residual liquor being thus readily furnished to fill the fissures, and that the fissures are contraction cracks due to the shrinkage accompanying crystallization and loss of temperature.

Locally an aplite dike or sheet will show along its center certain portions of unusual coarseness of crystallization, some of the individual crystals being several inches in diameter. Large plates of mica and some rare minerals of many species are found associated with this phase of the rock. The quartz is as a rule peculiarly intergrown in the form of a mesh through the feldspar. These peculiar coarse-grained rocks of aplitic composition and relationships are called pegmatites. Usually they occur in fissures by themselves and true aplite may be missing from the neighborhood.

The relationships of the pegmatites of southern Norway to the aplites (which are merely fine-grained acidic granites) and other features connected with their occurrence and intrusion have led Brögger[b] to regard them as true igneous injections, and Williams[c] held the same view for the greater number of those of the Piedmont Plateau of the eastern United States. On the other hand, many pegmatites show a tendency to a ribbon structure, certain planes within the fissure showing gradations toward vein quartz, and, as has been noted by Van Hise in the Black Hills, the same transition toward vein quartz may be noted on passing away from the walls of the main intrusion. Such transitions from what appears to be the result of true igneous injection to what is evidently the result of aqueous precipitation have led many geologists to the view that pegmatites are in fact produced by aqueo-igneous activity, differing from aplites in being formed in the presence of

[a] Spurr, J. E., Twentieth Ann. Rept. U. S. Geol. Survey, pt. 7, 1900, pp. 188-191; Am. Geologist, March 1900.

[b] Brögger, W. C., Syenitpegmatitgänge der Südnorwegischen Augit- und Nephelinsyenite: Zeitschr. f. Kryst., vol. 16, 1890, pp. 215-235.

[c] Williams, G. H., The general relations of the granitic rocks in the Middle Atlantic Piedmont Plateau: Fifteenth Ann. Rept. U. S. Geol. Survey, 1895, pp. 675-684.

abundant water and other vapors concentrated from the crystallizing magma.[a] Spurr[b] and Lindgren[c] have discussed the relation of pegmatite veins to ore deposits, Spurr considering that pegmatite veins form transitions into gold-bearing quartz veins, whereas Lindgren believes that while such transitions are not unlikely they remain to be proved.

From this outline it may be seen that the aplites and pegmatites associated with the Marysville batholith present many problems, for instance: Did they originate from local segregations, and if so, was it before or after the crystallization of the surrounding rock? Do they occur uniformly throughout the mass; and if not, why not? Have they been forced upward from a considerable depth into the already solidified upper portions of the batholith? Is there any relationship between the pegmatites and the auriferous vein quartz? The facts of the field will now be presented.

DISTRIBUTION AND CHARACTER.

GENERAL STATEMENT.

The aplites and pegmatites are found rather closely associated with the margin of the batholith, but are not equally represented in all parts of it. An inspection of the map, which shows only those intrusions conspicuous enough to warrant representation on a scale of 2 inches to the mile, shows that they are distributed almost entirely around the east end and especially on the northeast. Here they consist of numerous massive sheets of alaskite-aplite intruded in the hornstone along the bedding planes. As the hornstone itself is hard and light colored, detailed observation is required to separate the two. In places, as on the road leading up Silver Creek to Marysville, these sheets are observed to cut the granite as well as the wall rocks, but within short distances they fade out in the granite and are not noted very far from the border. The interior of the batholith, in fact, is unusually free from either small or large aplitic intrusions. As a rule these aplites are conspicuously free from biotite and hornblende, which gives them a notably white appearance. Locally, however, as seen in many places in the Drumlummon mine, a small amount of biotite exists, scattered in small scales through the mass, giving the rock a pepper-and-salt appearance and causing it to be classed as biotite-granite-aplite. Under the microscope it is seen to consist largely of microcline and quartz, with considerable amounts of an acidic plagioclase and small amounts of mica. Such forms appear to be intermediate between the typical alaskite-aplites and the typical quartz-diorite intrusions, also found in the mine, but lean rather more toward the alaskites. The pepper-and-salt or biotitic granites were not noted cutting the quartz diorite of the batholith, but occur as dikes and irregular intrusions at some distance from the margin, so that there is a question if they may not be outer acidic parts of the main intrusion rather than later injections, especially as aplitic segregations of the quartz diorite resembling these dikes are sometimes found near the margin and are distinct from the more clearly marked aplite dikes and sheets, which are demonstrably younger than the batholith. These relations give rise to several types, examples of which will be described in detail.

[a] For a review of this subject, see Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 720-728.

[b] Spurr, J. E., Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1898, p. 311.

[c] Lingren, W., Trans. Am. Inst. Min. Eng., vol. 31, 1902, pp. 242-244.

APLITIC SEGREGATIONS WITHIN THE QUARTZ DIORITE.

One type well exposed and studied in detail is found at the batholithic contact 0.7 mile southeast of Mount Belmont. Here a streaked or schlieren effect is noted for several feet from the contact and parallel with it, part of the banding being due to a fine-grained biotitic aplite without defined walls occurring within the normal quartz diorite. Precisely the same effect is noted at the upper end of the isolated chimney of quartz diorite immediately north of Mount Belmont, though here the cover, if once present, has been eroded. Under the microscope these segregations are seen to consist of microcline or orthoclase, quartz, some acidic plagioclase, and small amounts of biotite. Such segregations are not noted except near the immediate margin of the batholith and are not a marked feature even there. They are contemporaneous in crystallization with the true quartz diorite around them, and suggest, as has been mentioned, that the rather common marginal dikes, which closely resemble them in character, are of similar segregational origin and belong to the same period of invasion as the main rock of the batholith.

CONTACT ALASKITE BANDS.

Description.—On the road up Silver Creek to Marysville, about 200 feet east of the batholithic contact, a limestone cliff consisting of a welded breccia, mentioned elsewhere (see fig. 6), is penetrated by numerous granite dikes bearing nearly east and west and dipping steeply to the south. These dikes themselves resemble the aplitic segregations noted within the batholith, being more acidic than the normal quartz diorite, but within them are still further variations of a more marked alaskitic nature, especially along the walls, the biotite being missing from the contact zones.

Again, on the foot wall of the surface pits of the Drumlummon mine there is an irregular intrusion of the batholithic granite. (See fig. 4, p. 70.) The borders of this intrusion in places show alaskite grading on one side into the granite, while on the other side thin seams of comb quartz an eighth of an inch thick separate the alaskite from the hornstone.

The occurrence most carefully studied, however, was on the tenth level of the Drumlummon mine at the end of the east crosscut between No. 1 and No. 2 shafts. This crosscut ends in granite which has been intruded into the hornstone. The granite is of the light-colored, pepper-and-salt appearance and under the microscope is seen to consist of about equal quantities of quartz and somewhat perthitic orthoclase, with slightly smaller amounts of albite and a few flakes of biotite. This granite, therefore, clearly belongs to the aplites. Near the margin, however, the biotite disappears, nor is there any trace of its having been destroyed by later alteration. The granite shades into a white alaskite otherwise like the granite and thence into white massive quartz, which forms the actual contact. This border facies is a foot or more wide, sharply marked on the side of the hornstone, but showing a transition on the side of the granite. The hornstones have become much hardened for a foot from the contact owing to a crystallization, consisting predominantly of diopside. Within the quartz band small miarolitic cavities are noted, partly filled with secondary quartz and calcite. The igneous rock further shows evidence of shattering and recementation, the latter consisting in many places of a regrowth and healing of the quartz and feldspar crystals, so that the former shattering is observable only in plain light. In other places the lines of breakage are filled with a mosaic of quartz and feldspar. Similar instances were observed elsewhere in the mine and are a not unusual accompaniment of the intrusions, though not observable in the majority of cases. Contact bands of a somewhat different character were noted at the batholithic contact previously mentioned 0.7 mile southeast of Mount Belmont. Here a flat cover of brownish-red banded hornstones rests directly upon the quartz diorite, which shows a schlieren effect. Within 2 feet of the contact the quartz diorite includes many flakes of the hornstones with sharp margins and angles. Certain of the larger of these flakes lying parallel with the walls have narrow quartz or alaskite seams running through their middle or along the under side. Under the microscope the flakes show a coarser degree of crystallization than the hornstones of the cover.

Conclusions on shrinkage accompanying crystallization.—These contact segregations afford interesting evidence bearing on the physical conditions of the intrusions and the walls at the time of crystallization of the segregations. It is to be noted that they occur chiefly on the margins of small or irregular intrusions or, as in the case of the included flakes of sediments, against short and discontinuous surfaces. These relations suggest a contraction closely associated with the primary crystallization and very possibly due to it. The broader and more uniform surfaces during such crystallinic contraction might be held in contact by the general pressure existing within the rocks, while along the shorter and more irregular surfaces favorable conditions would be found for the formation of contraction cavities which would never be empty, but into which, as they formed, siliceous and feldspathic solutions might filter. The transition of these segregations into the main rock mass is so clear that the infiltration and crystallization must have been closely related to the primary crystallization. Consequently the open cavities could hardly have been due to loss of temperature, but rather to change of density on solidification and crystallization, presumably of the magmatic mass but perhaps in part during the metamorphism of the wall rocks. The pegmatitic texture and the transition into quartz segregations are considered by geologists as evidence of a concentration of water vapor and are, as a rule, especially prominent on the borders of large intrusions.

The contrary proposition, that segregation of a quartz-feldspar portion took place before any solidification, is not tenable owing to the fact that the peculiar form of the segregations as described indicates contraction cavities, and also owing to the highly siliceous nature of the material in many places. The contraction effects during solidification and cooling have been observed and measured in the laboratory by Delesse, Cossa, Barus, and others, and their results are summed up by Daly.[a] They show that the crystalline rocks are from 7 to 10 per cent denser than the glassy form of the same rocks, and Barus found that molten diabase in solidifying to a glass at the same temperature gave rise to a still further shrinkage of 3.9 per cent.

It would seem, then, that there is good experimental evidence indicating that on the solidification and cooling of magmas a very marked shrinkage must result.

[a] Daly, R. A., Mechanics of igneous intrusion: Am. Jour. Sci., 4th ser., vol. 15, 1903, pp. 273-281.

The question is, Why are there not more evidences of this in nature? It is probable that some of the evidence has been frequently overlooked or misinterpreted and that a great deal of the diminution of the magma volume is obscured by the fact that the surrounding rocks are under sufficient pressure to prevent the formation of open cavities.

POST-BATHOLITHIC APLITIC INJECTIONS.

Description.—The marginal aplitic segregations previously treated are of contemporaneous formation with the normal rock of the batholith. The contact bands are also of equal age with the adjacent granitic masses, though since they belong usually to isolated intrusions within the hornstone their exact relations with the larger mass of the batholith can not be proved. The next group to be considered comprises those dikes or sills which by cutting the rock of the batholith itself or associated dikes of aplitic granite show themselves to be younger than either. Such younger sheets may be seen at the granite contact by the roadside east of Marysville. Here the sheets, which dip about 20° NE., are branching and wavy in form and from 6 inches to a foot in thickness, cutting both granite and hornstone. At one point the aplite is seen to have insinuated itself along various joint planes of the hornstone, apparently isolating portions of the sedimentary rock with very little disturbance of their dip and strike. Two hundred feet east of this point alaskite dikelets are observed to cut the plexus of biotite-granite dikes which have been previously mentioned.

The several larger intrusions exposed in the railroad cut east of Marysville are cut by aplite dikelets, and the large dike of porphyritic granite exposed near the Big Ox mine, more than 2 miles north of the batholith, is also cut by distinct seams of aplite. Such seams are not found in the intermediate sedimentary formations nor in the microdiorite sheets and dikes, though noted in the large intrusions of gabbro in the northwest corner of the area, where they are, however, poorer in quartz and richer in soda than those related to the batholith. Around the batholith these snowy white aplites are found more abundantly in the zone of sediments immediately surrounding the batholith than in the granite itself, and may be especially well noted in the hornstone of the Drumlummon mine. Here it is, of course, impossible to draw a certain line between those which may be contemporaneous with the batholithic invasion and those which belong to a later stage. It seems more likely, however, that the snowy white varieties, which show little or no evidence of having at any time contained black mica, belong to the younger group. As shown on the geologic maps of the Drumlummon mine (Pls. VIII–X, pp. 68, 70, 72), their forms of intrusion are extremely irregular.

Conclusions as to origin and age.—The most characteristic features relating to the origin of these aplitic injections are found in their well-defined walls, their uniform sugar-granular texture, and their association with the marginal zone of the batholith or with outlying intrusions of considerable volume and granitic texture. The most reasonable explanation of their origin would appear to be that after the solidification of the batholith to some little depth, shrinkage due both to crystallization, which in some magmas has been shown to amount to as much as 14 per cent, and to cooling would result in a tendency to form contraction fissures, especially near the margins of the batholith, as the granite would there tend to draw away from its walls. The residual magmatic liquor of the still incompletely solidified portions of a somewhat lower level would be squeezed upward by the general pressure into the zones of greatest relief from pressure and would seek, therefore, the marginal sediments and outlying granitic intrusions. The fact that these rocks were still in a heated condition would allow the development of the holocrystalline texture. That these intrusive aplites are not merely segregations or injections from the immediately adjacent quartz diorite is shown by their irregular and concentrated distribution, by their considerable local volume, and by the fact that to a large extent they lie within the walls, but here and there cut the granite.

PEGMATITES.

The pegmatites occur both as segrégations and as dikelike intrusions in the border zone of sediments. As segregations they may be noted in the railroad cut 1,100 feet east of the Marysville trestle. Here in a dike of acidic granite 75 feet wide a pocket 2 by 3 inches is noted filled with fairly coarse-grained quartz, feldspar, and epidote. In this same vicinity may also be noted a few narrow aplite dikes grading into pegmatite in the center, one such dike 6 inches in width showing 3 inches of pegmatite.

In the Drumlummon mine pegmatites are frequently noted, mostly in irregular dikelike intrusions a few inches in width. Within these many of the orthoclases are an inch or more in diameter, with micropegmatitically intergrown quartz; a fair amount of well-developed albite, in places perthitically intergrown with orthoclase, is also present. Both orthoclase and quartz show in many places a tendency to a vein structure by possessing an elongation perpendicular to the walls. They form bundles of slightly divergent sheaflike crystals, but there is no development of crystal faces and, in the case of the quartz, the vertical axis is not in the line of elongation. Muscovite, where present, shows a tendency to stand in plates perpendicular to the walls and is locally interlaminated in sheaflike bundles with the quartz. In places the pegmatite passes into richly quartzose bands.

DISTINCTNESS OF PEGMATITES, DRUMLUMMON PORPHYRY, AND FISSURE VEINS.

Although the features discussed in the preceding paragraphs may indicate that the pegmatites lean in their nature toward the vein quartzes, there is no reason to believe that they are in any way closely related to the ore-bearing fissure veins associated with the batholith margin. On superficial examination such transitions may be suspected, from the proximity and common siliceous nature of the dikes and the veins, yet the microscope always clearly separates the two, since the ore-bearing fissure veins nowhere carry feldspar.

The relationship of the pegmatites to the Drumlummon porphyry dikes is not shown by mutual intersection, but the theoretically close association of the pegmatite intrusions with the primary crystallization of the granite and their relationship to the aplites, when contrasted with the micrograniticgroundmass of the porphyries, which show evidence of injection into comparatively cool walls, unite in giving some degree of confidence to the conclusion that the porphyries, which are younger than the granite, are also younger than the pegmatites. Since these porphyries are, however, older than the gold-bearing fissure veins, it follows that the veins are considerably younger than the pegmatites, sufficient time having elapsed between the formation of the two for the intrusion of the Drumlummon porphyry dikes.

BASIC DIKES OF POST-BATHOLITHIC AGE.

GENERAL DESCRIPTION.

Twelve hundred feet east of the railroad trestle over Silver Creek at Marysville are two vertical dikes about 50 feet apart. They are both dark basic intrusives containing solution cavities filled with a sky-blue secondary mineral. One dike is 3 inches in width, the other 15 feet. The narrower is observed to cut both granite and aplite, thus fixing their age as postbatholithic.

PETROGRAPHY.

Under the microscope the rock appears to vary from a basalt to a diabase, the narrow dike consisting of about 50 per cent groundmass, while the large dike was once nearly or quite holocrystalline. Even in the latter, however, the typical ophitic structure of the diabases is but poorly developed, the crystals of pyroxene, though now destroyed, having attained some individuality in the primary crystallization. Although the thinner dike approaches a typical basalt, the two are perhaps best referred to collectively as diabases.

The plagioclase crystals from 1 to 2 mm. in diameter are basic labradorites, the composition being not far from $AbAn_2$, and, in contrast to the degree of alteration which has effected the other minerals, they preserve a remarkable freshness. In the thin dike the phenocrysts are sharply separated in size from the minute feldspars of the groundmass, but in the thick dike they approach each other in size and show all gradations from the large to the small.

Of the femic minerals, small fragments of still unaltered pyroxene, embedded in a matrix of pale green or yellow hydromica, indicate that there has formerly been an abundance of a clear, colorless pyroxene in the rock. In addition, there are numerous amygdaloids from 2 to 4 mm. in diameter filling polygonal or rounded cavities, showing a geodic lining of calcite succeeded by chalcedony, which has completed the filling. No indication of the original mineral remains.

These were the only two instances noted of basic dikes clearly younger than the batholith, but except in railroad or mine cuttings or similar favorable situations such intrusions would be easily overlooked, and if seen, the weathered portions would not be separated on a superficial examination from the much older microdiorites. It is concluded, therefore, that there are probably other representatives of the postbatholithic dikes within the district.

LAVAS OF LITTLE PRICKLY PEAR CREEK.

GENERAL DESCRIPTION.

On the northern part of the district are a number of patches, one more than a mile in length, consisting of the remains of lava streams which flowed down the Tertiary valleys after they had become well widened. The lavas solidified in places as glasses, elsewhere as breccias or as microgranitic bases carrying phenocrysts of plagioclase, hornblende, and biotite. Nearly all are now extremely altered, usually to rough, spongy, purplish-violet or pinkish-brown rocks, though in places silicified and bleached to an ocherous color by vein waters from beneath, as discussed under the heading "River gravels."

The original character of these lavas has been largely masked by these alterations, but microscopic study shows that in all cases they have been of an intermediate or basic nature.

UNALTERED LAVAS.

In describing these lavas in some detail the first patch to be noted is that of the eastern side of the district, near Old Stage Station. This forms a low hill of fine-grained, almost black rock a quarter of a mile long and 100 feet high, whose base is mantled on all sides by the alluvium of the valley. It is the only instance found within the district of lava showing an unaltered character. Under the microscope it is seen to be a glassy pyroxene andesite, consisting of about two-thirds small plagioclase-feldspar laths, none of them more than 1 mm. long, and one-third brown glass, the pyroxene being in subordinate quantity.

ALTERED LAVAS.

The other localities of extrusives are found in the northwestern portion of the district. The least altered form is a gray-violet rock, in places with a fine-grained, even texture, in places porphyritic, the former phenocrysts having been destroyed. Along joint planes, owing to the state of the iron oxide, much of the violet tint disappears and gives place to a buff color, the iron being partly removed and that which remains existing in the form of limonite. Usually the absence of shaly lamination and the cellular character due to the former presence of phenocrysts serve to distinguish these lavas from the similarly colored Greyson-Spokane shales upon which they rest, but in some places a critical field study is necessary in order to separate the two. Under the microscope, however, the distinction will always be clear, as the igneous character of the groundmass is evident.

The more altered portions are completely silicified and bleached to a buff or whitish gray and are associated with the silicified gravels and localities of brecciation and mineralization previously discussed (see p. 36), one prominent area forming the high hill north of Sanford's ranch and the other the mesa north of Procter's. As the base of the silicified gravels is composed largely of lava blocks but slightly worn and recemented, close observation is necessary to separate the two formations where they lie in contact.

Under the microscope the rocks are seen to have possessed a groundmass of andesitic character, but in the more altered lavas this, as well as the phenocrysts, is completely destroyed and a secondary fine-grained mosaic takes its place, while solution cavities are lined with microscopic crystals of quartz. The original character of these rocks is best seen in plain light. It is probable that they were all andesites and are to be grouped with the pyroxene andesites described as occurring near the eastern border of the district. Fragments taken from the silicified gravels seem to possess rhyolitic affinities, but as the rocks have been so completely altered and these cobbles had been carried some distance from their original outcrops the evidence derived from that source is weak.

AGE RELATIONS.

The age relations of the lavas of Little Prickly Pear Creek may be determined from a study of their associations. It is noted that in places the outcrops lie between the Tertiary gravels and the Greyson-Spokane formations. The sheets are nowhere of great thickness, and the gravel over most of their area lie directly upon the shales. This shows that after the lavas flowed down the valley they were largely removed by erosion before the deposition of the gravels, and that the form of the ancient valley was nearly the same at the time of the lava flows as at the time when the filling in of the river bed began.

It is concluded, therefore, that after the valley had become well widened out and the topography had reached a state of relative maturity these lava flows took place, accumulating to a moderate depth. This was followed by a period of erosion long enough to remove the lavas in great part, but not to radically alter the valley contours nor deeply trench its bottom. Finally came the great disturbances which destroyed the old drainage adjustments and resulted in the accumulation of a great depth of gravels. The relation to the intrusive rocks is also clear. As in places the lavas rest directly upon the coarsely crystalline gabbros, a long interval had evidently elapsed between the origin of the two, during which erosion had bitten to some depth into the shales and beveled off the gabbro intrusions which they contained. That a long period of erosion had also elapsed between the time of the batholithic intrusion and that of the lava flows is seen on considering the relative elevations of the two. The patch of lava forming the hill near Old Stage Station is visible as low as 4,300 feet in elevation, while at a distance of only 4 miles the rock of the batholith still reaches in places an elevation of nearly 7,000 feet. It is improbable that this great reservoir of molten rock could be held at least 2,700 feet above the level of a valley so near by without rupture of the walls and the welling forth of a great lava flood. It may be concluded, therefore, that a period of erosion allowing the removal of at least several thousand feet of sediments intervened between these two events.

CHAPTER III.

STRUCTURAL GEOLOGY OF THE MARYSVILLE DISTRICT.

CONTACT SURFACES OF THE BATHOLITH.

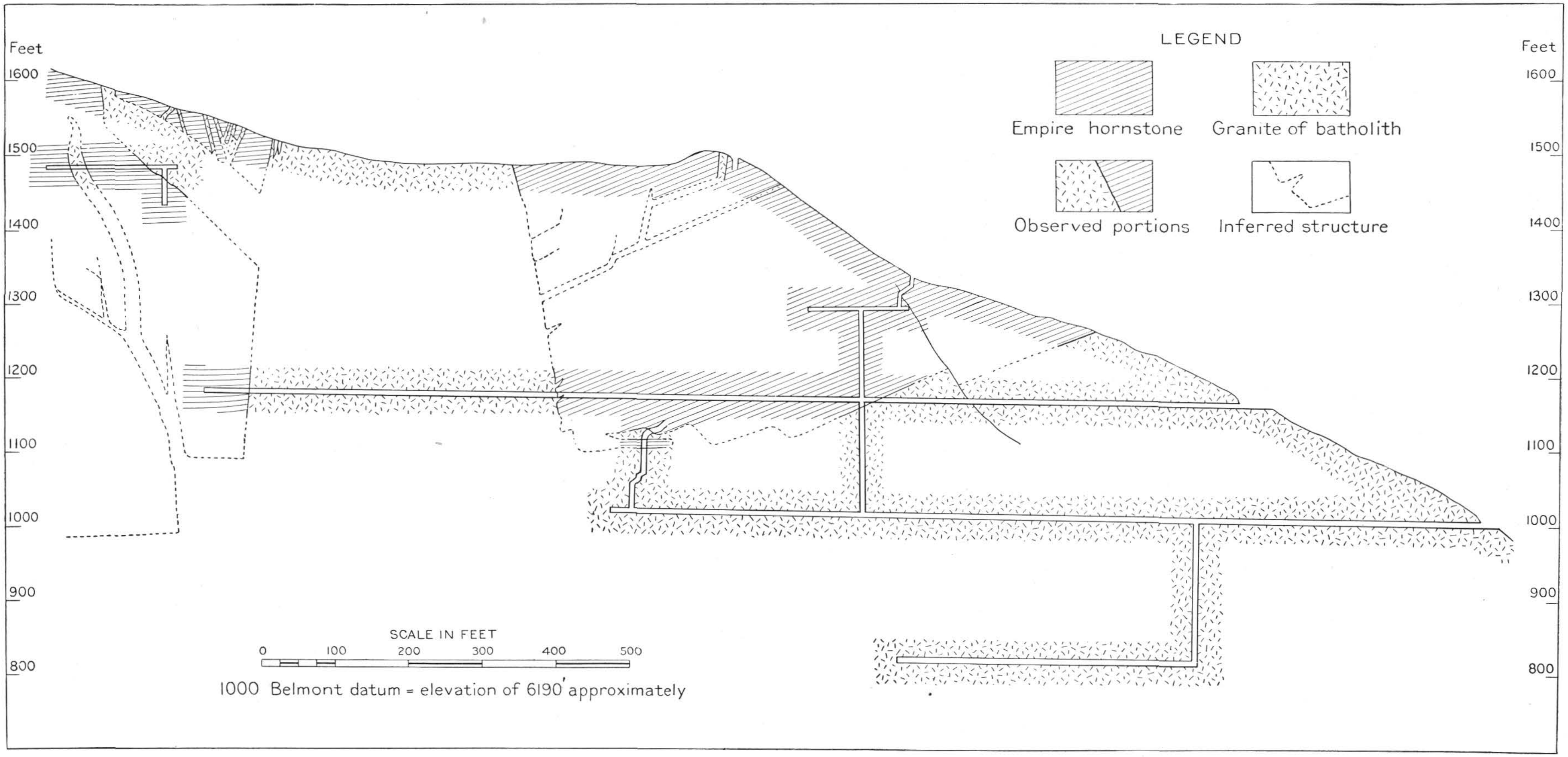
INTRODUCTORY STATEMENT.

The development of mines on the vein systems of the Marysville district, which are associated with the metamorphic zone of the sedimentary formations and the marginal portions of the batholith, has allowed unusual opportunities in a number of cases for studying the underground contact relations and comparing them with those of the adjacent surface. These opportunities, combined with the mountainous character of the region, have made it possible to work out with great detail the form and characteristics of the intrusion to an exceptional depth, rendering the subject worthy of fairly extensive treatment, especially as the manner of intrusion must be chiefly determined from a study of the contact relations. The methods of intrusion will not, however, be touched on in this chapter. A number of localities will first be described in detail, and then a review of the whole subject will be made to point out and classify the most essential features.

BELMONT MINE CONTACTS.

The Belmont mine is situated on the eastern slopes of Mount Belmont. The principal vein, bearing nearly west, is at right angles to the contact and has been developed for a length of 2,000 feet and to a depth of 700 feet from the higher parts of the surface, giving a section across the contact, as shown in Pl. VII.

The surface relations are also clear. From the geologic map it is seen that an arm of the hornstones projects northeastward from the main walls to a distance of nearly half a mile, being intersected by the Belmont vein. At the surface the slope of the contact around this arm is exposed at a number of places, the northeast end being cut off vertically. On the eastern hill slope is a prominent flat-topped buttress of granite, forming the eastern contact of the arm; the upper surface, parallel to the bedding of the hornstones, dips west under the hornstones at an angle of 25° and is perfectly smooth and regular over considerable distances. In many places the bottom stratum of the sedimentary cover still remains capping the granite. The mine workings (see Pl. VII) show that the granite slopes under the hornstones maintain the same character as at the surface, and indicate that this arm is nowhere more than 400 feet in depth. The section shows that the granite contact, although smooth and parallel to the bedding, breaks across from stratum to stratum. The western side of the arm is found, by joining the surface and underground contacts, to slope



CROSS SECTION THROUGH BELMONT MINE.

Looking northeast. Plane of section, N. 60° W.

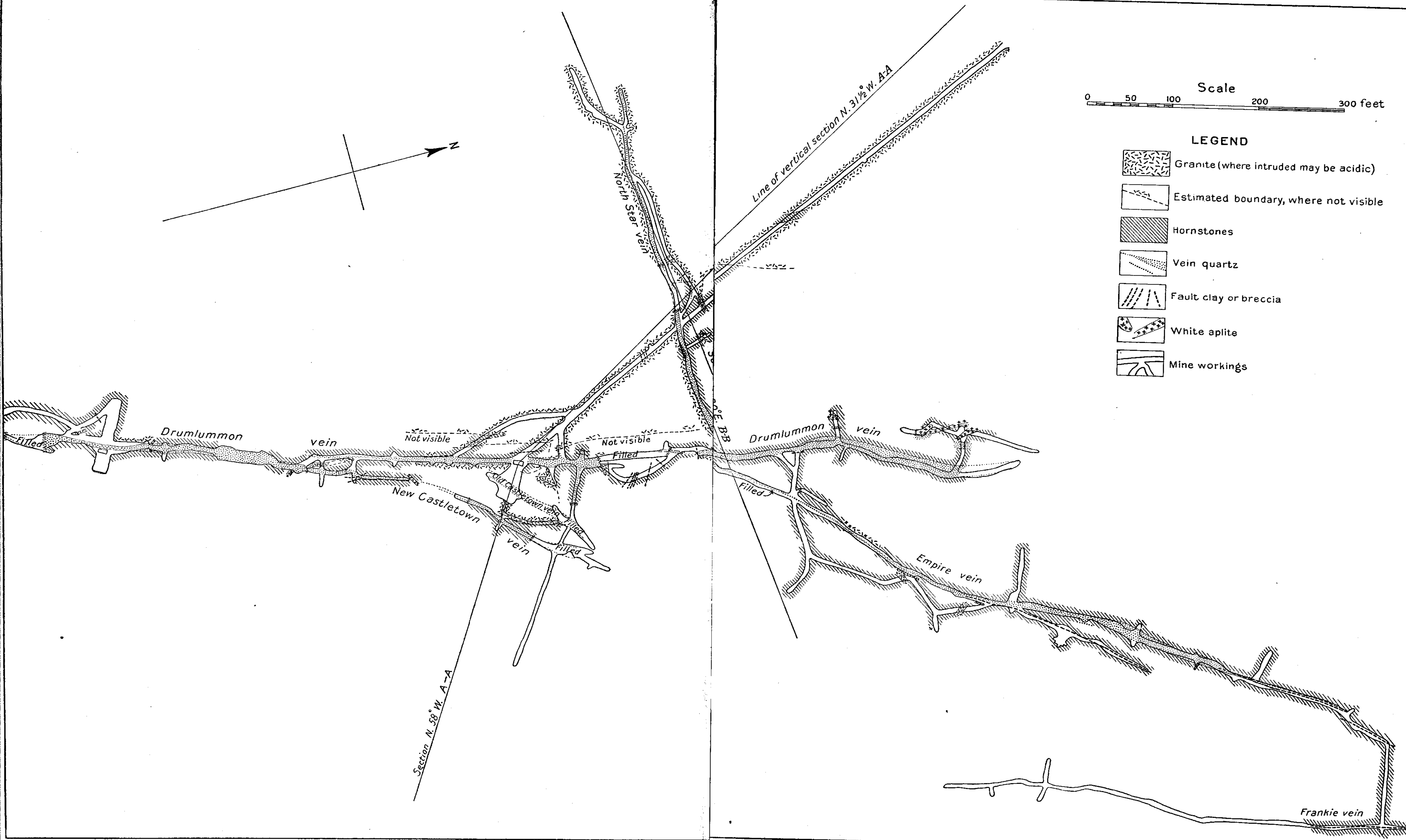
at an angle of 80°, the peninsula of hornstones being separated from the main walls by a dike from the batholith 300 to 500 feet wide at the surface and of somewhat greater width below, the dike showing a more basic character and a porphyritic facies. In contrast to the bottom contacts, which are smooth and regular with very few stringers penetrating the cover, on the east side the dike walls or vertical contacts, where exposed on the second level, show flat and irregular tongues projecting into the hornstone, and on the west an alternation of hornstone and granite indicates a splitting and penetration of the walls. The same feature is more strikingly shown at the surface, where, on the plane of the section, slabs of hornstone are held within the porphyritic granite dike to distances of 100 feet from the walls, while the batholith is remarkably free from such inclusions. A number of porphyritic dikes parallel to the walls occur close to this dike on the Mount Belmont side also. In the West Belmont mine the contacts show that an irregular intrusion has been pushed into the hornstone at a considerable angle to the main walls. This intrusion may be likened to the forward part of a ship's hull, heeled over so that one side is vertical and the other dips at an angle of 60°. As the section line cuts it at an oblique angle, it is shown on the plate as a large flat intrusion just below the surface. In contrast to this west wall the hornstone peninsula contains very few intrusions, only two being encountered on the plane of the section, one 10 feet, the other 5 feet wide. The dip of the strata, 23° to 28° NW., in contrast with the nearly flat dips of the adjacent hornstones, indicates a tilting which is partially explained by the greater thickness of the deeper portions of the dike, as shown in the section.

The exact depth of the main west wall of hornstones is not known, as is indicated by the dotted lines of the section, but it is concluded that it probably does not extend deeper than shown, from the fact that the contact line, as shown on the geologic map, skirts around Mount Belmont at elevations of 6,500 to 6,600 feet and in general dips beneath the hornstones at angles of 5° to 10°.

In the section those parts which could not be directly observed are indicated by dotted lines. There is of course some liberty of interpretation as to their detailed nature. They have been controlled by the points actually observed and a general study of the nature of the contact as seen here and at other places where the details were well exposed.

DRUMLUMMON CONTACTS.

The workings of the Drumlummon mine, immediately south of Marysville, furnish information of the character of the batholithic contact to a depth of 1,600 feet. The Drumlummon vein is approximately parallel to the margin of the batholith, while the North Star vein is nearly at right angles, allowing sections to be constructed in both directions. Such sections are shown in Pls. IX and X, the place of these on the mine workings being indicated in Pl. VIII. The detailed relations are exceedingly complex, but the most striking features will be first pointed out and then the smaller ones of greater complexity.



GEOLOGIC MAP OF FOURTH LEVEL, DRUMLUMMON MINE.

SEDIMENTARY COVER OVER GRANITE OF MAIN TUNNEL.

A study of the geologic map (Pl. I) and of Pls. VIII, IX, X, and fig. 2 shows that over the line of the main tunnel a wedge of hornstone projects outward about 700 feet at a horizontal angle of 30° to 45° to the general trend of the contact, but does not result in any topographic prominence. As shown in Pl. XI, both to the north and south of this promontory of hornstone the granite dips into the hill at an angle of 40° and is conformable to the bedding of the hornstone. At the entrance of the main tunnel, as shown in Pls. VIII and IX, the outlying hornstone mass does not continue downward, but overlies the granite at a flat angle which is approxi-

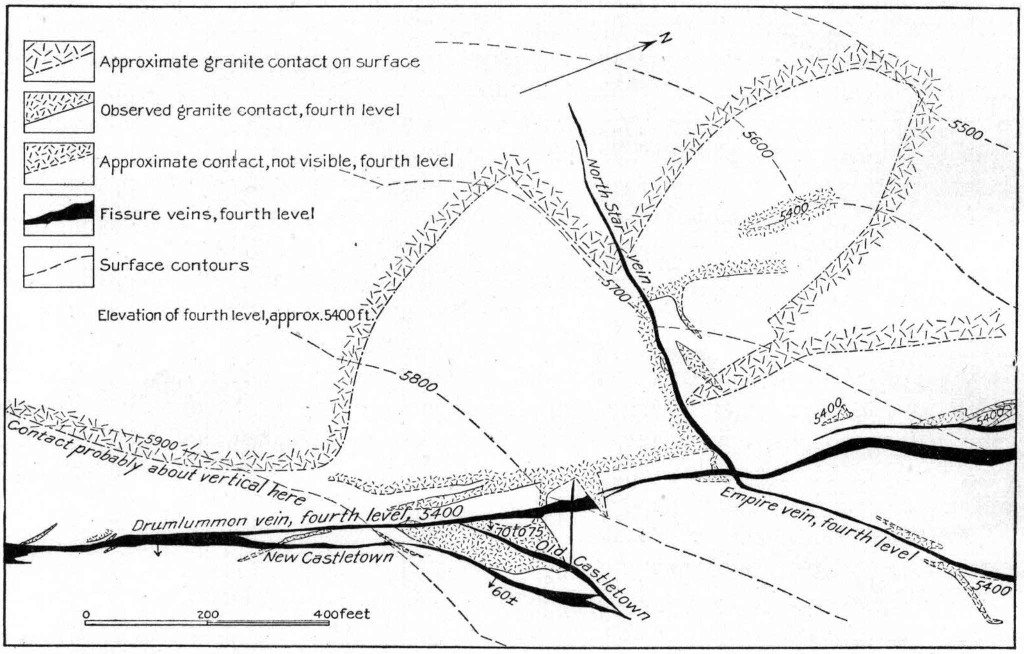
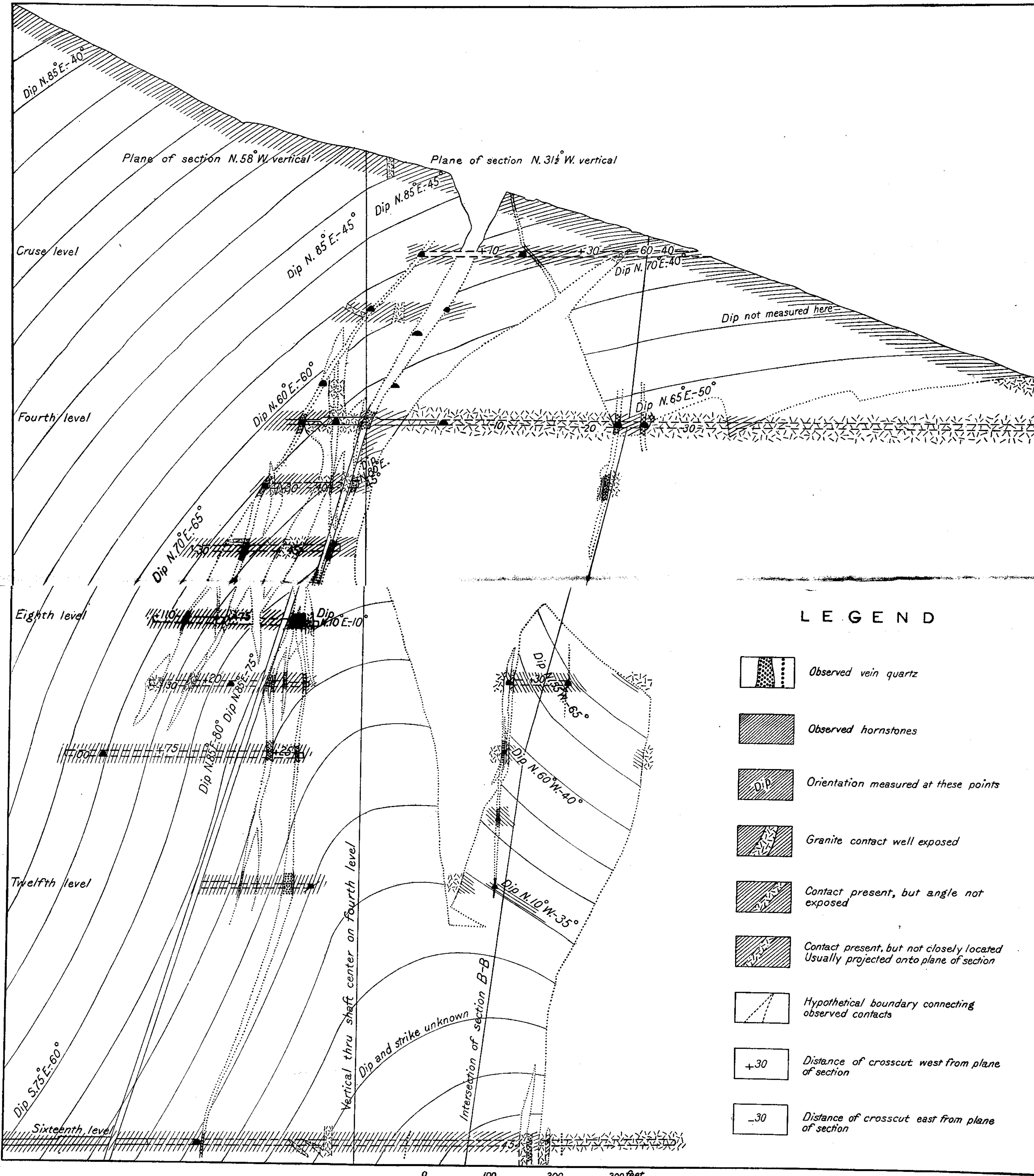


FIG. 2.—Sketch map showing approximate relations of granite boundary between the surface and fourth level, Drumlummon mine.

mately parallel to the bedding planes. Within the tunnel, about 650 feet from the entrance and 450 feet beyond the surface contact, the first hornstone is encountered, being merely a slab about 30 feet thick, then 120 feet of granite followed by 140 feet of hornstone, represented by only 50 feet on the exact plane of the section. Beyond this is over 300 feet of granite before the final walls of hornstone are encountered. The dip and strike of the hornstones forming the cap correspond with those of adjacent portions of the main body, indicating that there has been no great degree of disturbance. As the granite which covers 300 feet or more between the North Star and Drumlummon vein does not reach 250 feet above, on the Cruse tunnel, it can not extend far vertically, and the small amount of hornstone cut near the North Star vein is to be regarded as resulting from a downward roll in a continuous roof.



VERTICAL SECTION (A-A, PL. VIII), DRUMLUMMON MINE.

Section through main tunnel and shaft; looking southwest. Planes of section, N. 58° W. and N. 31½° W.

INTRUSIVE WEDGE OF GRANITE BETWEEN NORTH STAR AND DRUMLUMMON VEINS.

The next most striking feature is the wedgelike form of this granite between the North Star vein and the main shaft, which, as shown on the plan map of the fourth level (Pl. VIII) projects inward nearly 300 feet between the North Star and Drumlummon veins almost to the intersection of the two, giving a Z shape to the general trend of the hornstone contact. That this has not been done on the fourth level by merely wedging the hornstones horizontally apart is indicated by the fact that the dips and strikes on the two sides of the wedge approximately correspond. If it is suggested that a fault occurred along the course of the North Star vein by which the hornstone on the north side was brought to the level of the granite on the opposite wall, it may be pointed out that on the fifth level there is no evidence of extensive faulting along the plane of the vein, since a large granite dike cuts across the vein without being offset.

The shape of the lower part of this wedge is not known, since no crosscut exists between the two veins between the fourth and sixteenth levels, but the exposures of the North Star twelfth level indicate a considerable thickness of granite at that point. On the sixteenth level crosscut the wedge of granite is not cut, although the crosscut is almost vertically below the fourth-level tunnel, where the thickness of granite intersected was 300 feet. If it extends to that depth, therefore, the front must slope back under itself at an angle upward of 10°. The outer confining wall of this granite wedge is broken through at the seventh level, as shown in Pls. IX and X. From the ninth to the twelfth level it appears again, but the projecting portion, in contrast to that exposed on the fourth level, has here a widely different orientation of the bedding planes from that found within the main mass of the hornstones, the strata dipping steeply toward the batholith, while the normal dip is in the opposite direction. As interpreted on the sections this may be explained by supposing the magma to have entered from the southwest and to have twisted this block about 60° to the west round a vertical axis and also tilted it over about 30° toward the batholith.

The general character of the contact at the Drumlummon mine is therefore steep and irregular for a height of a quarter of a mile, from the sixteenth to the fourth level, the granite above this steep wall being overlain by a hornstone cap projecting over the batholith for 500 feet from the main walls at a flat angle.

DIKES AND IRREGULAR INTRUSIONS.

Next to the general contact the most noteworthy feature consists of the granite intrusions more or less parallel to the main walls and the Drumlummon vein. An inspection of Pl. IX and the several level maps, the latter not reproduced in this report, shows that even the larger of these intrusions are not regular for considerable distances, but are rolling in dip, swelling, branching, and pinching out, while the smaller masses are of all shapes and penetrate at all angles. The intrusions are most abundant and of greatest thickness from the fourth to the tenth level. There is a tendency for the dikes to branch, the branches usually sloping downward away from the batholith. A considerable number of dikes, however, dip toward the batholith, the hornstones being thus intersected in several directions. The smaller intrusions are apt to finger out and show very blunt or rounded ends. The form of these is shown in figs. 3 and 4. The intrusion shown in fig. 4, which occurs near the surface on the foot wall of the Drumlummon vein, was especially favorable for study since the decomposition of the wall rocks allowed the varying inclination of the contact surface to be determined, as is indicated in the figure. There is a great deal of granite present in the vicinity on both the foot and hanging walls, and this small intrusion is evidently an irregular lobe which was cut off by the vein fissure from a larger mass. In contrast to the abundant intrusions of the upper levels the twelfth and lower levels show but few, mostly narrow and wedgelike.

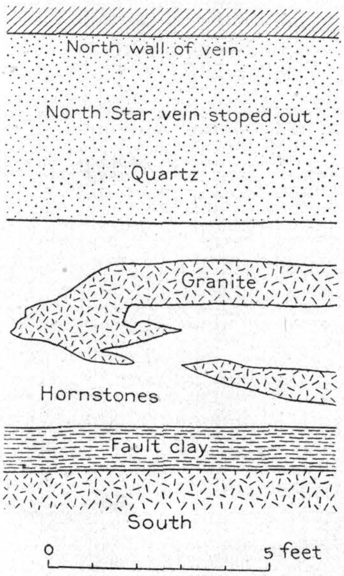


FIG. 3.—Irregular intrusion of granite on roof of drift, tenth level, North Star vein, Drumlummon mine.

COMPUTED DIPS OF THE CONTACT SURFACE.

Where a promontory of hornstone juts into the batholith it may be interpreted either as a cover overlying the granite, as was shown to be the case at the Belmont and Drumlummon mines, or as a vertical buttress extending downward with the same horizontal outline. Where certain of the gulches, however, expose the granite along their bottoms to a greater distance from the central parts than is shown on the intervening hills, there is a strong presumption that the bordering hills are the margin of a sloping cover which has been trenched by the streams rather than that the contact is an irregular vertical surface with wedgelike extensions which are coincident in position with the radial valleys developed on the surface. This interpretation is reenforced by observation at a number of places around the batholith where the contact angle could be observed, and therefore the slopes of the contact surface may be computed from the depth of the gulches and the resulting deviations of the granite outcrop. This has been done at favorable places and the results recorded in Pl. XI, with a plus and minus sign following, as they do not have the same degree of certainty as those dips which have been directly observed.

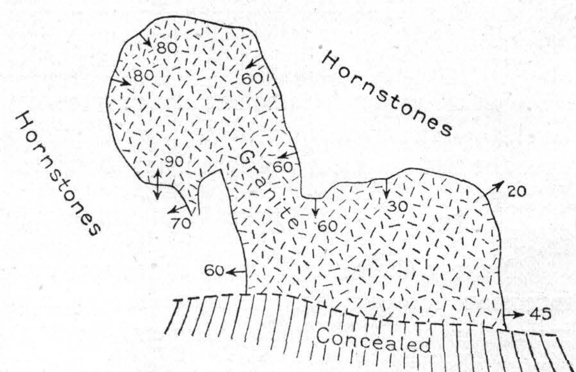


FIG. 4.—Side view of irregular intrusion of granite, foot wall of Drumlummon vein, surface pit.

The fact that these computed dips of the contacts check up in those cases where the actual dip could be observed gives them strong value as supplemental evidence on the general nature of the contact, but the method is liable to error in any individual instance, owing to a possible angle in the contact surface at that point.

Individual cases must therefore not be used for purposes of argument, but in the aggregate the results will be largely true.

From the straightness of the outcrop for a mile across Edwards Mountain and the fact that it bends slightly outward over the higher parts of the divide, it is concluded as probable that the contact surface is here nearly vertical and slopes inward toward the granite at an angle of about 70°. In the same way it is concluded that at Gloucester the contact slopes westward at an angle varying from 25° to 30°.

As the contact skirts around Mount Belmont at nearly the same elevation, it is computed that the general contact slopes under the mountain at an angle of about 5°, a figure which corresponds closely with several recorded dips in places where the contact can be observed. Again, the computed and observed dips concur in pointing to a slope of the granite surface of about 15° S. in Ottawa Gulch.

On Edwards Mountain the slight bow of the contact toward the summit, taken in relation to the two side slopes of the mountain, makes it possible, or even probable, that here the contact for some hundreds of feet in depth slopes southwestward at an angle of about 70°, making the batholith here slightly broader on this side above than below. This inference is strengthened by a study of the drainage

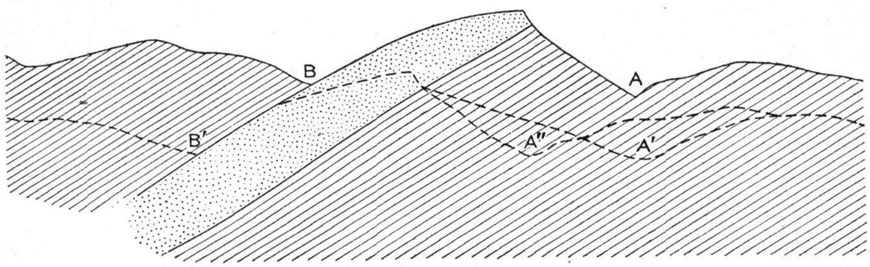


FIG. 5.—Relation of consequent stream courses to resistant formation with slanting dip during progressive erosion.

systems. Drinkwater Gulch is observed to flow for half a mile closely on the granite boundary, while the other streams, Jennies Fork and Ottawa Gulch, whose courses have become adjusted parallel to the contact during the erosion of the overlying rock, flow on the average a quarter of a mile from the contact surface. The general physiographic problem of the development of the drainage system is discussed later, but it may be observed here that the hornstones are more resistant to erosion than the granite, and it is known that in general denudation a consequent stream—that is, one whose course is determined by the structure—flowing parallel to a resistant formation having a slanting dip will on the upper side follow the outcrop and with further erosion tends to be crowded down the dip, as shown in B, fig. 5. On the lower side, however, erosion tends to keep the stream at least a certain distance away from the hard formation. As shown at A, fig. 5, a talus slope of not more than 30° to 40° will stretch up from the stream to the outcrop of the hard formation, giving the minimum distance between the two. On further erosion the stream will sink to a lower level, A′, which in a homogeneous rock will tend to be almost vertically below the old course, but which even if following down on the same stratum, as at A″ will be no nearer the hard formation than before.

In the case of Drinkwater Gulch the problem is not so simple, as the stream is developed on the side of a general mountain slope and would tend to be crowded downhill by the greater amount of wash from the uphill side. Still, the steepness and height of the wall on the north side of the stream make it seem probable that its close adjustment to the contact is due to the fact that the hornstone wall is either vertical or dips steeply to the southwest.

The evidence of the observed and computed dips is limited to the depth exposed by stream trenching. Below that depth the slope may abruptly change in character. It is shown later that from the evidence of the metamorphic zone it is highly probable that although at Ottawa Gulch the observed and computed dips gave a flat contact, immediately to the south the contact plunges down steeply for some thousands of feet. On the other hand, although the contact crossing Edwards Mountain is presumably steep, the whole mountain is probably underlain at no great depth by granite, indicating a change from a steep to a flat contact.

CLASSIFICATION OF CONTACT SURFACES.

The two localities where fullest observations could be secured have been described in detail. There are many places, however, around the margin of the batholith, as shown in Pl. XI, where the character of the surface could be studied. In describing the characteristic features of these contacts it will be well at the same time to classify them into types.

STEEP CONTACTS.

_n the Belmont and Drumlummon mines the contacts could be followed in depth, showing that the walls may stand at a high angle for many hundred feet. They are somewhat irregular, and in many places the hornstone against them shows evidences of disturbances, presenting the appearance of having been mashed and penetrated by the granite. Short, irregular tongues of the granite may penetrate a little way into the wall. Dikelike intrusions, more or less parallel to the main walls, are abundant; but as these pinch out and largely disappear with depth they appear to be intrusions whose material has entered from a small depth below and not independently from a great depth. In the Drumlummon mine the steep wall terminates against a flat roof, though the parallel dikes penetrate this roof to a certain extent. In the Belmont mine the steep walls belong rather to a dike 300 to 400 feet wide, which penetrates a flat roof.

Along the walls of the porphyritic Belmont dike there is a gradation from the hornstone split by dikelets to slabs of hornstone isolated within the main dike itself, and the same feature may be observed to a limited extent on the North Star workings of the Drumlummon mine.

BLOCKY CONTACTS.

The contact of blocky character is best seen at the east end of the batholith, just north of the road along Silver Creek, where excellent exposures may be studied on the steep and rocky hillside. A sketch of this contact is shown in fig. 6. The irregular outline is bounded by a system of joint planes found in the adjacent hornstones, it being noticeable that the bedding plane is not followed in this instance.

The hornstones appear to have been removed in blocks, and the granite maintains its normal character up to the immediate contact and in all the recesses. Aplite dikelets cut across both the granite and the hornstone.

FLAT CONTACTS.

The flat contacts wherever observed have followed the bedding planes of the hornstones. Though they step off from stratum to stratum, and therefore where observed over considerable distances, the contact and the bedding planes are not strictly parallel. They are found at all angles from the horizontal up to 40°. Besides the places mentioned at the Belmont and Drumlummon mines there are excellent exposures on the slopes of Drumlummon Hill, 1.34 miles southeast of Mount Belmont, and others are to be seen on the hillside 0.7 mile southeast of the summit of Mount Belmont. The dip of the hornstone cover in these localities is from 6° to 10°, and the contact surface may be followed for some distance. In both localities a marked schlieren effect was noticed, extending 3 to 10 feet from the hornstone surface, the normal granite showing light and dark segregations arranged parallel to the contact and giving a gneissoid appearance. This marginal feature, however, is uncommon and was noted only at a few of these very flat contacts.

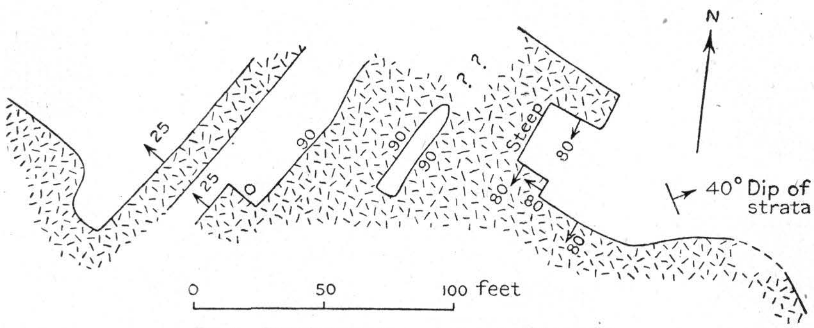


FIG. 6.—Detail of granite contact east of Marysville.

On Drumlummon Hill the contact was strictly parallel, and no inclusions of splinters or fragments of the hornstone were noted in the granite. On Mount Belmont the granite is overlain by brown and olive banded hornstones. The layer immediately against the fine-grained but otherwise normal granite is a band from 6 to 18 inches thick, of brown, lustrous hornstone which under the microscope shows a coarser degree of crystallization than the laminæ farther from the granite. The brown color, due to microscopic flakes of biotite, is changed along the seams to a pale gray, owing to the substitution of epidote. The lower margin of this band, that against the granite, is irregular and wavy to the extent of a foot. Many flat, angular flakes of this rock, averaging $1\frac{1}{2}$ inches in length, are found in the granite within 2 feet of the contact. These fragments differ from the main rock in having a coarser crystallization and apparently a greater content of feldspar, and they may grade into the darker, lamprophyric lenses present here in the granite. This represents the greatest amount of intermixture which has been found at any place along the main walls of the batholith, and it is seen to be very insignificant in quantity.

In all the observed cases of flat contacts the granite has shown little or no tendency to send tongues at right angles into the hornstone cover, and there is no such evidence of crushing and penetration as was noted at a number of vertical contacts. While this is the result of observation, the exposures of each character are too limited in number to warrant any positive general statement on the matter.

OBSCURED CONTACTS.

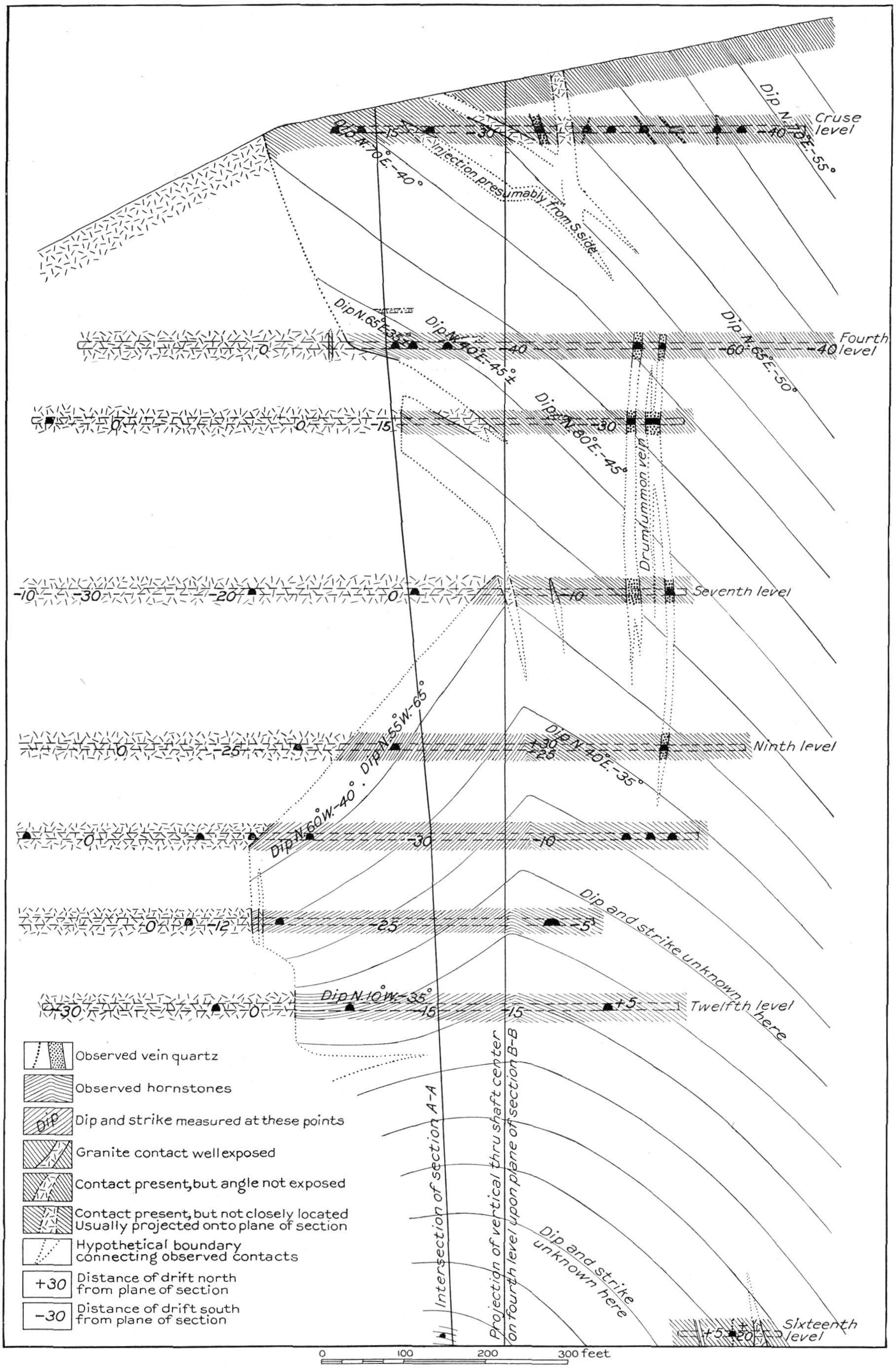
Difficulty of determination.—Although in the arid to semiarid regions of the Rocky Mountains there is a large percentage of rock exposures, and the topographically dissected and partly treeless condition of the country is ideal for detailed geologic study, yet even here there are many places where the geologic boundaries are obscured. Where these are mapped on a small scale and no question arises as to the nature of the boundary, this is of little importance. In the present instance, however, where the scale is approximately 1 mile to 2 inches and where the granite contacts are being discussed in detail as furnishing information in regard to the character of the invasion, the question of the methods used in determining the obscure boundaries becomes of some importance, and some estimate should be given of their accuracy.

In the Marysville district there are comparatively few cliffs and talus slopes of slide rock, and even the Continental Divide is mostly a thinly grassed pasture. The region has never been glaciated, and the soil is usually thin, showing a close dependence on the underlying formations. The contacts of the batholith are, however, characteristically on hillsides, since the metamorphic rim offers a superior resistance to erosion. Being so situated, they may be divided into, first, those which run more or less up and down the slope, as illustrated north of Gloucester and in general wherever a gulch crosses the granite boundary; second, those which trend approximately parallel to the hillside, as around Mount Belmont and along the Drumlummon Hill. The difficulty in locating the exact geologic boundary differs in the two cases. Intermediate between these two is a topographically oblique boundary, such as that which crosses Edwards Mountain.

In many places, as around Mount Belmont and along Drumlummon Hill, enough actual exposures were observed, so that no doubt as to the accuracy of the contacts is to be entertained, but across Edwards Mountain and around Gloucester no actual contacts are exposed, and in view of the detail which has been given to those outlines as drawn on the map some discussion of the methods used in locating them is warranted.

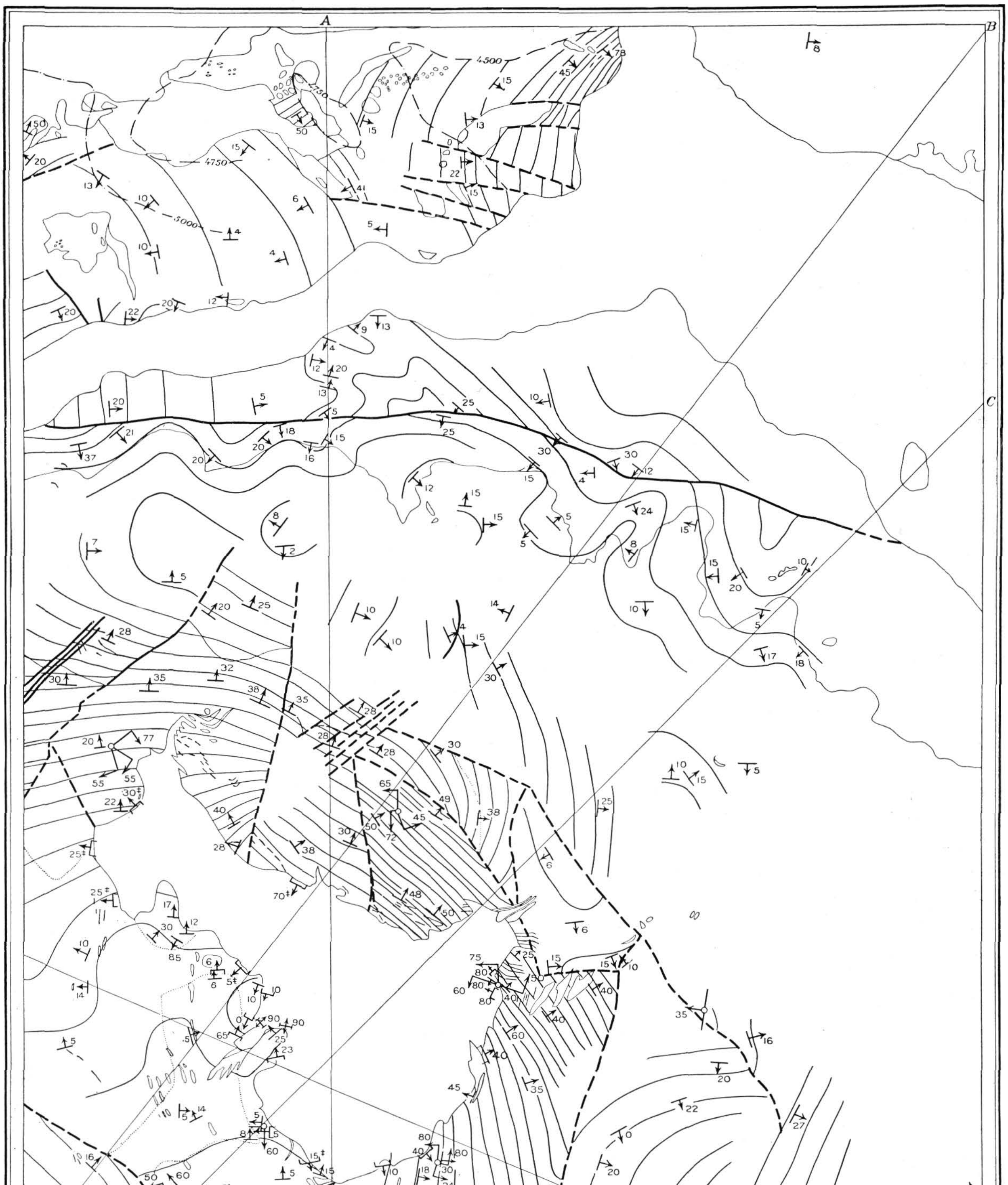
Location of outcrops through wash.—The precision of the location of formation boundaries where obscured by a surface covering depends chiefly on the angle of the slope and the thickness of the covering. Where the angle of the slope is near the angle of repose, from 30° to 40°, débris from the formation exposed higher up will slide downward rapidly as far as the slope extends. If of appreciable thickness, it will effectually mask the lower formation and render futile any efforts to locate the precise boundary.

At Marysville, on the contrary, the slopes as a rule are far flatter. Across Edwards Mountain, where the obscure contacts occur, the slope averages 16°.



CROSS SECTION (B-B, PL. VIII), DRUMLUMMON MINE.

Section parallel to North Star vein; looking north. Plane of section, N. 80° E.



EXPLANATION

Joint planes

Place where observed

Contact of batholith

Computed; others are observed

Dip and strike of sediments

Observed faults

Faults not observed but structurally necessitated

Formation boundaries

Probable boundaries between Helena and Empire

Strike contours (contour interval approx 250 ft.)

Contours of Tertiary valley bottom

STRUCTURAL MAP OF SEDIMENTARY FORMATIONS, MARYSVILLE MINING DISTRICT.

Under such conditions, if the soil is thin, there may be a fairly close relation between the superficial material and the rock beneath. Prospecting trenches and tunnels, if present, will show to what extent this is true. At this place these conditions are well met, the soil being thin and the slope sparsely grassed. A few prospecting trenches show the depth of soil covering and to what extent the surface cobbles are related to the solid rock beneath. It was seen that cobbles of granite appear on the surface a few feet below the contact and become increasingly abundant farther down the slopes. This conclusion as to the closeness of relations of soil to formation was strengthened by finding clearly defined belts of granite cobbles and soil parallel to the contact, but within the hornstone, belts which have been mapped as dikes. Most of the cobbles of granite are as large as a fist and many as large as a head. The contact in this way was closely mapped and field evidence found for every irregularity. This study showed the irregularities, but the sharpness of the angles was supplied by analogy with better exposures, where it is seen that more or less plane surfaces and sharp angles characterize the contacts of this batholith and not the smooth curves indicated on the maps of many intrusions. On Drumlummon Hill, on the contrary, the wash or slide rock is thicker on the steeper slopes which exist there, and outcrops of many dikes are effectually concealed. The boundary was there obtained directly from natural exposure and from prospecting tunnels.

North of Gloucester the general line of contact was easy to trace, since the contact runs up the slope and the downhill creep of the surface débris carries it but slightly across the boundary. The distinction between a soil of angular hornstone pebbles and one filled with granite cobbles is well defined, and the location of the line was further corroborated by the topography, drainage lines being developed near to and paralel with the contact, as at other better marked places, and the granite suffering easier erosion.

Errors of the method of locating boundaries by study of surface material.—A contact running straight uphill will have its irregularities concealed by the wash, but the general location of the boundary can be accurately determined, since there is no tendency for the surface rock to creep across the contact.

It is noticeable that the contact north of Gloucester is drawn as a smooth curve. Doubtless certain intrusive dikes and sheets, such as the one exposed at the top of the hill, have been concealed, but it is thought that the contact is, on the whole, such a curve, since the general form is best interpreted as an inclined plane cutting across the hill, and that for this reason no serious error is introduced here from the lack of direct exposures. On the other hand, a contact running parallel to a hillside would be likely to be located too far down in those places where the wash was thickest, giving more irregularity than would occur in the actual contact. This may possibly account for some of the irregularity of the line as mapped across Edwards Mountain, though from the rather distinct demarcation of the granite pebbles the error is probably to be placed at a minimum. That the contact should be smooth in the one case and irregular in the other throws no doubt on the location, since both smooth and irregular surfaces are well exposed in places. The minor details of these obscured contacts have not been used by the writer, however, in the final chapter in any arguments as to methods of invasion. It would seem, as the result of careful study in these obscured places, that the contacts can be located with sufficient precision for mapping in the indicated detail on a scale of 2 inches per mile. As an outside limit it is thought that the contact in the absence of ledge outcrops is ordinarily determinable in this region within 100 feet horizontally, if not closer. This is about 0.04 inch on the scale of the map, and is an error no greater than is often liable to arise from the ordinary use of the compass and aneroid.

DIKE AND SHEET EXTENSIONS FROM THE BATHOLITH.

The evidence of the mine sections in regard to the general form of a few wedgelike and dikelike extensions from the batholith has been given, but on the surface the underground form and structure must be interpreted from surface relations. Where an arm disregards the topography and runs straight up or down a hillside, as at the extreme north end of the batholith, the inference is that the form is that of a wedge-shaped dike penetrating the walls or roof. Where, however, apophyses show a relation to the topography, either following the contours or changing direction with a change of slope, the inference is that the form is that of sheetlike penetrations. Such flat intrusions are observed to occur near the base and beyond the summit of the dikelike apophysis just mentioned.

An inspection of the map will show a number of such occurrences. In a few places, but by no means everywhere, the granite in these arms passes into noticeably more basic and either uniformly fine-grained or porphyritic facies. One such occurrence is to be noted in the large dike cut by the Belmont section and another is found on the slopes of Edwards Mountain.

OUTLYING DIKES, SHEETS, AND CHIMNEYS.

Outlying portions of the batholith in the form of dikes and sheets which may be traced into it have just been described. Under the present heading will be treated those intrusions which while not traceable directly into the batholith yet from closeness of association or from chemical and mineralogical composition are judged to have underground connections with the same igneous mass and to have been intruded approximately at the same time.

DIKES AND SHEETS ASSOCIATED WITH THE CONTACT.

The nature of dikes and sheets associated with the contact has been discussed as they occur in the Drumlummon mine. Similar dikes may be found at many places near the margin, most commonly within a thousand feet of the outcrop of the main body. An excellent exposure of these dikes lies in the canyon of Silver Creek, about 200 feet east of the main contact. The limestone cliff consists of a giant breccia, the fragments, from 1 foot to 8 feet in diameter and of diverse character, having been pressed into a welded mass without interstices, as shown in fig. 7. A nearly vertical network of dikes, bearing east and west, and from a few inches to 3 feet in width, cuts this welded breccia in wavy lines without regard to the junction lines between the blocks. In composition the igneous rock of this locality is largely an acidic granite porphyry, with alaskite segregations, especially as marginal bands, and the whole is cut by later alaskite dikelets. The freedom from crushing shown by the dikes would indicate that their intrusion was later than a time of brecciation followed by a time of flowage and welding.

Another series of intrusions closely related to the batholith consists of a number of sheets, 1 mile N. 20° E. from the town of Gloucester, dipping to the north and away from the batholith but conformable to the stratification of the strongly metamorphosed hornstones. Again, northwest of these are a number of small granite dikes bearing east and west and associated with a rather conspicuous quartz vein. In composition and in granularity these approximate to the batholith, the northern wedgelike point of which is less than half a mile distant.

To turn to more distant occurrences, on the hill containing the Big Ox mine, $2\frac{3}{4}$ miles north of Marysville, is a dike of quartz diorite about 500 feet in length dipping to the northwest at an angle of 70° to 80° and cut by seams of aplite. This dike is so thoroughly granitic in texture that it does not show even as much of a porphyritic facies as the sheets only a quarter of a mile from the batholith, northeast of Gloucester, and in composition also it shows a striking approach to the normal type of the batholith. The hill to the north is of highly altered hornstone, forming a metamorphic zone far beyond the power of such a dike to produce. These features point almost conclusively to the presence of a considerable mass of quartz diorite below, or, in other words, an upward extension in this locality from a larger and deeper batholith, of which the Marysville area is another upward extension.

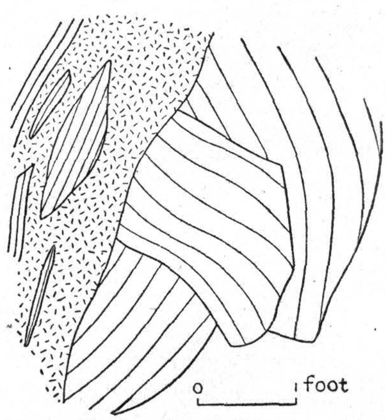


FIG. 7.—Crushed and welded limestones intersected by granite dikes near granite contact east of Marysville.

A similar occurrence is noted in Eldorado Gulch, in the south-central part of the district, a mile and a quarter southeast of the batholith. Here a number of sheets of quartz diorite, one of which is sufficiently prominent to be mapped, supply to the surface wash bowlders that, except for a slightly finer grain, are not to be distinguished from those of the batholith. Associated with these sheets are several bands of possibly igneous rock closely resembling lime-enriched contact forms of the Boulder batholith at Elkhorn. These bands, which have penetrated the calcareous hornstones irregularly along the bedding planes, are white, spotted with pale green, and, if related to the quartz diorite, as seems probable, represent the only contact modifications of this sort noted in the district. The surrounding rocks of this portion of Eldorado Gulch exhibit a degree of metamorphism similar to that observed closer to the batholith, corresponding to the holocrystalline nature of the sheets and indicating the near presence of considerable masses of igneous material. This belief has been expressed in section D–D, Pl. II (pocket), where a chimney from the batholith is shown as rising beneath this locality within a quarter of a mile of the surface.

SATELLITIC CHIMNEYS.

Only one good example of the form of outliers known as satellitic chimneys is noted. On the northern slopes of Mount Belmont is a prominent outcrop of normal quartz diorite not to be distinguished from the type of the batholith, about 400 feet in diameter and separated by 400 feet of hornstone from the margin of the batholith. It has a sharply marked elliptical outline, standing out from the hillside, and would more naturally be considered as the outcrop of a nearly vertical chimney than as the remains of a sheet which has penetrated from the side. The outcrop is covered with large loose fragments of granite and the true relations can be observed only at the upper end, where the rock was found unquestionably in place.

The upper 30 feet, as observed at the highest and southernmost point, has a well-defined structure of darker and lighter bands and lenses, from 1 inch to 6 inches wide, with a flat dip similar to that of the adjacent strata. Aplitic segregations that consist of differentiations along nearly horizontal parting planes and are without sharply defined walls are also present. In mineral composition they consist of coarse pinkish-brown poikilitic orthoclase, quartz, and finer plagioclase. At other localities in this vicinity this banded effect was found to occur under and parallel to a flat roof. To apply this interpretation, it seems probable that the chimney had a flat roof and did not rise above an elevation of 7,000 feet.

The most important feature to be noted, however, is the small disturbance of the strata surrounding the chimney, the dip immediately to the south being 6° N., while on the north side it is 16° N., the variation being thus no greater than is to be observed in the strata at places where there are no intrusions.

DIORITE INTRUSIONS EAST OF MARYSVILLE.

In the railroad cut immediately east of Marysville numerous dikes, some belonging to the older microdiorites, some to the batholithic quartz diorite, and some of aplite and pegmatite, are well exposed.

About 1,100 feet east of the trestle is one large dike, 75 feet wide, of fine-grained biotite granite resembling that of the Drumlummon mine and showing pegmatitic segregations within it. Beyond this, from 2,000 to 3,100 feet east of the trestle, are three large lenticular intrusions with somewhat irregular outlines. The composition and texture vary somewhat from those of the batholith, but are still sufficiently close to show an intimate relationship. They are noticeably more basic than the normal rock, containing less quartz and a considerable proportion of orthoclase and hornblende, giving them monzonitic leanings. Near the borders of these intrusions the texture is porphyritic, the elongated prisms of hornblende being the most conspicuous constituent of the rock and the appearance resembling that of the large dike in the western portion of the Belmont mine. In the center of the dikes, however, the texture is of normal coarseness and almost even-granular, with but a trace of the porphyritic facies. The hornstones at the margin are crumpled and form an interlocked contact with the granite.

No positive indication of the pitch of these lenticular intrusions was secured, but observations in prospect tunnels furnish some information. About 300 feet west of the westernmost of the three large intrusions and somewhat below it, near the level of Silver Creek, a tunnel is driven 300 feet south into the hillside and cuts but a couple of steep dikes of granite porphyry, one 9 and the other 15 feet wide. Five hundred feet east of the easternmost intrusion, on the contrary, a tunnel is driven S. 30° W. for 700 feet, the last 240 feet of which is entirely in granite, indicating that the underground extensions of these or related bodies lie to the east, the lower intersections being farther from the surface limits of the batholith. In conformity with this conclusion it may be noted that in another tunnel 300 feet long and about 300 feet still farther east a fault is cut 200 feet from the entrance and the final 100 feet is nearly all driven through a hard and massive fine-grained diorite which shows here and there leaves of hornstone from 3 to 18 inches thick floating nearly horizontally within it. A longer tunnel about 50 feet above showed nothing but hornstone in the dump, indicating that this diorite may form a flat sheet, or, if thicker, that the lower tunnel is driven near the roof.

UNDERGROUND EXTENSIONS OF THE BATHOLITH.

STUDY OF THE UNDERGROUND STRUCTURE.

In a stock or batholith a careful study of the form of the intrusion and its relation to the surrounding rocks is essential toward elucidating the method and causes of intrusion. The surface outline and relief give some indication of the form, but more is shown by studying in detail the dip and character of the contact surfaces and, especially in this region, by following them to considerable distances underground through the extensive mine workings which are fortunately available. There are three general conceptions of the form of the upper surface of such an intrusion. It may enlarge upward, an idea often expressed in theoretical sections of volcanoes; it may maintain essentially the same diameter, forming a typical stock, neck, or plutonic plug; or it may widen downward, the upper surface being pyramidal or domal, the usual conception of laccoliths and batholiths. The evidence of the contacts which has been discussed in detail indicates that this batholith in general has a highly irregular form. In places the upper surface is roughly flat for distances of a mile or more along the outcrop for at least a quarter of a mile at right angles to the outcrop, as seen on a large scale around Mount Belmont and on a smaller scale over the Drumlummon mine tunnel. Elsewhere the contact may be nearly vertical for heights of a quarter of a mile, but on the whole rapidly enlarging downward as indicated by the fact that the flat surfaces always slope away from the outcrop. The present limited area of the outcrop is, then, dependent on the shallow depth to which erosion has cut into the upper portion of the batholith.

The underground structure, however, soon passes beyond the limits even of the mine workings, and in this place will be considered the broader relations with other parts of the district and with similar intrusives beyond its limits. The evidence is necessarily of a more general character, but its cumulative proof may nevertheless be almost as convincing in regard to the nature of the underground extensions of the batholith as that of the details of the contact open to direct observation.

RELATION OF DEPTH TO METAMORPHIC ZONE.

It is shown in the chapter on contact metamorphism that the limits of the metamorphic zone depend somewhat on the character of the formation, the tendency being for it to extend farthest in the case of those impure limestones whose siliceous and argillaceous contents were sufficient in amount to combine with the lime and result in the expulsion of the carbon dioxide. A fissured state of the rock, by offering suitable channels for the escape of magmatic vapors, may also result in a more extensive metamorphic zone in some directions than in others. Not less important, however, is proximity to a large body of magma, sufficient to heat the walls to a considerable distance. Bordering the batholith the narrowest portion of the zone is along Drumlummon Hill, where it varies from a quarter to half a mile in width, and it is to be noted that this is in the vicinity of the Drumlummon mine, where the contact slopes downward at an angle of 70° for at least a quarter of a mile and possibly to a considerably greater depth. On the northern side of the batholith this zone is from half a mile to a mile in width. Here there are no mine workings to demonstrate the underground relations, but from the abundance of the granitic and aplitic dikes and sheets dipping away from the batholith it seems probable that the latter lies under Edwards Mountain at no great depth. On the southwestern side the contact, where exposed, and the mine workings, as well as the manner in which the granite boundary follows the topographic lines, all suggest that the batholith extends under this region at a flat angle. The fact that here the metamorphism is marked to distances of at least 2 miles from the outcrop is conformable with these indications. It is noticed, furthermore, that over this region there is a great abundance of the Belmont feldspar-porphyry dikes, which, while not strictly contemporaneous with the batholithic intrusion, seem to be closely related to it in time and are doubtless intrusions from the same general magma. The most conspicuous of these dikes, that cutting across the southwest corner of the district, dips toward the southwest and away from the batholith, indicating that its source is even farther than its surface from the outcrop of the batholith.

This dependence between the general limits of the metamorphic zone and the underground extensions of the batholith having been indicated, the statement may be made with some confidence that intense local metamorphism indicates in such places the approach of a considerable body of magma to the surface. Such indications may be noted in Eldorado Gulch, 1 mile southeast of the batholith, and at the Big Ox mine, more than 2 miles to the north. In both places small intrusions of quartz diorite similar to the batholithic rock come to the surface as sheets and dikes, indicating the character of the magma producing the metamorphism, but the volume of the dikes is by no means sufficient to account for the width of the surrounding zone, similar intrusions of the microdiorites showing no such power of metamorphism. The presence of a considerable body of magma at no great depth would also explain the degree of granulation shown in the crystallization of these dikes. It may be concluded, therefore, that not only does the Marysville batholith broaden downward but that other though smaller prolongations upward are associated with it, differing in not being exposed at the present level of erosion.

RELATION TO ADJACENT GRANITIC INVASIONS.

The great Boulder batholith, extending 60 miles in latitude by 32 miles in longitude, lies to the south of the Marysville batholith, and is distant but 6 miles at its nearest approach. Not only does it strongly resemble the rock of the Marysville batholith megascopically and also chemically, as shown on page 55, but its contact in those places studied by the writer is of the same general character as that described at Marysville, breaking irregularly across the strata, in some places vertical, in others passing under the sedimentaries at a flat angle. Further, stocks of the same rock break up at intervals around its borders to distances of several miles, as seen in the city of Helena, and such larger but still subordinate batholiths as the Scratch Gravel Hills near Helena, the Marysville batholith, and the Phillipsburg-Granite batholith will naturally be considered as parts of the same general intrusion, connected underground and probably at no abyssal depth.

In the opposite direction from Marysville the first extensive outcrop of closely related rock is the Granite Peak stock, 11 miles to the northwest. Between the two intrusions are several miles of country with scattered residual patches of far later lava flows, but, so far as observed, free from igneous injections. Seven miles northwest of Gloucester, however, numerous dikes of diorite porphyry grading into true diorite become abundant, their strikes bearing in a northeast direction. As is commonly observed in other regions, these outlying dikes show considerable variability in mineral composition, certain of them leaning toward mica traps. Farther to the northwest they become wider and more abundant, passing into the diorite stock of Granite Peak, on the Continental Divide, extending to Gould, and covering an area of several square miles. The margin of the diorite is interfingered with the country rock to a much greater extent than in the case of the Marysville batholith, giving to the intrusion a somewhat different character. No analysis has been made of the Granite Peak stock, but in mineral composition it is found to be a hornblende diorite, differing chiefly from the Marysville type in the much smaller amount of quartz, not over 5 per cent being present. This difference is no greater than is often noted in marginal portions of a single granitic mass.

Such are the grounds for believing that the great Boulder batholith is but the largest exposure of a widespread intrusive mass which underlies a considerable region in western Montana and of which such occurrences as the Marysville batholith are upward prolongations exposed by erosion.

FORMER COVER OF THE MARYSVILLE BATHOLITH.

GENERAL STATEMENT.

It has been shown in the detailed description of the batholith contacts that in many places the granite passes under the metamorphic rim at a slight angle and that consequently the size of the area exposed at the surface is dependent on the depth of erosion. The hornstones still lying at a flat angle upon the granite may be regarded as portions of a cover which was originally more extensive, and the question arises as to what height the granite formerly attained, if, indeed, it did not reach the surface at the time of its intrusion. The inferences drawn from the character of the present margin become weaker and more indefinite toward the center of the batholith, as do those regarding the underground extensions at a distance from the present outcrop. As, however, in the latter case considerable general information was obtainable through study of the areas of contact metamorphism and of the petrographic and structural relationships with other exposures, so general conclusions in regard to the former cover may be reached through physiographic studies.

PHYSIOGRAPHIC EVIDENCE.

RADIAL CHARACTER OF THE DRAINAGE AND ITS CAUSE.

An inspection of the map shows how the metamorphic wall surrounding the batholith stands up on all sides except where trenched by the escaping streams, indicating a superior resistance to erosion. That it is also harder than the unmetamorphosed sediments goes without saying. In connection with this fact the general radial character of the drainage away from the batholith may be noted. On the north and east this is conspicuous, while beyond the western border of the district Lost Horse Creek flows westward for 4 miles before turning to the north to join Little Prickly Pear Creek, emphasizing still further this character of the drainage. On the southeast alone this feature fails, Sawmill Gulch flowing parallel with the metamorphic wall and just beyond its limits. It is possible and perhaps even probable that this radial character of the drainage may have been due originally to doming of the roof at the time of the intrusion, as has been shown to be true of the drainage surrounding the laccoliths of the Black Hills,[a] but in the erosion of some thousands of feet which has certainly taken place since the time of the intrusion the greater hardness of the metamorphic zone would tend to perpetuate this condition and may be considered as a secondary and more recent cause.

PASS BETWEEN MOUNT BELMONT AND EDWARDS MOUNTAIN.

The next point to be considered is the peculiar character of the drainage within the Marysville end of the batholith, which is eroded in an amphitheater, Jennies Fork and Rawhide Gulch forming an almost circular bow, uniting at Marysville and leaving the batholith through a steep-walled valley. On one side Ottawa Gulch has eroded its valley forward for a mile beyond the limits of the granite and into the more resistant metamorphic zone. On the other side Jennies Fork, instead of finding its headwaters in the granite pass to the northwest, has no tributary in that direction, but bends around to the south. The avoidance of this apparently easier course is striking and can not be explained on any theory of capture, since this stream is more favorably situated than those draining the other end of the batholith, and the granite in the pass, instead of being eroded into a low col, stands up as a high, narrow ridge, separating the two ends of the granite outcrop. The natural explanation is found on inspecting the granite contact of Mount Belmont, as shown in section B–B, Pl. II (pocket). At a number of places near this point the hornstone lies upon the granite at a low angle. An extension of this cover at the observed angle would meet the hornstone wall on Edwards Moun-

[a] Jaggar, T. A., jr., The laccoliths of the Black Hills: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, pp. 267–279.

tain at an elevation of not over 7,000 feet, calling for an erosion of the pass of less than 800 feet, since the bridge of hornstone had been cut by the lowering of the general surface. Thus the character of the Mount Belmont contact and of the drainage of the Marysville amphitheater agree in pointing to a once continuous sedimentary cover between Mount Belmont and Edwards Mountain at an elevation of not over 7,000 feet. This explanation is suggested by the flat contact, but really finds its proof in the character of the drainage.

DRAINAGE NORTH OF MOUNT BELMONT.

Relations of the streams.—The noteworthy features of the area north of Mount Belmont are found in the relations of Deer Creek and Drinkwater and Piegan gulches. At the headwaters of Deer Creek a deep, broad pass is cut through the metamorphic wall without any adequate stream to occupy it. The breadth and roundness of this pass stand in contrast to the V-shaped valley and trenched character of Deer Creek, as shown on the map, beginning a quarter of a mile to the north of this pass. Again, in ascending Piegan and Drinkwater gulches it is to be noted that they are of precisely equal length from their union to the points where they enter the batholith, having thus an equal resistance to meet in cutting their gorges through the metamorphic wall. Yet Drinkwater Gulch drains an area of 1.11 square miles, of which 0.54 square miles is within the batholith, while Piegan Gulch drains but 0.56 square mile, of which but 0.17 square mile is within the batholith. Thus Drinkwater Gulch drains three-fourths of the northwest arm of the batholith. It is to be noted also that Drinkwater cuts squarely across the head of Deer Creek and receives no tributaries in that direction, but, on the contrary, turns at right angles and extends its drainage area up Mount Belmont in two faintly marked divisions in the general line of Deer Creek Valley.

In connection with these statements fig. 8, showing the stream profiles, should be studied. It is there noted that in all cases the grade is cut deeper within the granite than across the metamorphic zone; also that Piegan Gulch just above its junction with Drinkwater Gulch shows a marked change of grade, resembling a flat cascade, although Drinkwater, flowing across similar rocks, has nothing of the kind.

Hypothesis of stream capture and its cause.—The peculiarities of the head of Deer Creek and the relations of Drinkwater and Piegan gulches may be naturally explained by the hypothesis of stream capture. Drinkwater Gulch, by pushing its headwaters eastward, has at last appropriated the upper portion of Deer Creek, accounting for the "wind gap" at the head of the latter, the southern turn to the headwaters of Drinkwater Gulch, and its greater drainage area than that of Piegan Gulch. Furthermore, not many hundred feet of erosion have taken place since the time of capture, since the abandoned pass is but about 50 feet above the level of Drinkwater Gulch immediately to the south of it. This is confirmed by the profile of Piegan Gulch near its junction with Drinkwater. The accession of a greater drainage area would give the stream occupying Drinkwater Gulch greater power of cutting its channel and at first give to Piegan Gulch traces of the character of a "hanging valley." After sufficient time the tributaries would adjust themselves to the more rapid deepening of the main stream and a new gradient, steeper but uniform, would be attained. The profile shows that not only has this not been done, but the dotted line must be an approximate representation of the stream

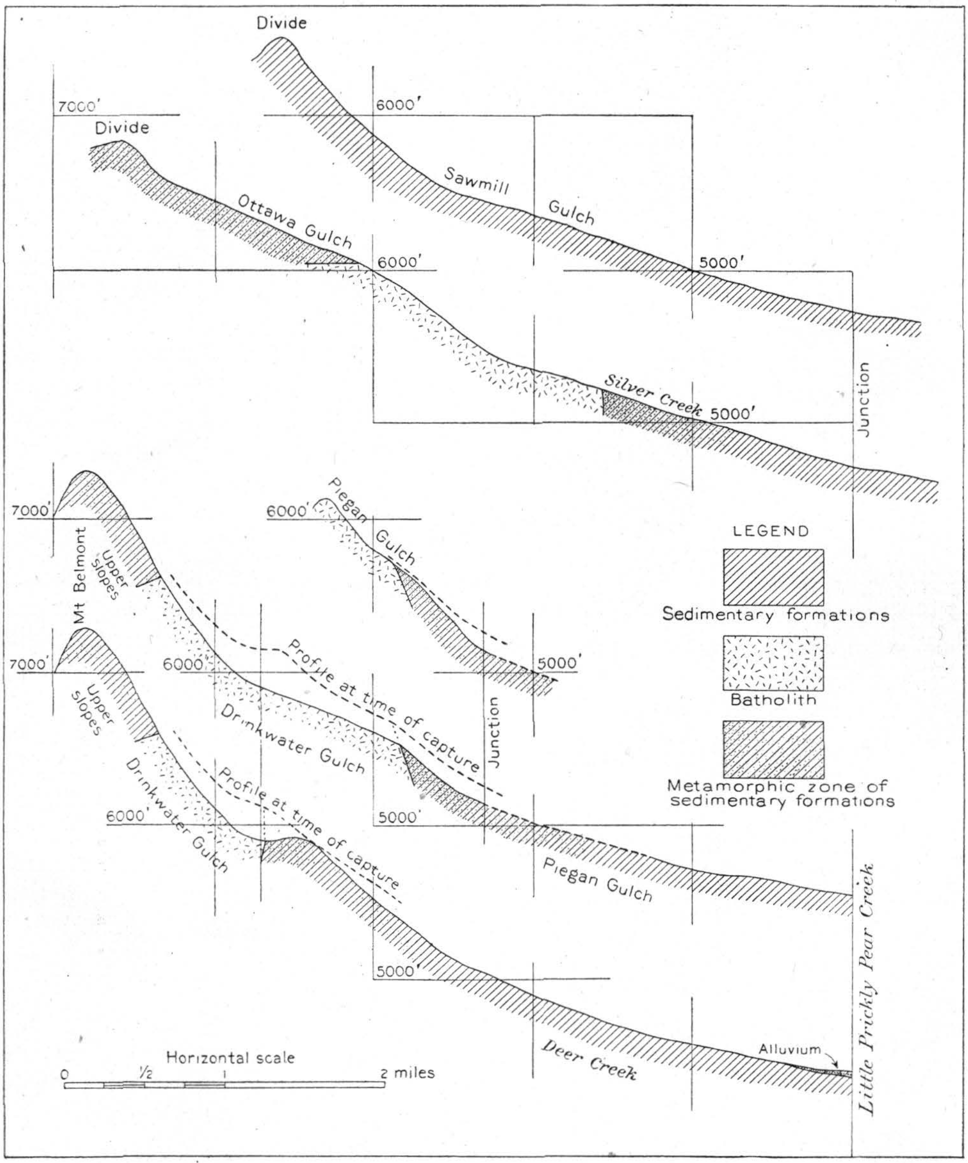


FIG. 8.—Relation of stream profiles to granite areas.

gradient at the time when Drinkwater began to deepen its channel at a more rapid rate. Since that time it has eroded probably about 100 feet and certainly not over 200.

The next question which arises is as to the cause of the capture. From the point where Deer Creek leaves the granite it is about half a mile longer than the course of Drinkwater Gulch through Piegan Gulch into Little Prickly Pear Creek, but this disadvantage is offset by the fact that Piegan Gulch flows into the master stream a mile and a half above. The metamorphic and sedimentary rocks are also similar in the two cases.

The cause of this capture is therefore doubtless to be found in the presence of the granite and the relative recency of the capture points to the recent removal of a cover; otherwise the adjustment should have taken place long ago. A slight difficulty in the way of this hypothesis is found in the present elevations to which the granite extends. For Drinkwater Gulch to have captured the headwaters of Deer Creek through possessing a more favorable course within the granite, the rock should have reached a higher elevation at the northwest end and have been exposed there first. Yet, on the contrary, it may be seen that over the pass leading from Marysville to Gloucester the granite has reached at least to 6,500 feet, but probably was never above 7,000 feet, while at the point where Drinkwater Gulch leaves the batholith the granite slopes under the hornstone at an angle of about 30° and at an elevation of about 5,500 feet. The escape from this difficulty lies in the fact that the northward prong from the batholith, running at right angles to the contours of the hill, has the appearance of being a vertical, wedgelike dike, which may readily have extended to a great height, terminating the sloping surface to the west and carrying the granite to an elevation as great as that in the original course of Deer Creek. The possibility of this suggestion is strengthened by the adjustment of Drinkwater Gulch to the granite contact for half a mile. This was discussed under the heading "Computed dips of the contact surface" (p. 70), and the probable inference drawn that the contact here slopes steeply to the southwest. It is easily possible, in view of the irregularities found in the Belmont and Drumlummon mines, that along this north wall, to which Drinkwater Gulch is now adjusted, the granite once rose to a greater height than elsewhere in this northern arm. It has been noted that but a moderate degree of erosion has taken place since the time of capture. In the stream profiles (fig. 8) the dotted lines indicate the approximate stream gradients at that time, derived from the level of the Deer Creek wind gap. If the capture, however, was effected through the presence of the granite, several hundred feet of erosion must have taken place after the exposure of the granite and before the capture, during which the balance between the two streams was slowly changing. Just what this depth was it seems impossible to say, but these problems are merely additional to the major hypothesis—first, that a change of drainage has been effected; second, that it was due to the presence of the granite; and third, that the recency of this capture points to the somewhat less recent exposure of a granite mass which was once covered.

Recency of granite exposure as indicated by interstream profiles.—Another line of evidence, not so strong in itself but corroborative of the preceding, is derived from a study of the steepness of slope of the ridges between adjoining streams. Since the granite is eroded more readily than the hornstone, the streams in flowing over the granite areas tend to erode toward a local base-level, determined by the level of the stream at its escape from the granite. Being checked in downward erosion by the hornstone rim, the streams will tend to widen out their valleys and by the lowering of the interstream granite areas give gentler slopes to the gulch sides. This is very strikingly illustrated at the town of Marysville by the low ridges between Jennies Fork and Rawhide Gulch.

North of Mount Belmont, Drinkwater Gulch and the upper portion of Piegan Gulch form a similar arc, but between them, on the contrary, is a high, narrow ridge of granite, which bends southward and runs into a promontory of the cover projecting into the granite. This feature, taken in connection with the shelving character of the west end of the granite contact, is additional evidence that until recently the granite in the region of Gloucester was not exposed. It is to be noted that Gloucester is situated in a small amphitheater, which has not yet widened in circumference sufficiently to break down the walls separating it from Drinkwater Gulch. Thus the characteristic erosion features of a granite area surrounded by more resistant formations have begun to be apparent, but there has not yet been sufficient time for them to have reached a stable condition.

FORMER BATHOLITHIC COVER OVER MARYSVILLE.

Evidences.—As to the extension of a cover over the Marysville end of the batholith, the evidence is much less satisfactory. Around the extreme southern portion the observed contacts dip away from the exposed portion of the batholith at flat angles varying from 5° to 40°. In the neighborhood of the Drumlummon mine, as has been shown, a mass of hornstone with a flat bottom formerly projected over or into the granite and still remains, but on the whole the contacts at the east end are steep. On account of the irregular surface inferences derived from the extension over the batholith of the contact surfaces found at its margin lose their force as the center is approached, and other lines of evidence must be sought. These are noted as follows: On comparing the profiles of Sawmill Gulch and Silver Creek, as shown on fig. 8, that of the former is seen to be a very smooth curve, indicating the presence of rocks of approximately the same hardness throughout. Silver Creek and its extension, Ottawa Gulch, on the contrary, show a number of well-marked changes in angle, depending largely on the character of the underlying rock. At the contact on Ottawa Gulch, however, the gradient existing along the metamorphic zone is observed to extend downstream over the granite for nearly a thousand feet before steepening. On the whole, the gradient is observed to be higher than that of Sawmill Gulch, to which it is parallel, yet the stream has pushed its headwaters farther westward than Sawmill Gulch.

The geologic map (Pl. I, pocket) shows that no abandoned stream-cut channels similar to the wind gap of Deer Creek cut Drumlummon Hill, so that here there is no evidence of a change in drainage.

Explanation of evidences.—An explanation of these features may be sought by showing what would have been the course of stream development under several different theories of the structure, following thus a deductive method and observing how the conclusions fit the facts, in this way determining the limitations of the original structure.

First, suppose the granite to have been recently covered with hornstone, forming a dome of hard metamorphic rock inclosed with softer formations. The exposure of this dome at the surface would finally result in a radial adjustment of the drainage, as indeed exists on all sides except the southern. Here there has been no such radial drainage during the erosion of the last 900 to 1,000 feet measured vertically, as otherwise remains of one or more dry gaps should show across Drumlummon Hill. On the contrary, Sawmill Gulch and Silver Creek are well adjusted to the structure, both flowing upon softer formations with a harder ridge between. Since some degree of erosion in the softer formation would have to take place before there would be an adjustment to structure, it may be concluded that the granite once extended to an elevation greater than that of Drumlummon Hill. This conclusion is in line with that derived from a consideration of the low interstream hill slopes between Jennies Fork and Rawhide Gulch, which have been already discussed, and indicate that the granite has been exposed long enough for the interstream topography to become adjusted to present conditions.

Second, suppose the granite to have extended indefinitely upward, possibly to the ancient surface, with its present or even a larger area. In that case the greater ease of erosion within the granite would have given Silver Creek an advantage in drainage area and in power of erosion which would have made it easily the master stream over its immediate neighbors. It is to be noted, however, that in Trinity Gulch a minor stream flows for 4 miles roughly parallel to Silver Creek, being at two places less than half a mile distant, yet at no place is there any approach to capture. This may be taken as an indication that the granite in large volume did not extend indefinitely upward. The precise limits to its original height over the town of Marysville can not be stated; it probably reached to 7,000 but not over 8,000 feet above tide. It is possible that dikes or chimneys may have penetrated the roof above this level, but not in sufficient volume to become a factor in the adjustment of the drainage.

At the extreme south end of the batholith, on the other hand, the peculiar convex curve in the gradient of Ottawa Gulch over the upper 1,000 feet of its course on the granite area points to an exposure of the granite so recent that the stream gradient has not yet become adapted to the new conditions. This is in conformity with the flat contacts observed at some distance from the stream on each side (see Pl. XI) and also with the flat slope of the surface computed on the assumption that the angle it makes in crossing Ottawa Gulch is due to the deeper erosion along the course of the stream bed. By these three lines of argument the same conclusion is reached and reinforced, that over the extreme south end of the batholith the cover has once extended from the present contacts at an angle of 10° to 15°, sloping southward away from the batholith. This flat portion of the cover appears to have terminated along a line parallel to the line of section D–D, Pl. II (pocket), and 800 to 1,000 feet southwest of it.

DOMING OF THE BATHOLITHIC COVER.

GENERAL STATEMENT.

By the batholithic cover is meant not only a former extension over the granite, but also the marginal zone of metamorphic rocks beneath which, as there is reason to believe, the granite lies at no great distance. As the strata of the entire region show folding, crushing, and faulting, it is not a simple matter to differentiate forms immediately related to the batholithic intrusion. The method used to do this is described under the subject of block faulting. Numerous dips and strikes were recorded, well-defined and regular bedding planes being chosen in all cases. An extension of these strike lines gives the strike contours, shown in Pl. XI and drawn at such a distance apart that they represent vertical intervals of approximately 250 feet on any bed. It is noted that on the southern margin of the area the dips are easterly from 15° to 30°. Around the batholith, however, the dips are very different; on the southwestern side the strata lie at a flat angle, while on the north and east the dip is steeper than elsewhere, the strike lines sweeping in an arc of several miles radius about the batholith, as shown in Pl. XI (p. 74). This is precisely the effect which would be given by the doming of a cover which previously had a more or less uniform dip of about 20° NE. In addition to the doming the margin, as shown in the discussion of block faulting, is cut by many obscure normal faults, the nature of whose movements has been an unequal lifting and tilting. That the movement was one of lifting rather than subsidence is shown especially by the two large faults north of Gloucester, the crust block between them having moved upward with respect to the adjacent walls. The tilting or doming and the faulting have therefore worked in the same direction and are presumably due to the same intrusive cause.

The vertical sections, as shown in Pl. II, also bring out the same effect, showing an amount of doming which has certainly reached over 1,000 feet and has probably approached nearer to 3,000 feet.

DEPARTURE FROM THE LACCOLITHIC FORM.

In accounting for the doming two alternative hypotheses may be advanced—first, that it was done previous to the batholithic invasion by forces which were not directly related to the invasion, but which may have had a determining influence in the subsequent location of the batholith, the doming thus being a cause and not an effect; second, that the intrusion of the batholith itself was the cause of the domed structure. If the latter view is accepted as the natural one, it may still be pointed out that the intrusion is not in the form of a natural laccolith. The form of the simplest type of laccolith is plano-convex and tapering at the margins, the intrusion making a space for itself by a doming and stretching of the cover. Many departures from the ideal symmetrical form exist, examples of which have been pointed out by a number of observers. The essential feature, however, is the penetration of the magma along more or less horizontal planes of parting and the lifting of the cover by doming and not by marginal faulting, the name of bysmalith being applied to intrusions of the latter type.[a]

The Marysville batholith, however, departs widely in form from either of these types. Its upper surface, instead of being more or less regular, is extremely irregular, steep or vertical surfaces alternating with flat surfaces, giving the whole a rudely pyramidal form with a somewhat steplike surface from which project dikes, sheets, and chimneys. Of these more or less vertical walls the Drumlummon mine exposes one for a depth of 1,300 feet, and the physiographic evidence which has

[a] Iddings, J. P., Mon. U. S. Geol. Survey, vol. 32, pt. 2, 1899, p. 170.

been discussed leads to the belief that it has extended upward at least another 1,000 feet. On the other hand, room for the intrusion has not been made by marginal faulting, as is indicated by the underground extensions, by the irregular upper surface, and especially by such features as are shown in the Drumlummon section, where a flat cap projects outward from the steep wall for several hundred feet into the batholith, giving rise to shoulders and reentrant angles. Again, the fact that a cover, portions of which still exist, once in great part, if not completely, covered the granite indicates that the intrusion can not be regarded as a volcanic stock or chimney and justifies the distinctive name of batholith.

A further inference may be drawn from the absence of masses of hornstone pendent from the roof. If such masses occurred it would be expected that the erosion which has produced the present surface would near the margin of the batholith have planed away their former connections with the cover above and that they would now appear as islands of hornstone whose dip and strike would conform with those of the adjacent walls. Not a single such instance is noted.

FOLDS OF THE MARYSVILLE DISTRICT.

INITIAL WARPINGS ACCOMPANYING SEDIMENTATION.

The disturbances of the sedimentary formations in the Marysville district may be divided into a number of separate classes, the first of which, taken in the order of time, comprises those gentle warpings which result in subsidence and sedimentation in one place and perhaps uplift and erosion in another not far distant.

Such movements accompanied the deposition of the Belt formations, as have been discussed under "Belt Group of Montana," in Chapter II (pp. 28), and the differences in these gentle downward warpings allowed a greater accumulation of sediments in certain areas than in others. The resulting bends in the lower strata, named by Willis the "initial dips," have been shown by him to determine in certain cases the location of the principal folds when mountain-making stresses accumulate in the region.[a] Although such influences may have been operative here, not enough is known of the sedimentary formations in this and the immediately surrounding regions to make any statements on this matter.

THE PRICKLY PEAR DOME.

As shown by Walcott,[b] the Belt formations are exposed over an oval area about 40 miles long by 25 miles wide, reaching from Missouri River to the Continental Divide, with Helena on its southern and Marysville near its western limit. Silver Creek, flowing eastward from Marysville to the Missouri, roughly bisects this exposure of the Belt rocks. Around it are upturned the truncated edges of the entire Paleozoic and Mesozoic series, reaching, where measured at some distance to the south and west, thicknesses of 7,000 to 10,000 feet. That these formations have extended over the district with at least considerable thickness is indicated by their upturned and truncated outcrops and the character of the sediments, especially the Paleozoic limestones, which do not indicate any local or marginal land conditions.

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[a] Willis, Bailey, The mechanics of Appalachian structure: Thirteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1893, pp. 253, et seq.

[b] Walcott, C. D., Pre-Cambrian fossiliferous formations: Bull. Geol. Soc. America, vol. 10, 1899, p. 205.

From these statements it is seen that over the present valley of Prickly Pear Creek a domal uplift has occurred to such a height that subsequent erosion has removed the entire Paleozoic and Mesozoic column and extended far into the underlying Algonkian. By study of the outlying regions it is known that the close of the Mesozoic witnessed the beginning of the intense volcanic activity and mountain-making movements of western Montana, and this uplift, as well as those of the Big Belt and Little Belt mountains, is to be referred to the latest Mesozoic or early Tertiary.

LOCAL DISTURBANCES.

Although the broad relations show that the Marysville district lies on the southwestern slope of this domal uplift, there is nothing within the limits of the district which would render this evident. On the contrary, the dips of the strata, instead of being southwesterly, are, on the whole, toward the east.

An inspection of Pls. II and XI shows the complicated structure of the district. The strikes in many places follow curved lines and are broken by faults. The dips of the southern portion are toward the east, but around the margins of the batholith the dips, as noted previously, are flattened on the southwest side and steepened on the northeast, as if a local uplift had been produced by the batholith, which is doubtless the true explanation. In addition, the country is cut by many faults.

A clearly marked feature of the region is the synclinal axis which passes through the district in a nearly east-west direction to the north of the batholith. North of this again the country is broken by many faults and the strikes are exceedingly irregular. A study of the deformations of the sedimentary rocks is thus largely a study of the fault systems.

MINOR ROLLS AND CRINKLES IN LIMESTONE STRATA.

At several places in the southern half of the district the purer beds of the Helena limestone show sharp local rolls, the laminæ of some being bent to a radius of not more than 10 inches, while the limits of the bed are fairly plane. In other places the radius of curvature may be 5 or 10 feet. In two instances where careful observations were taken the axes of the rolls run northwest and southeast, parallel to the direction of the cleavage, suggesting that if the cleavage were due to compression these rolls may be corrugations in beds too strong to yield by homogeneous flow. In another case noted the folding was on a much smaller scale, but may be described as a puckering which had resulted in a shortening about equal in both directions. As this was a thin band of granular limestone partly replaced by quartz, with a hard, evenly bedded, tremolite rock on both sides, it seems probable that the puckering had been caused by mineralogical changes at the time of metamorphism.

A certain amount of concretionary action is noticeable in the thin-bedded limestones, resulting in lenticular segregations, but this feature is of course easily separated from those already described. Such segregations may, however, have originated at times far earlier than that of the Laramide cordilleran disturbances, as it is known that, in the case of limestones, irregularities in original deposition, solution, redeposition, intraformational conglomerates, and concretionary action may be more or less closely associated with the original formation and not necessarily due to dynamic or to metamorphic causes. They are to be looked on as results of such causes only so far as other evidence relates them.

CLEAVAGE AND FISSILITY IN THE MARYSVILLE DISTRICT.

DEFINITIONS.

Before the facts bearing on cleavage and fissility in the Marysville district are presented it will be necessary to define the two terms as here used, since they are frequently employed with varying meanings. Van Hise[a] has defined cleavage as "a capacity in some rocks to break in certain directions more easily than in others. By virtue of this property rock masses may be split into slabs or into leaves." Fissility is defined as "a structure in some rocks by which they are already separated into parallel laminæ in a state of nature." A slate is defined as "a rock having the property of cleavage or fissility, or both combined, the rock parting into layers with relatively smooth surfaces." These terms as given here, as previously used by Le Conte, and as later followed by Leith[b] are purely structural terms and independent of mode of origin. With regard to origin they may be subdivided into such terms as bedding cleavage or fissility, flow cleavage, fracture cleavage or fissility. The terms are commonly employed, however, to denote secondary structures only—that is, structures not connected with the origin of the rock mass. In this usual sense they are here employed. Fissility must be further distinguished from jointing, into which it grades.

OBSERVED RELATIONS.

True slaty cleavage, though not conspicuous, is readily observed in formations of suitable composition. In order to eliminate the local effects of intrusions, it will be well to note first those districts situated at the greatest distance from them. In Pl. XI, at a number of places, arrows indicate the directions of joint planes. Within the metamorphic zone there are commonly three such joint planes intersecting, but beyond its limits there is but one and this is found to correspond with a cleavage structure. In both the southeast and southwest corners of the district this joint plane dips from 35° to 45° SW., while on Silver Creek the dip is directly westward. Cleavage is developed to some extent in the Marsh shale within the limits of the district and in certain shaly beds of the Helena limestone. In the metamorphic zone, cleavage, as distinct from the joint systems, was noted at a number of places, especially in the arm of hornstone cut by the Belmont mine and again on Drinkwater Gulch. At both places the dip is still to the west or southwest, and on Drinkwater Gulch the cleavage plane was observed to lie more nearly parallel to the bedding in those laminæ where it was best developed.[c]

On the eastern side of the batholith, in the railroad cut near the contact, evidence of normal faulting along the bedding planes was observed at one place, and for several hundred feet there is a cleavage dipping on the average 80° E. This is an exception to the general direction and, as pointed out later, seems to be related to the intrusion of the batholith.

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[a] Van Hise, C. R., Principles of North American pre-Cambrian Geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 633.

[b] Leith, C. K., Rock cleavage: Bull. U. S. Geol. Survey No. 239, 1905, p. 11.

[c] This phenomenon is considered by Van Hise to correspond to a sliding of the upper beds with respect to the lower in the direction of the inclined cleavage, the varying inclination being an indication of the relative amounts of sliding on the several laminæ.

In the northern part of the district true cleavage was not noted, except in so close a relation to the faults that its independence of them would be difficult to prove. Nor is it observed to be developed in the igneous rocks. These have not shown any marked tendency to follow the plane of cleavage rather than other directions, with the possible exception of the Belmont porphyry dikes. In the large dike at Bald Butte this tendency is noticeable, and the microdiorite intrusions on the hanging-wall side is sheeted and infiltrated parallel to the cleavage direction and that of the dike.

The cleavage of the Marysville district is in all cases subordinate to the bedding and does not obscure it.

The local evidence as to the time relation of the cleavage to the igneous intrusions is defective, since the cleavage is not sufficiently pronounced to have governed the direction of the intrusions if they were younger, and it would not ordinarily be developed in hard and strong igneous rocks after their solidification. The only observation bearing on this point is that the local cleavage immediately east of the batholith appears to be influenced by it, and also that cleavage is developed parallel to the large dike of Belmont porphyry at Bald Butte. As this dike, however, is in general parallel to the regional cleavage its direction of intrusion may have been determined by that cause, and on that view the later sheeting has merely taken advantage of a much older cleavage structure. On the whole the cleavage seems to have been comparatively little influenced by the presence of the batholith, and as the granite is thought to underlie much of this region, at no great depth, the conditions would hardly be favorable for a uniform development of cleavage not parallel to the contact in the softer cover rocks after the intrusion and solidification of the massive granitic basement.

Again, the Boulder batholith to the south, with which the Marysville batholith is closely related, was intruded after the general orogenic structure of the country had been assumed.

These general considerations lead to the belief that the cleavage originated previous to the batholithic invasion.

INTERPRETATION.

THE TWO THEORIES.

The relation of the development and direction of cleavage to the forces involved has received two interpretations.

The older view developed by Sharpe, Sorby, Tyndall, Haughton, and others, and recently strongly urged by Van Hise and Leith, conceives cleavage to arise in the plane of maximum extension, and therefore perpendicular to the line of greatest compression. This has been called "flow cleavage" by Leith.

More recently Becker has argued that cleavage arises on planes of maximum sliding.[a] In a homogeneous body suffering simple compression these planes at any moment are inclined at 45° to the line of compression and either two or four such planes of fracture may be developed. The observed prevalence of cleavage

[a] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 13-90; Experiments on schistosity and slaty cleavage. Bull. U. S. Geol. Survey No. 241, 1904, vol. 4, 1893, pp. 13-90.

in one direction and not in several is explained by rotation accompanying continued compression, by which sliding on one set of planes is favored in preference to the others. On this view cleavage is to be considered as an evenly distributed faulting, and may be the same in direction as faults of various magnitudes produced by the same forces at the same time. Leith has recently named this "fracture cleavage." Becker cites the Sierras as furnishing field evidence substantiating this view and more recently Lindgren[a] has noted similar phenomena in the Bitterroot Mountains of Montana.

Leith[b] in discussing the subject considers that cleavage due to both causes undoubtedly exists, but that the form belonging to the metamorphic rocks is flow cleavage arising in the zone of flowage through the parallel development of minerals. He regards it as in general the more important, while fracture cleavage arises in the zone of fracture, is not accompanied by the development of new minerals, and is not of so intimate a nature as flow cleavage.

It will be well to apply both theories to the facts previously cited in order to show what interpretation each gives to the origin of the cleavage of the Marysville district.

FLOW CLEAVAGE.

According to Van Hise, if movements of compression act horizontally to exactly the same extent at different depths the horizontal elements of the crust will suffer simple shortening, the vertical elements simple extension, and the cleavage planes will stand exactly vertical. If, however, an upper part moves laterally with respect to a lower, sliding between the different layers is involved, resulting in the development of what he has termed parallel cleavage. Inclined cleavage in general, therefore, signifies not alone a horizontal compression, but a certain degree of horizontal movement or sliding of upper portions of the crust with respect to the lower, the latter having moved relatively in the direction of the dip of the cleavage. Since in the Marysville district the general direction of the cleavage is toward the southwest this would involve a relative movement of the upper portions of the crust toward the northeast, such as would occur on the limbs of a dome formed by horizontal compression. As the district lies on the southwestern flank of a large domal uplift, the possible relations of the two should be considered in this connection. Again, it is shown under "Thrust faults and brecciated strata" (page 94) that the region has at some time been subjected to an east-west compression sufficient to crush the harder rocks in certain places and to produce a slight amount of thrust faulting. A compression which has produced this effect on the harder strata might well be competent to impose the observed cleavage on the softer formations. It must be borne in mind, however, that although it is easy to correlate the domal uplift, the cleavage, and the brecciation, there is no positive proof that they are the several expressions of a single geologic act, but, on the contrary, they may have occurred at distinctly different epochs. The reasons for this cautiousness of decision are developed in the following pages.

[a] Lindgren, W., Prof. Paper U. S. Geol. Survey No. 27, 1904, pp. 47-50.
[b] Leith, C. K., Rock cleavage: Bull. U. S. Geol. Survey No. 239, 1905.

FRACTURE CLEAVAGE.

If the cleavage is considered as the result of distributive faulting, there has been a progressive uplift toward the northeast, since the cleavage pitches to the southwest. This is in agreement with the major faults, which may be considered as planes on which the movement became concentrated. It is also, as was the hypothesis of flow cleavage, in conformity with the situation of the district on the southwestern flank of the great dome, the erosion of which has exposed the area of Belt rocks; but the formation of the dome under this view would be by concentrated or distributive faults around its margin with a horizontal extension of the strata, the chief cause of the uplift being a vertical upthrust combined with horizontal extension and not tangential compression around the circumference. The dip and strike of the beds within the limits of the district is in conformity with this view, since they do not dip away from the center of the dome, but, if anything, toward it, showing that the lower horizons in the northern portion of the district do not owe their exposure to an anticlinal structure, but to the fact that they have been faulted up with relative downthrow of the southern portion.

The interpretation, on this view, of the local cleavage dipping 80° E. on the eastern side of the batholith is that the latter, presumably at or close to the time of its intrusion, acted with an upward thrust, resulting in normal faulting and to some extent a cleavage which in all cases should dip away from it. This interpretation is in agreement with the other lines of evidence, presented elsewhere, on the domal thrust of the batholithic intrusion.

CONCLUSION AS TO CAUSE OF THE MARYSVILLE CLEAVAGE.

It is evident that this application to the structural facts of the Marysville district by the deductive method of these two theories in regard to the causes of slaty cleavage results in opposite interpretations as to the forces which have operated to bring about the cleavage here; yet since in certain instances it may not be easy to decide finally which form of cleavage is present it is necessary to present both views.

It seems, however, that vertical upthrust with distributive marginal faulting accounts more fully for the phenomena within this district, as the minute structure does not show any notable development of minerals to account for a flow cleavage, but appears rather to be of the nature of fissility. The hypothesis of fracture cleavage is also in conformity with the movements on the major fault planes and the lack of an anticlinal structure within the limits of the district. This would ally the Prickly Pear dome with other characteristic Cordilleran uplifts such as the Bighorn and Uinta mountains, where broad, flat, anticlinal arches have apparently been lifted not by horizontal compression, but by vertical upthrust along their axes, in places attended by marginal faulting of a normal nature.

THRUST FAULTS AND BRECCIATED STRATA.

DESCRIPTION.

In many places the more resistant strata show brecciation and thrust faulting. This may be well observed along the gorge of Silver Creek. West of the entrance to Sawmill Gulch the rocks are greatly shattered, the hard bluish hornstone layers being broken and thrust through the softer strata. The thin layers of purer limestone in the latter show puckerings which in places have reduced their original length one-third. On the railroad immediately to the south many of the harder limestone layers are brecciated, this structure sometimes showing well under the microscope when not conspicuous to the unassisted eye, owing to the small scale and to the fact that a recementation has followed the brecciation. Again, on this same road at a distance of 200 feet from the main granite mass occurs the exposure illustrated in fig. 7, where a giant brecciation and rewelding of limestone took place before the intrusion of the granite dikes.

Nearer Marysville, along the wagon road, a small thrust fault is noted with 2 feet throw, the fault plane dipping to the west.

Another favorable locality for noting the presence of crushing, and to a limited extent of thrust faulting is in the bluffs on the north side of Little Prickly Pear Creek. At this place one fault dips to the west at an angle of 45° and is seen from the throw of the strata to be a reversed or thrust fault. The Woodchuck mine is situated on another fault near by, dipping 70° SW., though probably not a thrust fault, and the entire region is cut by nearly vertical zones of brecciation. Through this broken country silica-bearing waters have penetrated, silicifying and bleaching the normally reddish rocks. These zones of brecciation, however, must be distinguished from the thrust faulting with flat dips, since their nearly vertical position shows that they have resulted from adjustment to vertical rather than horizontal stress, the steepness of their dips indicating but little or no compression or extension of the strata.

SUMMATION AS TO DEGREE OF COMPRESSION.

From the foregoing statements it is seen that the amount of crushing in the harder strata corresponds in degree with the amount of cleavage developed in the softer. While locally the rock may be much shattered, the greater part of the district shows but little effect from crushing forces, the bedding is always clearly evident, and the extreme mashing characteristic of more metamorphic regions, producing schistose or gneissoid structures, is entirely absent. The pressure seems to have been independent of the igneous intrusions and would most naturally, but not necessarily, be regarded as operative at a time when the folded structure was imposed. At that time the present surface of the region was buried under some thousands of feet of overlying sediments and the softer members yielded partly by mashing. Besides the relief from tangential thrust found in folding, there was under that hypothesis, a limited amount of brecciation of the harder and more brittle beds.

As no final opinion is expressed as to whether the cleavage was due to shearing or compression, it is not advisable to connect it with the thrust faulting and brecciation, and they have been described as separate phenomena.

While the brecciation and mashing afford evidence of a period of strong compressive stress, the normal faulting indicates another period marked by relief from horizontal thrust. What effects these two periods have left on the softer members it is not ventured to say.

NORMAL-FAULT SYSTEMS.

INTRODUCTORY STATEMENT.

Normal faults, or those in which the rock on the upper side of the fault plane has slipped down with respect to that on the lower side, should be sharply distinguished from reversed or thrust faults. Normal faults result from adjustment to unequal vertical support combined with a horizontal extension of the thrust. Reversed faults, on the contrary, rise from exactly opposite conditions, compressive stresses reaching a value which the strength of the rock is unable to resist. As a result shear takes place along planes oblique to the direction of compression, and one part of the bed overrides the other. The normal faults of this district are of the utmost complexity, certain parts being broken up into blocks a few thousand feet across, which have risen and fallen with respect to each other until the result may be likened to the shifting of blocks in an ice pack. In most cases these give little or no topographic indication of their existence, and they are detected by carefully noting the dips and strikes in the field wherever possible and as often as possible, and then making constructions in the office to determine the stratigraphic relations. The mine workings also cut numerous fault zones marked by clay and brecciated rock and indicating throws along the fault planes from a few feet to 50 feet or more. These faults also are ordinarily unobservable at the surface.

The difficulties are further increased by the fact that the normal-fault systems are not all of one age, since some appear to have preceded the batholithic intrusion and some to be caused by it, while others are later than the batholith and are filled with the ore deposits which have given so great mineral wealth to the district, and still others are later than the time of ore deposition, producing strike faulting along the veins or cutting them at considerable angles. In attempting to unravel this complexity the faults of major importance will be first noted and subsequently the minor block faulting.

MAJOR FAULT NEAR LITTLE PRICKLY PEAR CREEK.

LOCATION.

The existence of a great east-west normal fault near Little Prickly Pear Creek is clear throughout the greater part of its length. To the north the strata are the deep-red shales and sandstone characteristic of the Spokane; to the south, the greenish, yellowish, or reddish shales of the Empire formation, the line between the two not being such as would be shown if they were in stratigraphic continuity. The fault plane is nowhere exposed, as is natural in shaly formations, but in the bottom of Long Gulch the shaly sandstone is seen to become crackled near this line, as from the presence of a shear zone. The dip here of the fault plane is judged to be not more than 35° S., but farther west it approaches verticality, as is shown by the straightness of the line in crossing hills and valleys. On the hill separating Missouri and Piegan gulches the line separating the Spokane red shale on the north from the Empire shale on the south is very clear, but in the bottom of Missouri Gulch the line of the fault is not evident and must be projected through from the east and west, since here red sandy shales of the same character are found on both sides of the fault plane.

THROW.

A fault traceable for a distance of 5 miles would naturally be expected to possess a very considerable throw. The exact amount is not determinable, since the stratigraphic column and the distance between the strata on the opposite sides of the fault can not be measured within the district. Some idea of the minimum amount may, however, be derived from an inspection of Pl. XI. Here the structural contour lines are drawn approximately at a vertical interval of 250 feet, as they would appear on any bed if the dips to the greatest depths shown remained as they are at the surface. At several places, as for instance, at the west end, it may be noted that several contour lines on the north side of the fault cover about the same distance as two or three on the south side. These relations are indicated in fig. 9, where the folds on the two sides of the fault are projected upon the fault plane, those of the south side being drawn in dotted lines. It is seen that any two intersecting lines, if followed a mile laterally, will separate from 500 to 1,000 feet, indicating great local variations in the throw of the fault. This shows that the total throw must be at least 1,000 feet and may be as much as 2,000 feet. A maximum limit to the throw is determined by the fact that the strata on the south side belong to the Empire shale, grading, perhaps, in a few places into the Spokane, while on the north side the strata throughout are Spokane. Therefore, the throw can not be greater than the entire thickness of the Spokane and Empire, since otherwise the Greyson formation would show in contact with even the uppermost Empire. The estimated total thickness for the Empire and Spokane has been given by Walcott as 2,100 feet, so that 2,000 feet may be considered an utmost possible maximum for the throw, but since the Greyson is not observed anywhere on the north side of the fault nor the Spokane at more than a few places on the south side, a much more probable maximum is 1,500 feet, the thickness of the Spokane.

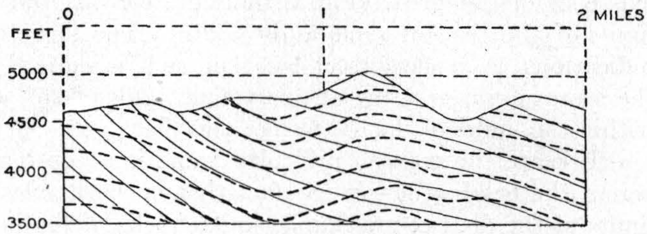

FIG. 9.—Folds on north and south sides of fault, west side of district near Little Prickly Pear Creek, looking north. Full lines indicate stratification on north side of fault; dashed lines the same on south side.

It may be said by way of parenthesis in this connection that although a comparison of the folds on the opposite sides of the fault plane is allowable within limited distances, this construction can not be safely carried uninterruptedly across the entire district, since it is quite possible that cross faults which have been undetected may break the continuity of the folds.

AGE.

No evidence was brought to light in regard to the age relations of this fault to the igneous rocks except that it is far older than the andesite extrusives, the latest igneous rocks of the district, this being indicated by the facts that the broad Tertiary valley occupied by Little Prickly Pear Creek was developed on both sides of the fault without any topographic distinction and that the andesite flows are younger than this valley, being found within it.

MAJOR FAULT NEAR BALD BUTTE.

DESCRIPTION AND NATURE OF EVIDENCE.

The fault near Bald Butte, in the southwestern part of the district, could not be observed anywhere within its limits, yet the evidence gathered from adjacent localities was sufficient to justify its approximate location along this line. Only a few hundred feet beyond the southern boundary, on the line of cross section, A–A, Pl. II, a brownish-red quartzite is encountered, succeeded by the characteristic Marsh shale of Greenhorn Mountain. This is abruptly terminated to the east against this fault and on the eastern side reappears 2 miles to the southeast, the eastern continuation of this second outcrop being in the southeast corner of the district, as shown on map. The fault is approximately at right angles to the strike, being thus a dip fault. The horizontal throw of the Marsh shale is about 9,200 feet and its dip varies from 20° to 30°. If 23° is taken as the average dip, this gives a vertical throw of 3,900 feet and a throw perpendicular to the bedding of 3,600 feet. In the opposite direction a reconnaissance trip was taken on a line bearing N. 70° W. from Marysville to the continental Divide, 9 miles beyond the limits of the district. Along this line, from Little Prickly Pear Creek to the Continental Divide, a great thickness of red shales which appeared to be stratigraphically above the Helena limestone was encountered, uniformly dipping to the southeast, while on the parallel ridge to the north the strata were found to be Helena limestone, thus necessitating a fault between them. The existence of this great fault is therefore certain, but the exact location within the limits of the district remains in doubt. The structural map (Pl. XI) gives some indications as to the correct location, as it is noticed that on the hanging-wall side the strata dip to the east at an average angle of 25°, while on the other side the beds within the limits of the district lie very flat.

Perhaps the greatest difficulty found in accepting this great throw of 3,600 feet across the bedding lies in the fact that on both sides of the fault plane within the limits of the district are found similar rocks of the impure calcareous nature of the Empire-Helena beds, showing that these formations must have a total thickness greater than 3,600 feet. Walcott has given the estimated thickness of the Helena limestone as determined at Helena as 2,400 feet and of the Empire shale at Marysville as 600 feet, making a total of but 3,000 feet. Measurements on the line of section D-D, however, from Sawmill Gulch to the outcrop of the Marsh shale, gave a thickness of 4,500 feet to the Helena limestone, and there is no evidence of reduplication by faulting within these limits. The entire thickness of the Helena limestone was judged to be at least 4,000 feet, equaling its equivalent, the Siyeh limestone of the Lewis and Livingston ranges, and this would be sufficient to explain the presence of the similar formations on the two sides of the fault within the Bald Butte region.

AGE.

The age of this fault relative to the igneous intrusions can not be told with certainty, but on the presumption that the location is approximately correct, the origin apparently antedated the intrusion of the Belmont porphyry dikes, since these dikes are found of similar nature and of equal abundance on both sides of the fault plane. The force of this statement lies in the fact that it is not probable that dikes of this thinness, discontinuity, and rather local distribution would occur of practically uniform character throughout a height of 5,000 feet. Yet, if the faulting was later than the intrusions, dikes once that distance apart would now lie at the same elevation.

COMPARISON OF THE TWO FAULTS.

The two great faults thus far described bear certain resemblances, both having a great downthrow on the southern and southwestern sides. They are parallel to the southwestern side of the Little Prickly Pear domal uplift and lie not far from its margin. The uplift in this region therefore is seen to be in considerable measure due to marginal faulting rather than to simple domal folding.

BLOCK FAULTING SURROUNDING THE QUARTZ-DIORITE AND GABBRO AREAS.

GENERAL OUTLINE.

A careful study of the region surrounding the batholith and of that between the Gravel Range and Little Prickly Pear Creek indicates that a great number of faults running at various angles have cut the strata into blocks a few hundred to a few thousand feet across, which have become lifted and tilted with respect to each other. Around the batholith these are rather closely associated with its margin, but as the contact line is not offset, the greater number of them do not appear to have cut the batholith. North of Little Prickly Pear Creek considerable intrusions of gabbro are rather closely associated with the faulting. These relations resemble somewhat the block faulting or regional shattering of the Globe region in Arizona, caused by extensive intrusions of diabase into Paleozoic quartzites and limestones and termed by Ransome intrusion faults.[a]

The differences in the Marysville district lie in the general absence of igneous intrusions into the fault planes and in the fact that these planes do not take part in forming contact surfaces of the main mass of igneous rock. On the contrary, the batholith cuts across the several fault blocks with little or no regard for the presence of the faults. This relation indicates that the faults are older than the intrusions, but probably associated with them in origin. As later movements may have taken place on older fault planes and independent younger faults may have also arisen after the igneous intrusions, the age of many individual faults will be in doubt, yet on the whole they may be grouped into several systems whose age relations are determinable.

In the zone of faults located around the batholith the field evidence is extremely obscure, and only in a few cases have they been directly observed, most of them being determined and located in the office to meet the necessity of several lines of structural evidence. They are, however, of importance in relation to the intrusion of the batholith, and the subject must be developed in some detail in order to show the reasons for their location.

DIFFICULTIES OF DIRECT OBSERVATION.

As fault planes are surfaces of weakness, they are very commonly occupied by drainage lines, and the plane itself is thereby concealed from direct observation. In the presence of such difficulties the next most conclusive evidences consist in a

[a] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903, pp. 97-107.

dissimilarity of formation on the two sides of the fault plane, which can not be explained by the supposition of one formation normally overlying the other or, in the absence of stratigraphic differences, a change in dip or strike on the two sides too marked to be due to folding. The difficulty of applying these criteria in this region is due to three causes, as follows:

First. The majority of the fault planes do not show a soft clay or brecciated zone, the surface weathering exhibiting but little regard for the fault lines.

Second. The sedimentary formations are of great thickness and without sharply marked members, several thousand feet of them around the batholith consisting of calcareous strata with varying amounts of aluminous and siliceous impurities, which on metamorphism are turned into hard-banded hornstone and other more richly calcareous beds, being locally silicified. Again, in the northern part of the district is a great thickness of red to dark-gray sandy and shaly sediments. As the majority of these faults probably have throws of no more than 100 feet, and as the ground is usually covered with soil and grass, a moderate amount of faulting fails to bring dissimilar formations into proximity. Consequently in most cases this means of identifying faults will fail.

Third. The orientation of the beds throughout the entire district is so inconstant that careful work is necessary to decide where it is due to local bending and where to faulting.

In view of these difficulties several lines of evidence were worked out, the most conclusive being what may be called a method of determining faults by strike contours. As, so far as the writer is aware, just this application has never been described, though it has doubtless been employed by many, it will be explained in some detail.

DETERMINATION OF FAULTS BY STRIKE CONTOURS.

When it is desired to express the underground structure on a map of folded sedimentary formations, contour lines may be drawn on any chosen bed. This method was employed many years ago by the engineers of the anthracite coal companies of Pennsylvania, the contour lines being drawn on a certain coal bed and the contour map representing the folds and varying depths of the coal throughout the basin. This plan was adopted by the Second Geological Survey of Pennsylvania, and contour maps of many of the coal basins were published. The same method has since been frequently employed in the folios of the United States Geological Survey to elucidate the folded structure of the Appalachians.[a] The present application consequently is merely the use of an old device for another purpose and is believed to be one of the most certain methods for the location of obscure faults in all cases where the faulting has been attended by a change of dip or strike in one of the blocks. The method is illustrated in Pl. XI and was applied in the following manner: As large a number of exact observations of dip and strike were obtained as possible, only smooth, well-defined beds being chosen for measurement. Next the strike lines were extended as if they represented the intersection of a certain bed with a horizontal plane. Except in a region of recumbent folds or flat thrust faults, the dip and strike will be practically the same for limited depths on the same vertical line. This strike contour then may represent the intersection of the stratification

[a] See, for example, Pocahontas folio: Geologic Atlas U. S., folio 26, U. S. Geol. Survey, 1896.

with horizontal planes of varying depth. Suppose such planes to be passed at an approximate vertical interval, in this case 250 feet. Where the beds are flat these strike contours on the same bed will be shown farther apart; where steep they will be projected closer together. This construction will give a true view of the sedimentary structure for limited depths below the surface. But it is well appreciated that a contour line in ordinary topographic maps can not have a loose end, no matter how great the extent of the map, the contour nowhere ending except by returning into itself. The same holds true of the strike contours. Therefore where, as may be especially noted in the region north of the batholith, the strike lines drawn from one locality do not at all match in closeness and in number those drawn from another locality the only possibility is that a fault plane separates the two localities, and on this plane the contours of the adjacent blocks are continued.

It is seen that the precision with which faults are located in this manner will depend entirely on the number and accuracy of the observations of dips and strikes and the relative tilting of adjacent blocks. A great many observations were taken in the region immediately surrounding the batholith, and from these a series of faults has been located; but greater accuracy would require that after such office work the region should be revisited and the stratification more closely examined along the lines of the fault planes in order to determine their position more exactly and to check the dips and strikes taken. In the case of the Marysville region this could not be done, with the result that this system of faults has not been located with as much precision as the method allows. In a few instances the faults determined in this manner coincide with drainage lines and in others with the boundary of the highly metamorphic zone, but most of them show but little relation to other features and could not have been located except by this method.

MAPPING THE LIMITS OF THE METAMORPHIC ZONE.

Several other methods of determining the sedimentary structure were employed. Of these the next to be described is the relation of the contact metamorphism both to the proximity of the batholith and to the composition of the sedimentary horizons affected. It is found on tracing the limits of extreme contact metamorphism that for distances of half a mile or so the metamorphic limit will coincide with the stratification and then break sharply across it with an offset which may be a few hundred feet or possibly half a mile in width. This feature is well illustrated on the northern side of the batholith. The question constantly arises as to how much of this irregularity is due to an irregular penetration toward the surface of the metamorphosing agents, either the batholith or its emanations producing local variations in metamorphism, which advances in places into higher beds and gives them a resemblance to those stratigraphically below, and how much is due to faulting of a single formation of such composition that on metamorphism it is converted into resistant hornstone. In the case of contact action on a pure limestone the possibility must be held in mind of siliceous and basic magmatic emanations impregnating the marble and converting it into a hornstone, especially as in some regions such a process has acted extensively.[a]

[a] Lindgren, W., Genesis of the copper deposits of Clifton-Morenci, Arizona: Trans. Am. Inst. Min. Eng., September, 1904.

This question is discussed in detail at the conclusion of the chapter on contact metamorphism (pp. 143–150), and it is shown that while in the immediate neighborhood of the batholith or along brecciated zones additions have taken place, especially to calcareous strata, such additions have not been the cause of metamorphism and do not extend to the metamorphic limits. On the contrary, in the outer portions of the metamorphic zone beds of diopside or tremolite hornstone lie in places between unmetamorphosed limestones in positions not favorable for the passage of vapors. Further, they exhibit a homogeneous texture and a structure strictly conformable to the stratification and correspond to originally siliceous limestones of the Helena formation, such as are known to exist, from which the carbonic acid has been completely or in large part expelled.

This feature is best noted in the cliffs of hornstone 1 mile north of Drinkwater Gulch and the nearest approach of the batholith, where there is a layer about 50 feet thick of diopside hornstone, extremely hard and of a light-gray color, consisting of about 85 per cent of diopside, with small amounts of tremolite, muscovite, and calcite. Surrounding this cliff, both above and below, are but slightly metamorphosed limestones, buff on weathered surfaces and light gray to blue on fresh fractures. The very flat dip and the absence of local intrusions forbid this being considered as a horizon showing local siliceous impregnation. The evidence on this latter point is more fully discussed under the topic of contact metamorphism.

From the above statements it may be concluded that a metamorphic limit will tend to follow certain horizons and be rather sharply marked; that where it cuts across the strata the limit of metamorphism should be very indefinite, and, further, that if the metamorphic zone consists of a lime-silicate rock it usually does not correspond with more or less originally pure limestones, but rather with siliceous or argillaceous limestones. With these principles in mind, a number of faults may be determined which would otherwise escape detection. These will be briefly described.

Beyond the north end of the batholith, 1 mile north of Gloucester, the topography is determined by hard ridges of diopside hornstones interbedded with softer tremolite limestone, the outcrops running obliquely down to Piegan Gulch. Above the hornstones lies relatively unmetamorphosed thin- to thick-bedded limestones. Then for somewhat over half a mile the sharply distinct metamorphic limit runs northeastward across the bedding, hornstones on one side and blue limestone chips showing in the soil on the other, leading to the belief that a fault of considerable throw separates the two. The only difficulty here results from the creep of the hornstones beyond their outcrop down the steep hillsides. Beyond this the metamorphic limit for three-fourths of a mile follows the bedding planes, blue and buff limestones lying to the north of hard diopside hornstones. Then another reentrant angle nearly half a mile in length is found on Deer Creek, followed by the hornstones sweeping outward around Edwards Mountain, where a short distance to the north are found rather massive blue limestones. If all the hornstones belong to one stratigraphic horizon, these boundaries can be explained only by supposing one fault of considerable throw to exist on the west side of Deer Creek and a series of step faults on the east side. This conclusion is corroborated by another line of evidence to be mentioned presently, under the heading "Determination of faults by vertical sections."

On the eastern side of the batholith the relations are more difficult to determine and it seems probable that here the metamorphism has extended for considerable distances into the Helena limestone, thin-bedded limestones being found interbedded with light-colored hornstones between Edwards Mountain and Trinity Hill. On both sides of Silver Creek hard light hornstones appear with but little marble, and the same rock is found along the eastern half of Drumlummon Hill, passing into horny limestones on reaching Sawmill Gulch.

For reasons stated in the chapter on metamorphism (p. 116) it seems probable that silicification from the magma of the batholith has taken place here to a considerable extent and so no fault line is drawn between the hornstones and limestones in this locality. Immediately south of the batholith the hornstones contain a greater amount of limestone and marble.

DETERMINATION OF FAULTS BY VERTICAL SECTIONS.

The northern boundary line between the Empire and Helena formations, lying immediately south of the east-west fault of the Little Prickly Pear region, was carefully mapped. The strata are unmetamorphosed and the top of the Empire beds was taken at the line separating flaky, grayish-green shales below from well-defined buff and pale-blue limestones above. Within the Helena formation are many beds of shaly limestones and limy hornstones, so that no sharp transition occurs, but in general the line can be followed with reasonable precision. Furthermore, it is noticed that a syncline runs across the district between this boundary and the metamorphic zone north of the batholith. This same boundary should outcrop, therefore, in the metamorphic zone and the hornstone cliffs there presumably correspond to the shales of the more northern outcrop.

By carefully noting the dips between the two outcrops three sections were drawn to see if the one corresponded structurally to the other. It is to be noted that the majority of the faults radiate from the batholith on the northern side and that each vertical section had to be constructed within a single block. Such sections were constructed for each of the larger faulted blocks in addition to the sections given in Pl. II. As the northern and southern boundaries of the Empire formation on these sections agree it may be taken as evidence that the fault offsets near the batholith were correctly determined and that cross faults between the two boundaries of the Empire do not materially alter the relations. The outcrops determined in this way checked up to a fair degree of accuracy with the field location of such points.

GENERAL CHARACTER AND RELATIONS OF THE BLOCK FAULTS.

Wherever these faults are exposed they are seen to be normal in character. They may be divided into major and minor faults. The latter are as apt to be exposed as the former but have a throw of only a few feet. Mineralization has occurred in many of the fault breccias and, though in few cases of economic importance, the prospect shafts opened on these have enabled a number of them to be studied.

The general effect of the faulting has been to raise the crust blocks on the side toward the batholith, steepening the dip where it was originally away from the granite, flattening it where it was toward the granite. This effect is very apparent in a general view of Pl. XI. There is no evidence that these faults cut the granite, since if such were the case offsets in the boundary would be expected to occur, and yet they are clearly related to it. The conclusion would appear to be that the faulting immediately preceded the invasion of the batholith, being caused by the upward pressure of the igneous mass, but that when the batholith reached its final limits it cut across the various blocks, making a contact which shows little or no relation to them. Not only has normal faulting taken place, but the crust blocks must have changed their form to still fit compactly after rotation, a change which has doubtless been facilitated by the abundant systems of joint planes within the metamorphic zone, the adjustments probably resulting in many of the minor faults. Such regional brecciation in connection with intrusion has been discussed by Ransome,[a] who says:

> The number of the dislocations and the comparatively small size of the fault blocks indicate that the beds did not at the time of their rupture lie under great load, and the facility with which the blocks were shifted by the magma is evidence that the intrusion also took place under no great superincumbent mass. * * * The fact that an overwhelming proportion of the faults are demonstrably normal is of prime importance. * * * The fact that beds when normally faulted tend to occupy a greater area than before their dislocation can not, however, be taken as evidence that tangential tension has been a cause of fracturing. The existence of such a stress is geologically improbable, and even if set up it would be relieved by the first fracture formed. The only conceivable stresses that can offer any satisfactory explanation of the faulting * * * are those acting in directions more nearly vertical than horizontal, such as would result from differential elevations or subsidences over the area. The behavior of the rocks may be likened to that of a large and thick sheet of plate glass lying horizontally upon an uneven surface and fissuring under its own weight in consequence of unequal support. The generally rather thick-bedded and brittle rocks of the quadrangle are, however, far more easily and thoroughly fissured by geological processes than would be the relatively insignificant mass of glass by the feeble stresses of the suggested experiment.

These conclusions would seem to apply in large part to the faults surrounding the Marysville batholith. Brögger[b] has also noted what he terms an enwreathing system of faults surrounding the Drammenfjord batholith. Such features, however, have not been noted as usual and stand in contradistinction to the zones of schistosity surrounding other and presumably originally more deeply seated batholithic masses such as those of the Black Hills and New England.

VEIN FISSURES MARGINAL TO THE BATHOLITH.

INTRODUCTION.

The fissure veins which give the district its mineral richness and economic importance are situated around the batholith uniformly within the metamorphic zone, though this zone at Bald Butte is more than a mile and a half from the nearest outcrop of the granite. From the degree of metamorphism, however, and from structural evidence which is given in detail under the heading "Underground extensions of the batholith," it is believed that the granite underlies all of the

[a] Ransome, F. L., Geology of the Globe copper district, Arizona: Prof. Paper U. S. Geol. Survey No. 12, 1903, p. 105.
[b] Brögger, W. C., Die Eruptivgesteine des Kristianiagebietes, pt. 2, 1895, pp. 116-153.

metamorphic zone at no great depth. The veins are thus everywhere in close relation to the granite. Many of them cut the granite, but in every case near the margin, none being known in the center of the batholith. A complete field study of the veins and their contents has been made by Mr. W. H. Weed[a] and here only those features of general geologic importance necessarily treated in a general discussion of the district will be described.

CONCLUSIONS ON ORIGIN OF THE VEIN FISSURES.

Before presenting the detailed evidence in regard to the nature and origin of the veins it will be well to state the conclusions reached in order that the bearing of the details may be perceived. It is believed that these veins, as shown by their structural and mineralogical features, are due to contraction effects on the margins of the granite mass, at that time recently solidified and cooling.

STRUCTURAL EVIDENCE.

The structural evidence consists of the relation of the veins to the vicinity of the contact, or at least to the metamorphic zone; the fact that their courses are either approximately parallel or at high angles to this contact surface; the parallel and branching character of the fissures; the generally shattered and infiltrated character of the walls; the dying out of the vein fissures, many of which are continued in parallel lines offset to one side; and lastly the absence of marked throw along the fissure planes.

MINERALOGICAL EVIDENCE.

The mineralogical evidence is found most clearly in the study of the vein fillings and alteration of the walls in the Bald Butte mine, since it is believed that fluorite, which is there a characteristic mineral, is indicative of magmatic emanations, though the deposition may take place under hydrothermal as well as under pneumatolitic conditions. Fluorite is often found in the contact aureole of granitic masses and is presumably given off as acidic vapors in water solutions from solidifying magmas. The probability of this view of the origin of the vein fissures is seen when the effects of such contraction from cooling are considered in some detail. The central portions of a granite intrusion the size of the Marysville batholith would cool slowly and as a whole; the contraction would be equal throughout and there would be little or no tendency to form wide contraction cracks in any direction. This agrees with the absence of vein fissures in the center of the intrusion. The cooling of the zone of contact metamorphism and of the marginal portions of the batholith, however, would result in a shrinkage away of those portions from the surrounding rocks, producing fissures parallel to the contact; while the lessened circumference of the outer zone, caused by its cooling before the center, would tend to set up another set of fractures more or less radial in nature.

[a] Preliminary papers on the Marysville ore deposits found in Bull. U. S. Geol. Survey No. 213, 1902, pp. 88-89; Trans. Am. Inst. Min. Eng., vol. 33, 1902, p. 745.

This view of the origin of the Marysville fissure veins has already been expressed by Weed,[a] who says:

In addition to the pneumatolitic deposits on igneous contacts and those in altered strata near the contacts there are many productive mines working true veins cutting the igneous rock and the contact rocks above them. Such vein fissures are caused both by the contraction due to the crystallization and cooling of the igneous rock and by the shrinkage of the metamorphic zone above the igneous rock. Examples of this type have already been mentioned. As shown by Pirsson,[b] the radial fissures which form so remarkable a feature of certain igneous centers are not due to the initial expanding force of the intruded magma, but to the contraction cracks. The vast amount of heat given off by the cooling magma effects a considerable expansion of the surrounding rocks. As the magma and its surrounding shell of heated sediments cools down it must contract, and this contraction will result in a cracking both of the igneous rock and the contact zone; and if the rocks of the contact zone are homogeneous the cracks will assume a more or less radial position. If these cracks extend to a depth sufficient to reach this molten magma, they will be filled and dikes will be formed; if not, cracks become channels for pneumatolitic vapors and later circulating waters, and thus pegmatitic veins and true mineral veins may be formed and may merge into one another. It is possible that the (now brecciated) Granite Mountain vein at Phillipsburg, and the very productive veins at Marysville, Mont., may have originated in this manner. But in addition to radial cracks the shrinkage would also tend to produce cracks parallel to the borders of the intrusion[c]—a phenomenon observed in casting and also in the cooling of lava sheet—as, for example, those of Obsidian Cliff, in the Yellowstone Park region, a discussion of which has been given by Iddings.[d]

If it is considered in advance that the details given in the next section justify the foregoing conclusions, it is seen that the Marysville fissure veins are excellent examples of the closeness of relationship between igneous eruptions and the associated ore deposits, the latter being formed through the agency of the primal heat of the magma and representing a portion of the magmatic emanations carried off in part by primal waters, in part doubtless through leaching by heated meteoric waters. These views have been especially urged in recent years by Kemp, Lindgren, Spurr, Suess, Vogt, and Weed, in contradistinction to another theory which tends to minimize the agency of the primal heat and emanations and assigns the chief cause of the accumulation of the ores of fissure veins to the ordinary circulation of meteoric waters, the igneous rock simply serving as the holder of the precious metals in a disseminated state.

On the assumption that the correct view is that of the intimate relationship of the igneous intrusions to the vein fissures and their fillings, it may be seen, however, that some little time elapsed between the solidification of the batholith and the opening of the vein fissures, since not only had there been a period of aplitic and pegmatitic injections, but a number of later intrusions of porphyry had occurred previous to the formation of the vein fissures. It would appear probable, therefore, that the fissure veins, if indeed they are contraction effects, belong not to an initial stage but to the final stages of cooling.

DETAILED RELATIONS OF FISSURE VEINS.

The preceding statements are of sufficient geologic importance to require some presentation of the details on which they are based, and accordingly a description of the more important occurrences is given.

[a] Weed, W. H., Trans. Am. Inst. Min. Eng., vol. 33, 1903, p. 745.
[b] Pirsson, L. V., Complementary rock and radial dikes: Am. Jour. Sci., 3d ser., vol. 1, 1895, p. 116.
[c] For ore deposits of this type see Beck, Richard, Lehre von den Erzlagerstätten, 1901, p. 182, fig. 119.
[d] Iddings, J. P., Seventh Ann. Rept. U. S. Geol. Survey, for 1885-86, 1888, pp. 249-295.

DRUMLUMMON MINE.

Description of veins.—The Drumlummon mine shows a set of intersecting and branching veins, the principal one of which is the Drumlummon. A brief description of these has been published by Weed,[a] whose statements in regard to the Drumlummon vein are quoted as typical for the whole system.

It is a fault plane with white opaque quartz inclosing angular fragments of black, green, and drab slates, which are sometimes distinct and unaltered and at others have been much decomposed. Where the ore bodies are found the replacement has been complete and the former presence of the fragments is only recognizable by the outlines of the banded quartz. The vein has distinct walls, which are rather wavy and vary from 2 to 20 feet apart. Southward the Drumlummon vein itself splits into several branches. It has been developed for a distance of about 3,000 feet horizontally and to a depth of 1,600 feet; but no ore was found below the 1,000 foot level. This vein, which is the largest and the most productive in the district, consists in its lower levels of a mass of angular rubbish, derived from the walls of the fissure, and in places cemented by quartz, in other places still retaining its original character. Compared with the Empire and other veins, it is much more extensive, both laterally and vertically, and the values have gone deeper. In general it may be said that all the veins of the district carry rich ores in bonanzas and ore shoots within the first 200 feet from the surface, but that in depth the ores rapidly decrease in value until the vein is no longer workable. It may also be said that the ore shoots were well defined and the intervening vein matter barren and unworkable. The pitch of the ore shoots conforms to the usual habit, dipping to the right when looking down the dip of the vein. The ores consist of sulphides and sulphantimonides of silver, with gold aggregating 60 per cent of the total value. In the upper levels the ore is somewhat oxidized and in the ore shoots of the Drumlummon mine carried extremely high values.

Pl. VIII (p. 68) shows that the arrangement of the veins is rather complicated. The New Castletown is a branch which separates between No. 1 and No. 2 shafts, runs parallel with the main vein for a short distance, and then diverges first at an angle of 30° and finally, beyond the limits of the workings on the fourth level, at an angle of 60°, being then parallel to the trend of the North Star. The Old Castletown appears below the second level as a connection between the Drumlummon and New Castletown near their junction, and as seen on the fifth and sixth levels appears to be governed in its direction largely by a neighboring granite intrusion forming the hanging wall. Above and below this it becomes irregular.

The Drumlummon vein splits at the north end, a large horse being inclosed between the two divisions of the vein. The Frankie is a parallel vein 540 feet east on the fourth level, prominent where the Drumlummon disappears and dipping toward it at an angle of about 70°. The other important vein is the North Star and its continuation, the Empire. This cuts across the Drumlummon and on the seventh level, where the relations are well exposed, it is seen to be younger than the Drumlummon, but has not faulted the older vein, which is here rather poorly developed, consisting of a mesh of quartz veinlets in brecciated slates. On the west side the North Star has been stoped to a maximum distance of 750 feet from its intersection with the Drumlummon and has been prospected for a short distance farther west. Down to the fifth level the vein is practically vertical; for the next 400 feet it dips to the south at an average angle of 70°, and is then again vertical for 300 feet, the greatest depth to which it is developed. Below the twelfth level, as shown by the workings on the sixteenth, it probably dips once more steeply to the south. On the west the vein

[a] Weed, W. H., Contributions to economic geology, 1902: Bull. U. S. Geol. Survey No. 213, 1903, p. 89.

branches and from the seventh to the eleventh level, over that distance where the main vein dips to the south, the branch is continued eastward as a closely parallel vein, in some places meeting, but for the most part distinct from the main vein and running under it. Thus the North Star vein is seen to branch downward as well as laterally. Beyond the intersection with the Drumlummon this vein, here called the "Empire," swings to the northeast, making an angle of about 30° with the Drumlummon and therefore assuming the direction of the New Castletown near its junction with the Drumlummon.

Character of vein fissures.—Pl. VIII and the above description show that in this part of the mine the veins tend to run in three directions, the Drumlummon N. 15° E., the Empire N. 35° E., and the North Star N. 80° E. The southward extension of the Drumlummon vein in the 9-Hour ore body trends in the direction of the Empire system. Throughout its course this vein maintains a parallelism to the general line of the granite contact, while the North Star cuts across it at an angle of about 60°.

The Drumlummon vein exhibits a tendency not to cut the larger intrusive bodies. Where these are dikelike masses, the main vein or one of its branches runs parallel to the intrusion, the latter in places forming one of the walls. Where the intrusion is irregular and runs across the direction of the vein fissure, the latter may split up against it, becoming also irregular, and large masses of vein quartz and replacement quartz may be formed This is especially to be noted on the fourth and eighth levels in the southern part of the Drumlummon mine. Again, in places oblique stringers given off by the main vein thin out in a short distance with no apparent continuation, except perhaps as fault planes. This feature may be well observed on the tenth level north of No. 2 shaft. Locally the fissure is not continuous but is offset, the two parts tapering out as they pass by each other, with possibly a multitude of parallel veinlets in the intermediate rock, as shown on the twelfth level. A study of the walls, especially where branch veins or closely parallel veins occur, shows that the rock must have been much shattered in all directions since a mesh of quartz veinlets penetrates the intermediate country rock. This may be observed in the granite as well as in the hornstones. The North Star vein, cutting across the granite contact, shows no variations in width depending on the nature of the wall rocks, though the detailed features of the walls depend on the character of the rock and its manner of fracture.

Age of vein fissures.—The age relations of the veins to the neighboring intrusions are clear. Not only is the main granite mass cut by them, as in the case of the North Star, but dikes and irregular bodies, while they have shown some influence in governing the directions of the fissures, are cut by them also. Again, while the granite in many places near its margin shows acidic phases there were later injections of alaskite-aplite and pegmatite into the marginal granites and the bordering hornstones. These are also cut by the vein fissures and the distinctness of the vein fillings from pegmatitic fillings is marked throughout, indicating that the veins belong to a later, separate, geologic phase.

The relation of the Drumlummon vein to the porphyries in the southern part of the mine is also noteworthy. These porphyries, which are distinct in character from the aplites, were found in one place at the surface in two parallel dikes cutting the granite. In the mine a large, irregular mass occurs which has been described under "Drumlummon porphyry dikes" (page 52), which is cut by the vein fissure, the relations of the two being best exposed on the ninth and tenth levels. This indicates that between the invasion of the granite and the origin of the vein fissures sufficient time elapsed for the solidification of the granite and for the intrusion into it and into the neighboring hornstone walls not only of aplites and pegmatites, but of a distinct set of porphyritic dikes solidifying with a microcrystalline groundmass.

BELMONT MINE.

Description of veins.—The Belmont mine, situated on the eastern slopes of Mount Belmont, has been developed on a system of veins running in general at a high angle to the contact surface. What is known as the main or south vein, running from west to northwest, forks to the west into two main branches which diverge at a slight angle, and the southern of these branches splits again. The north vein begins at a point about 100 feet north of the main vein, bearing at first northwest and then nearly north. This vein, as shown on the map of the second level, tapers out into a fork at the east end and passes into a barren fault to the northwest. The dip of the vein is toward the main vein at an angle of 70° to 75°. The veins are very short, and the ores are found only from the fourth level to the surface. They do not continue across the large dike of porphyritic hornblende-quartz diorite which separates this arm of hornstones from the main sedimentary body, but, as mentioned above, show a disposition to branch and taper out. Where the branches separate, the country rock near the junction shows considerable brecciation with infiltration of quartz veinlets, and many such parallel quartz seams may be noted in the granite in association with the main vein, even where the latter does not branch. In the hornstones the vein matter is more sharply limited to the principal fissures, but these have an aggregate width as great as in the granite, indicating no greater opening of one than of the other. Within the mineralized zone the average aggregate width of vein quartz is estimated at about 3 feet per 100 feet of granite. On the fifth level the vein quartz shows widths of 3 to 5 feet, but contains many opening vugs and is almost barren.

Accompanying faults.—A series of east-west normal faults with dips to the south, later than the veins, in some places follow the strike and in others cut across the veins. These ore deposits have probably received considerable secondary enrichment in which the fault fissures have taken part. Where the later strike faults follow one of the vein walls it is impossible to tell how much of the faulting may date from the origin of the vein fissure and how much may be later than the vein filling and due to more recent adjustments. On the second level, however, the total amount of the faulting may be observed, and in one instance the original movement may be differentiated from the later. To state the case in detail, on this level the rather flat bottom surface of the hornstones is offset from 15 to 20 feet vertically where each vein crosses it. On the north branch of the south vein the strike fault departs from the vein fissure near the contact with the granite, and there the vertical offset of about 20 feet in the granite contact is seen to be probably due to the original opening. Between the two branches of this vein some further vertical offsetting of the contact surface takes place, but as the details are not exposed it is not known whether this is a part of the original irregular igneous contact surface or due to later fissuring and faulting. Elsewhere on this level later strike faults accompany the veins across the contact and obscure the relations, but it is clear that though the development of fault clay and breccia has been considerable the actual amount of throw on these faults has been not more than a few feet at the most, and the original throw on the vein fissures has also been comparatively small, probably averaging 10 feet on each, but nowhere over 20 feet.

BALD BUTTE MINE.

Description.—The Bald Butte mine is situated just beyond the Continental Divide, on the western slope, in the extreme southwest corner of the district. The workings are partly underground and partly open cuts, and the larger veins are clear instances of filled fissures. The open cuts follow the course of the large dike of Belmont porphyry, in which they are excavated. The prophyry, with the micro-diorites and hornstones which form its walls, especially the hanging wall, are intimately and minutely fractured, the direction of the principal set of fractures running parallel to the course of the dike. The cracks are infiltrated with quartz and fluorite and the wider seams show many alternations of these two minerals, the fluorite on the whole appearing to be of later origin and in one case at least to have penetrated the primary quartz along a second set of fractures. They are not sharply distinct, however, as some deposition of quartz has followed the fluorite.

Metasomatic alterations of wall rocks.—The surrounding rocks show various degrees of alteration. The typical hard greenish-gray banded hornstones of Bald Butte consist in their normal state largely of tremolite, actinolite, and green biotite, all microscopic, with feldspar, some quartz, and small amounts of apatite and epidote. Adjacent to the seams of quartz and fluorite a considerable degree of alteration is found. In one thin section the original rock consisted largely of an aggregate of colorless grains of diopside. This had been thoroughly brecciated and on the margin of the fractures the diopside had been converted into a mass of pleochroic hornblende needles tending to stand at right angles to the seams, and in places these same needles project into miarolitic cavities which have been later filled with quartz. Some areas show minute fluorite grains scattered through the body of the rock and some infiltration of quartz may also have taken place, but this would be naturally difficult to separate from that which may have been original in the rock.

The petrography of the large dike of Belmont feldspar porphyry has been described in Chapter II (pp. 49–51). The rock consists of phenocrysts of an acidic plagioclase, lesser amounts of biotite, and a few crystals of hornblende, the whole set in a microgranitic groundmass dominantly feldspathic. Where moderately altered within the Bald Butte zone of mineralization the plagioclase and groundmass are largely sericitized and the original biotite is in great part destroyed, its place being taken by secondary mica, light green in thin section, more or less quartz, and in places feldspar. Iron is scattered through the rock as a hydrous oxide dust. In the more completely altered rock the feldspars, both phenocrysts and groundmass, are transformed into a mass of sericite and finely granular quartz. The biotite phenocrysts still show unaltered laminæ, but these are interleaved with fine-grained layers of quartz, fluorite, and sericite. Like the adjacent hornstones the whole rock mass has been minutely shattered and infiltrated with quartz and fluorite.

SUBORDINATE MINERAL VEINS.

The features of the Drumlummon and Belmont mines have been described in some detail, as they show clearly their relations to the batholith. Time did not permit the writer to examine the geologic relations of other mines of the district. It may be noted, however, that a number of the smaller mines and prospects are opened on mineralized and cemented fault breccias. Usually, as in the case of the Little Ox mine, north of the batholith, they lie within the metamorphic zone, though this can hardly be said of the now abandoned Woodchuck mine, situated on the bluffs immediately north of Little Prickly Pear Creek.

The Big Ox mine is noteworthy, however. This lies 2¼ miles north of the batholith, within a zone of local metamorphism perhaps a quarter of a mile wide by half a mile long, and is not more than 700 to 1,000 feet distant from a dike of quartz diorite of slightly porphyritic facies which dips at an angle of 70° to 80° toward the batholith. Attention has already been called to the resemblance of this dike rock to the normal rock of the batholith, the granularity of the rock and the extreme metamorphism of the region to the north within which this mine is situated leading to the belief that a larger body of this same magma lies at no great distance below. The ore consists of true vein deposits of quartz and calcite, holding a little galena, chalcopyrite, and light-colored sphalerite. A sheet of microdiorite shows pyrite deposited within the planes of fissility and an alteration similar to that noted at many places in the microdiorites adjacent to the batholith. The workings, so far as examined, are on a flat bed on the hanging-wall side of a fault parallel to the dike and dipping from 50° to 60° NW.

MINOR NORMAL FAULTS AND VEIN FISSURES.

These smaller faults and vein fissures are noted chiefly in the mines and prospect pits, but here and there on cliffs. Their age is usually not determinable with certainty, but some from the character of the mineralization are judged to belong to the epoch of the larger fissure veins, while others are much younger and slight movements may still occasionally occur upon them. It is intended to describe under this head such as are with certainty or probability younger than the fissure veins related to the margin of the batholith.

STRIKE FAULTS AND CROSS FAULTS.

First and most prominent are the strike faults encountered in the mines. Later fractures, following the surfaces of least resistance, have in many places taken advantage of the older vein fissures and may follow them for some distance. In such cases their presence is noted by selvages of fault clay forming one wall of the vein and locally by a grinding up of the vein contents, so that in mining running ground is encountered and close timbering is necessary. The well-developed fault zones are marked by a clay several feet in thickness holding rounded and altered fragments of the wall rocks. Again, clay may be largely absent and the plane of yielding may be marked by a zone of crushed and softened wall rock. As the direction and magnitude of the forces leading to these later adjustments do not seem in general to have coincided closely with those of the earlier forces opening the vein fissures, the later faults do not parallel the veins throughout, but after following the older surface for some distance, either die out or branch obliquely from it.

Cross faults, at a considerably different angle, also occur. In many instances, where a considerable development of fault clay and breccia exist, it may be shown that the total throw is not more than a few feet at the most, so that the magnitude and prominence of a fault zone must not be used as a guide to the throw of the fault. In view of the development of these fault zones, as shown in the mines, it seems not improbable that many of the smaller side streams of the region may be adjusted to them.

BRECCIATED ZONES AND VEINS NORTH OF LITTLE PRICKLY PEAR CREEK.

Aside from the strike faults and cross faults developed in the mines of the batholithic margin and the metamorphic zone, another region of later faults and vein fissures to be noted is that lying to the north of Little Prickly Pear Creek and west of Canyon Creek. This region has already been mentioned in connection with the Tertiary silicified gravels and the conglomerate which in places overlies them.

The description of these later faults and vein fissures may be begun with those farthest west. On the bluffs along the north side of Little Prickly Pear Creek a number of hard, rough reefs stand out prominently. On examination these are found to be brecciated, vertical, north-south zones of the Spokane shale, which have been so hardened and cemented by silica-bearing waters as to be markedly more resistant than the unaltered rock. The mineralization has consisted more in a silicification of the brecciated wall rocks than in the deposition of quartz in open fissures, and in the process the reddish-brown color of the shales and sandstones has become changed to an ocher. Along with the brecciated zones are many gashes of vein quartz, represented on the geologic map (Pl. I) by short dashes. The Woodchuck mine is driven on a fault which probably belongs to this same system, and the development work has been done on a fault breccia, but, as the abandonment of the work indicates, the ore is not profitable and the mineralization of this system in general appears to be almost or quite barren of the precious metals.

Farther north, in front of the Gravel Range, a prominent individual vein may be traced for upward of a thousand feet, the vein quartz being from 2 to 3 feet wide. The walls have been impregnated with siliceous solutions to a width of 20 to 50 feet on each side and, like the brecciated zones to the south, are stained yellow from the deposit of limonite. Similar though smaller veins are found at intervals along the bluffs to the east as far as Procter's ranch, and a prominent group with a northwest bearing are found along the conglomerate-capped hill north of Procter's.

These veins are younger than the andesites and the conglomerates with which they are associated, since they cut the latter; and in Chapter II reasons have been given in detail (pp. 34–38) for believing that these conglomerates were once the basal gravels of Tertiary age which are still found in the Gravel Range and which have been silicified by the rise and diffusion into them of the vein waters.

Arguments have been advanced for believing that the precious-metal bearing veins associated with the batholith and its metamorphic zone are but a little younger than the batholith, having been caused by the cooling following its consolidation and filled with deposits given off from it by the aid of waters that were probably in part of magmatic origin. Between this epoch and that of the andesite flows and Tertiary gravels a long period of erosion elapsed, sufficient to trench the valleys several thousand feet below the level reached by the once plutonic rocks of the batholith. This second epoch of fracturing and vein filling is later still. Since the silicified gravels have been preserved, however, by the fact of their silicification, while the surface of the surrounding country has been lowered several hundred feet, it is evident that this last stage of vein formation can hardly belong to the present geologic epoch, but must be ascribed with probability to the later Tertiary.

Thus there are in the Marysville district evidences of two distinct epochs of fracturing and vein filling, separated from each other by a considerable portion of Tertiary time.

JOINT SYSTEMS.

DESCRIPTION.

Within the batholith the joint planes are observed to run at various angles, two or more existing at one place. The joint systems vary with the locality, and no fixed relation was noticed between them and the contact surfaces.

In the unmetamorphosed sedimentary formations the principal joint system dips from 35° to 45° SW. and is coincident with the plane of cleavage. Within the metamorphic zone joint systems are well developed and regular within any one locality, but vary from place to place. There are normally two well-developed planes dipping at angles of 50° to 80° in various directions, save directly east. A third and flatter plane is developed in many places, dipping from 20° to 50°, and one or two further subordinate planes may be noted. The exact positions of the principal planes were measured at a number of localities around the batholith and are recorded on Pl. XI.

The two best of these joint planes by their intersection form square or diamond-shaped prisms, commonly but a few inches across, which in all the places measured pitch in directions varying from northwest to southwest at angles of 45° to 75°. The third joint plane, which locally coincides with the bedding plane, is apt to cut these columns into segments. No constant relations between the directions of the columns and the direction of the adjacent batholithic contact could be made out.

MINERALIZATION OF JOINT PLANES.

The relation of the joint systems of the metamorphic zone to certain mineralizing actions was noted at a number of places. At the excellent exposure of the contact, 0.7 miles southeast of Mount Belmont, the tremolitic and biotitic hornstones are cut by a system of joints which do not extend into the granite beneath. These are bleached to a buff color, the action extending to a slight but irregular distance laterally; under the microscope it is found to be due to an infiltration of colorless epidote and its substitution in place of the hornblende and biotite. Again, 0.6 mile north of Gloucester the hornstones of similar nature are cut by several well-marked joint planes, the two chief ones cutting the rock into a series of columns which are further broken up by the intersection of the subordinate systems. In two of the directions an infiltration of colorless epidote has taken place along many planes but a fraction of an inch apart, more or less thoroughly recementing the rock. The present joint planes are spaced at a wider interval, and most of them are along surfaces which show no such infiltrations. The microdiorite sheets which are found here are broken up into irregular tetrahedral blocks several inches to a foot or more square, the joints being rude continuations of the joint systems of the hornstones. A few of these joints in the microdiorites, mainly north-south seams, show a bleaching which under the microscope is found to be found to be due to a substitition of light-colored pyroxene in place of the hornblende and biotite normally found in the rock.

AGE OF THE JOINT SYSTEMS.

From the foregoing statements it is seen that certain of the joint planes were present in the hornstones and their included sheets at a time when mineralizing action, doubtless more or less closely connected with the intrusion of the batholith, took place. At a later time the present systems were developed.

A slab of the hornstones lies as an inclusion diagonally across one of the larger microdiorite sheets and is without the joint planes which are shown within the hornstones on the two walls, indicating that these systems were absent at the time of the intrusion of the microdiorite and were doubtless prevented from forming in later time by the protecting action of the massive rock.

INFERENCES FROM THE JOINT SYSTEMS.

The marked development of the joint systems in the metamorphic zone indicates a close relation to the physical state of the rock, but that other causes besides mere metamorphism were necessary for the production of the jointing would appear from the general pitch to the west of the best developed prism systems, as well as from those features just described which show that a part of the joint planes have originated at a later time. Doubtless the most necessary condition is that of relative nearness of the rock to the surface at the time when the joint systems originate, and that is furthermore one of the most important inferences in the present case.

It is generally accepted that the phenomenon of jointing belongs to the outer zone of the earth's crust, termed the zone of fracture, since planes of fracture can form and remain open only under superincumbent loads which are less than the strength of the rock to sustain. The depths at which fractures cease to form must vary greatly, depending, as Van Hise has shown, on the strength of the rock and the rapidity with which the stress is applied.

The metamorphic rocks of this district, being of great hardness, would fracture at depths greater than their unmetamorphosed equivalents, but still the joint planes could not have been formed in the zone of flowage, and the rock at the time of their formation must have been certainly within 5 and probably not more than 2 miles of the surface. This is quite different from the flowage phenomena indicated by the schistosity which so commonly accompanies batholithic intrusion in the Sierras, in the Black Hills, in New England, and elsewhere, usually considered as indicating a relatively great depth at the time of intrusion. It is, however, in line with some observations which have been made on the relative shallowness of certain cordilleran batholithic masses. Smith and Mendenhall have noted that in a batholith of the northern Cascade Mountains the intrusive granite was covered only in places by a series of older extrusive andesites,[a] and in 1899 Mr. W. H. Weed and the writer, working as his field assistant, noted independently precisely the same relations in Montana in regard to the Boulder batholith.[b] It is evident from these facts that in the invasion of the western batholiths great bodies of granitic magmas have frequently been brought within 1 or 2 miles of the surface, reenforcing the inference from the character of the joint planes in the metamorphic zone at Marysville.

EXPLANATION OF GEOLOGIC SECTIONS.

Observation, except in the rare opportunities offered by mine workings, reveals only the actual facts at the surface. The underground structure is determined entirely from inferences, though in the general relations of the formations these may sometimes approach the certainty belonging to actual observation. In spite of their inferential character, however, geologic cross sections of a region are of the utmost value as showing the probable structure. Since the sections of Pl. II are based on the ideas of structure developed in the preceding discussions, it will be well to review briefly the reasons for drawing them as shown.

Underground features not showing at the surface, such as the large dike south of the batholith in section A–A and the gabbro intrusions north of Little Prickly Pear Creek, are, of course, not observed. They are indicated in their particular form and position merely to represent the general truth that such dikes and sheets occur in the neighborhood in sufficient abundance to make it probable that the section will intersect some which are not revealed at the surface.

The general outline of the batholithic surface is determined from the observations and discussions on the batholithic contacts and the underground extensions, as inferred from the observed dips, the mine workings, and the limits of metamorphism. The irregular angular details are in conformity with the character of the contact where studied in detail in the mines or at favorable exposures on the surface.

Marginal diorites have been shown in certain reentrant angles and apophyses from the quartz diorite of the batholith, since they are occasionally met at the surface in such positions.

The microdiorites being older than the batholith, are shown cut off by it in section C–C.

The aplites abundant at the northeast corner of the batholith, for reasons discust in Chapter II, are believed to come from a depth below the level of the sections and are shown in section C–C as intrusive dikes and sheets.

Obscure marginal faults have been shown to inwreathe the batholith and were approximately located by working out in the office the relations of dips and strikes. They have not been checked up by a reexamination of the field and are accordingly represented by dotted lines. They are believed to have originated in connection with the batholithic intrusion and before the latter became solid, and do not cut the granite.

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[a] Smith, G. O., and Mendenhall, W. C., Tertiary granite in the northern Cascades: Bull. Geol. Soc. America, vol. 11, 1900, pp. 223–230.

[b] Weed, W. H., Geology and ore deposits of Elkhorn mining district, Montana: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 2, 1901, pp. 450–453.

CHAPTER IV.

CONTACT ACTIONS.

INTRODUCTION.

PROCESSES INVOLVED.

The literature of contact actions shows a great diversity of opinion as to the manner and significance of the processes involved. As a single instance many writers, judging from the extensive contact zone locally showing pneumatolitic or impregnation effects surrounding many granitic bodies, consider that the acidic magmas as a class carry a greater amount of occluded vapors, especially water vapors carrying silica and other elements, which are given off on the intrusion and crystallization of the rock. Such results have been found by Hawes, Lindgren, and a number of French geologists. On the other hand, Rosenbusch, Zirkel, and Harker have found that in instances studied by them no accessions of material to the walls from granitic magmas have taken place, while Roth, Zirkel, Hutchings, and Clements have found evidence of a transfer, especially of silica and soda, from the magma to the walls in the case of basic intrusions. Without multiplying instances of other classes of contact action it is evident from these statements that the presence and kind of action due to occluded gases does not depend on the composition of the magma alone. It is to be expected that other factors, such as the mass, depth, temperature, and form of the igneous bodies, and the strength and porosity of the intruded formations will also have vital influence on the character and extent of contact actions. In view of the great variety of these governing conditions connected with igneous intrusions there would seem to be room for the most diverse results. To bring such results into coordination not only must the manner of the action be critically studied, but, as far as possible, contact actions should be discussed in connection with the governing conditions, such as depth of intrusion, mass, temperature, composition, relation to walls, etc., which have brought about the particular kind of changes involved. By the accumulation of sufficient data of this kind from many regions, doubtless in the course of time a complete understanding of the subject will be had. The writer has endeavored as far as possible to study in detail the contact phenomena of the Marysville district, and has described also the ascertainable physical conditions attending these phenomena. It may be stated in advance and by way of an introduction to the subject that the facts showed evidence of three distinct classes of contact action.

CONTACT METAMORPHISM.

Contact metamorphism is very extensive on the margins of the Marysville batholith, but was not noted in connection with the other intrusives, taking place without addition of material and resulting merely in a crystallization of the wall rocks. By this process silica and alumina existing in carbonate rocks have combined with the bases and set free a proportionate amount of carbon dioxide. This and the water present have been eliminated from the rock mass. With this exception the changes have been those of volume and not of mass. Simple metamorphism of this sort takes place most readily in impure limestones, the purer types being affected with greater difficulty.

CONTACT METASOMATISM.

The word metasomatism as here used indicates a mass change in the composition of the rock other than the elimination of gases involved in simple metamorphism. The action takes place through magmatic emanations, of which silica and iron in water solution seem most important, sulphur and other elements also being involved. The types of rock most readily affected are the purer carbonate rocks and this appears to be due to the ease of reaction of the dissolved elements with the carbonates left in the rock after the simple metamorphism has been completed. While contact metamorphism, on account of the more or less complete elimination of water and carbon dioxide, may be spoken of as a process of subtractive metasomatism, it is seen that the magmatic emanations result in both additive and subtractive metasomatic processes.

Contact metasomatism may be divided into pneumatolitic and hydrothermal metasomatism, according to whether the magmatic emanations are above or below 365° C. and 200 atmospheres pressure—the critical temperature and pressure of water. Pneumatolitic action results typically in the formation of the heavy anhydrous minerals within the contact zone, while hydrothermal action takes place at greater distances from the portions of the magma still hot and results in vein fillings and metasomatic alterations of their walls. One kind of action appears to grade into the other and there are many minerals which may be formed in either way. The magmatic emanations are conceived of in pneumatolitic metasomatism as chiefly primary, but in the hydrothermal process much water of meteoric origin doubtless mingles with the magmatic water.

One of the chief results of the study of this district is to show the dependence of contact metasomatism here on a temporary permeability of the affected rocks. This permeability has been due to a minute fracturing or parting, the evidence of which has been in many places nearly destroyed by the metasomatic recrystallizations. Contrary to the opinions expressed by others in regard to some localities, the emanations, even where apparently under pneumatolitic conditions, seem to have altered the rocks only to a depth of a few millimeters from the fractured surfaces, but these surfaces may be so close together as to result in a transformation of the whole body of the rock. The more extensive alteration of the carbonate rocks seems to be due, so far as observed, both to a greater depth of permeation into the walls and to a closer fracturing. Such fracturing may be dependent in some way on the reactions with volume changes which take place, as well as on the greater weakness of the rock as compared with the harder hornstones resulting from the metamorphism of other types.

Being determined by the permeability of the rock the limits of contact metasomatism are naturally variable, in places extending to or beyond the limits of simple metamorphism, but usually the metasomatism is more restricted than the metamorphism and may extend but a few feet from the batholith. The peculiar dependence at this locality on a permeable state of the walls is doubtless largely due to the comparatively shallow depth of the granite at the time of its intrusion. To judge from the analogy of the near-by Boulder batholith, the Marysville rock appears to have been intruded after the orogenic structure had been attained and the bulk of the subsequent erosion had been completed, a few thousand feet of postbatholithic erosion having served to expose it with its present aspect.

The cover of the batholith was thus entirely within the zone of fracture, and the stresses involved in intrusion, in heat expansion, and in the volume changes of metamorphism would appear to be adequate to account for the closely shattered condition which in many places preceded the metasomatic changes. To illustrate the dependence of lateral subcapillary penetration of the walls on depth and porosity of the cover rocks, three cases of the relation of porosity to depth may be considered: (*a*) Where the depth is small—a few thousand feet, for instance—and highly porous beds or brecciated zones extend from the magma to the surface, the gases with their dissolved burdens can find easy escape along these special passages and there will be but little back pressure to force the gases into the walls after they have left the magma. Consequently metasomatic additions would be expected only along the actual lines of gaseous escape. (*b*) Where the depth is medium, say in the deeper parts of the zone of fracture, the frictional resistances along the lines of gaseous escape would be heightened on account of the greater length of the channels to the surface and the less open character of the rock. The back pressure would be greater and a more general permeation of the wall rocks would take place in consequence. (*c*) Where the depth is great, the intrusion being in the zone of flowage, the rocks are dense, the gases permeate them with difficulty, and, according to Van Hise, the transfer of material into the walls is limited, while the temperature effects, on the contrary, are far-reaching and enduring. The greatest metasomatic effects due to escaping magmatic emanations might be expected, therefore, to border those intrusions whose irruption was into the deeper parts of the zone of fracture.

CONTACT REACTIONS.

In the two classes of contact action already discussed the wall rocks have exercised no chemical influence on the magma, the endomorphic effects being simply those due to slow or rapid cooling. But with large intrusions at such a depth as to be in the zone of flowage the conditions are quite different. The temperature effects must be widespread and profound, and, as remarked by Van Hise, the heated condition must endure for geologic epochs if not for periods. In such situations the borders of large masses also show in many cases numerous parallel injections along planes of easy parting in the walls, producing complex and extensive contact surfaces. Under such conditions the composition of both walls and magma may be locally modified. Van Hise[a] states that the general law is to make the intruded and intrusive rocks approach each other in composition. To such a class of actions belong the feldspathization sometimes noted within the margin of siliceous wall rocks and the assimilation of the walls into the magma.

[a] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, p. 713.

At Marysville only a trace of this action was noted at a couple of places, calcareous wall rocks having slightly enriched the margin of the granite with lime previous to the crystallization of the magma. On the borders of the far larger Boulder batholith, a few miles to the south, this action was locally more pronounced and was there studied in detail. This work involves numerous chemical analyses, however, and the material is not yet fully prepared for publication.

DETAILED DESCRIPTIONS OF CONTACT PHENOMENA.

ORDER OF PRESENTATION.

As apparently no sharp line can be drawn between pneumatolitic and hydrothermal action, the detailed studies here presented are arranged in the following order: The first are clearly examples of simple metamorphism and limited metasomatism, in which pneumatolitic conditions are judged to have prevailed. These are succeeded by examples of more extensive metasomatic action adjacent to the batholith and presumably under a high temperature. Finally the metasomatic actions at Bald Butte are considered—changes connected with vein fissures and a brecciated state of the rock at a considerable distance from the batholith and under conditions which were probably hydrothermal, though the resulting metasomatic changes in the wall rocks resemble to a considerable extent those which are thought to be produced under conditions of higher temperature and pressure.

RELATION OF COMPOSITION TO DISTANCE FROM BATHOLITH.

The only igneous formations within this district producing noticeable effects on their walls are the larger gabbro intrusions north of Little Prickly Pear Creek and much more noticeably the Marysville batholith. The discussions except where otherwise stated apply throughout to the walls of the batholith. The ideal way in which to study the effects of the quartz-diorite invasion on the surrounding sediments would be to follow strata of various compositions from the surrounding region into the metamorphic zone and through this up to the margin of the batholith. This, however, is not possible in a detailed way within this district, since the exposures are not sufficiently numerous, the many obscure faults break the continuity of the strata, and, moreover, shaly limestones, which beyond the limits of metamorphism are relatively soft and show few prominent outcrops, become within the metamorphic zone among the most resistant of formations, the lime-silicate hornstones yielding more slowly to erosion than the granite itself. Under such circumstances, although it is not possible to compare different states of the same bed, a comparison may be made between the strata as a whole in the original state in the outer portions of the metamorphic zone and again adjacent to the granite. In this way it may be determined not only what strata suffer metamorphism most readily, but possibly if additions of material from the magma have been received.

STRATA OF THE METAMORPHIC ZONE.

The batholith is surrounded entirely by the Empire and Helena formations, a detailed description of which has already been given, the Empire consisting predominantly of greenish-gray banded siliceous shales, the Helena of thin to thick beds of impure bluish-gray and gray limestone with bands of siliceous or calcareous shales.

The limits of severe metamorphism are in general not difficult to determine, and the altered rocks are predominantly hard-banded hornstones, light gray or green in color, locally with bands of brown. Some of the lighter colored rocks effervesce feebly with acid, showing that a small amount of carbonate still remains in them. Among these hornstones, as may be noted on Edwards Mountain, are intercalated a notable proportion of distinctly calcite-bearing strata, white or light-gray in color, rather granular, and softer than the hornstones. The same features may be noted on the hill between Drinkwater Gulch and Deer Creek.

In the unmetamorphosed Helena limestone the more massive and calcareous beds are stratigraphically the most prominent and liable to be proportionately overestimated. In the metamorphic zone the opposite is true. This factor being taken into consideration, it may be stated that *on the whole in the metamorphic zone more than a thousand feet from the batholith the composition of the strata points to little or no general accession of material from the magma during metamorphism.* This conclusion can be more positively stated in regard to the zone on the north side of the batholith.

Petrographic evidence of limited pneumatolitic metasomatism along joint planes and in particular strata will be presented later. On following the granite contact around the batholith, on the contrary, it is noted that the immediate wall rocks show almost no calcite, being predominantly hard, smooth hornstones not effervescing with acid. North of Mount Belmont, however, this statement does not apply, as there interlaminated limestones and hornstones occur not far from the immediate contact.

Along the crest line of Drumlummon Hill for a distance of 2 miles the rocks are well exposed and more than three-fourths of the strata are seen to consist of hard, light-colored, in places banded, hornstones, some of which have a worm-eaten appearance, due to the weathering out of segregations of calcite. Not more than a quarter of the strata contain enough carbonate to be designated as limy hornstones, while a few beds, not aggregating 1 per cent of the total thickness, possess the distinctive character of marbles. Yet to the south, just beyond the metamorphic limit, the apparent stratigraphic equivalents are dominantly limestones, many of the beds being massive, dark blue, and as conspicuously calcareous as any portion of the Helena limestone. As there is no evidence of a fault separating the two, the simplest explanation appears to be that here large additions of silica, doubtless with lesser amounts of other oxides, have taken place, displacing the carbon dioxide and converting the limestones into predominantly lime-silicate hornstones. The second conclusion, therefore, is that *within a variable distance of the batholith, usually from 600 to 1,000 feet, emanations, largely silicious, from the magma have generally combined with the lime and other bases, with the resulting elimination of carbonic acid.*

Near the contact north of Mount Belmont this action fails, marbles occurring relatively near the granite, and, on the other hand, siliceous infiltration appears to be most extensive on the eastern half of Drumlummon Hill. This general conclusion having been reached, the question arises as to how it agrees with the petrographic details. For this purpose selected localities where the relations are best exposed must be studied as types. A number of such were chosen and will be described in detail.

METAMORPHISM FOLLOWED BY LIMITED INFILTRATION.

GENERAL DESCRIPTION.

On the steep northern slopes of Drinkwater Gulch, a quarter of a mile from the granite contact, but probably at a much less vertical distance above the granite, which at the contact appears to slope under the cover at an angle of about 30°, the intensely metamorphosed hornstones are well exposed. They are here strongly banded in the sedimentary planes. The bands are of four characters, as described below, the texture of all being uniform and of microscopic fineness. (See Pl. XII.)

First, grayish-brown bands, marked 1 on the illustrations, weathering to a grayish green, consisting of a fine-grained groundmass of quartz or feldspar or both, the proportions being difficult to determine. Within these bands, which comprize about half the rock mass, greenish-brown mica in minute chunky crystals is rather uniformly scattered, forming about 30 per cent, together with about 15 per cent of pale-green hornblende in small, well-formed, lath-like crystals.

Second, gray-white bands, marked 2, forming a large part of the rock, differing from the first class in the absence of mica and the greater development of tremolitic, almost colorless hornblende, which forms about one-third of the rock mass.

Third, calcite bands, located within the tremolitic bands just mentioned. These are white, but become rusty on weathered surfaces. They are finely granular and weather out on exposed faces, leaving a series of small rusty pits. Instead of being of uniform width they show a marked concretionary structure, the stratum being separated into lenses, commonly 7 to 10 mm. in thickness, the lenses in places touching each other, but more commonly separated by short intervals, locally by as much as 40 mm. This segregated concretionary character of the purer calcareous laminæ in the mixed sediments of the Cambrian and Algonkian is rather common in western Montana, and is not believed by the writer to be necessarily related to the contact metamorphism. It is true, however, that the shape of the lenses has been modified to a slight extent by the fracturing which accompanied or followed metamorphism and which is described in the next section, since the major axes of small, nearly spherical lenses, may lie in the plane of parting and not in the plane of bedding. Moreover, the larger lenses show a partial pinching against the surfaces of fracture, as if the calcite retreated or was destroyed in their neighborhood. These changes, however, have involved movements of but 2 or 3 mm. In composition these nuclei are roughly estimated to consist of 70 per cent carbonates, 20 per cent zoisite, and 10 per cent epidote.

Fourth, brown bands, judged to be mostly garnet, locally abundant, though forming but a small part of the whole.

These several layers are spoken of as bands rather than laminæ, since the rock shows no tendency to part on the bedding planes. It is noted that the calcite lenses are uniformly surrounded by at least a narrow margin free from mica and in many places holding diopside and epidote.

The mineral compositions point in the bands of the first class to high alumina, iron, and potash; in those of the second to relative increase of lime and magnesia, with decrease of alumina and potash and probably of iron; in those of the third to a great predominance of lime and magnesia in the form of carbonates. In the absence of exact knowledge in regard to the groundmass more positive statements can not be made. The border of the second zone separating the first and third is in places not more than 1 to 3 mm. thick.

PLANES OF JOINTING AND INFILTRATION.

As noted on the map (Pl. XI, p. 74), the dip at this locality is 20° N. and the rock at present shows no parting on its bedding planes. It is cut, however, by two well-developed systems of joint planes which break it up into small rhomboidal columns pitching 55° SSE., a direction roughly perpendicular to the general upper surface of the batholith as it was computed to lie at this locality. Parallel to these two planes the rock has abundant partings accompanied by infiltration, which for the space of 1 or 2 mm. has bleached the micaceous bands to a gray-white color through the destruction of the mica. The cracks themselves, nowhere more than half a millimeter in width, are filled with colorless epidote and some calcite. At this place a microdiorite sheet 7 to 8 feet thick is intruded within the strata. The seams showing bleaching cut it at intervals of several feet, but within the sedimentary formations they average only a quarter of an inch apart. In the calcite lenses they are more abundant still, forming a fine network of epidote, prominent on the weathered surfaces. Only a portion of these planes of infiltration are, however, developed as joint planes; these are several inches apart, while the remainder are thoroughly cemented. Besides these infiltrated parting planes are a couple of other joint systems not infiltrated and poorly developed, which, in combination with the others, cut the whole into rude tetrahedral blocks. The absence of infiltration along these planes is taken as evidence that they are of later origin than the others and not related to the metamorphism.

A couple of slabs of the sedimentary formation lie within the microdiorite, which is older than the batholith, and show an absence of the infiltrated partings of the neighboring strata, in this respect resembling the microdiorite and indicating that the partings arose later than the time of the microdiorite intrusion. No change in the character of the metamorphism is noted on approaching the dike walls. One of the included slabs, however, 4 inches thick, shows granular calcite in the center margined on each side by a quarter inch of garnet and then a ¼-inch bleached band, as on the joint planes. Beyond this is the unaltered dike rock. This is a local effect, which may have been due partly to the microdiorite intrusion and partly to later infiltration connected with the general metamorphism.

NATURE AND CAUSES OF PARTING.

The closeness, straightness, and parallelism of the parting planes suggests that they originated by forces of compression being brought to bear on the rock, causing fracturing on the planes of maximum shear. As Becker[a] has shown, there may be two or four of such planes, which in a homogeneous rock tend to be inclined at 35° to 45° to the direction of maximum pressure. Tension joints such as those produced by cooling and shrinkage are apt to be farther apart and in at least three sets of planes, as illustrated by the columnar structure of basalt. The

[a] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 13-90.

belief that the parting was due to compression with the development of shear planes is further substantiated by a slight bending and offsetting of the fracture planes in crossing the calcite layers, as may be seen by holding the eye nearly parallel to the surface of the paper in looking at Pl. XII, suggesting that these calcite laminæ may on account of a greater weakness have acted to a slight extent as planes of shear also. The greater abundance of the parting planes in the calcite layers and their scarcity in the microdiorite sheets are, however, peculiar and from the data in hand no final opinion can be expressed as to the cause.

TIME AND CAUSE OF INFILTRATION.

The most noteworthy mineral filling the open cracks is colorless epidote, with perhaps diopside as an infiltration product along the walls. Biotite is everywhere destroyed and the recrystallization has been so complete that no trace of its former presence remains. Lindgren[a] states that these minerals, common in dynamic and static metamorphism, are rare in fissure veins or in the altered rocks of their walls. The epidote where so occurring has a deep-yellow color, unlike that of the present instance, which is colorless. In view of the vicinity of the granite and their occurrence within the metamorphic zone the conclusion is drawn that the infiltration is associated with the contact metamorphism and not with a later possible hydrothermal action. However, since it has not influenced the greater part of the rock it is distinct from the general crystallization which has resulted from the contact metamorphism. There is evidence, therefore, of two processes, both connected with contact metamorphism—the first a crystallization of the whole mass of the rock, the second a close fracturing arising at the time or immediately following, accompanied by infiltration and limited metasomatic action on the walls of the fissures.

CHARACTER OF PRIMARY CONTACT CRYSTALLIZATION OF SEDIMENTS.

In the original crystallization there is no evidence of infiltration, but, on the contrary, considerable evidence against it. This may be summed up as follows: (1) The several strata are exceedingly fine grained and homogeneous throughout, so that infiltration if taking place would have to be exceedingly uniform, the solutions permeating the whole rock without the usual selective action and coarser crystallization along some lines than along others. (2) If the infiltration depended for its action on chemical reactions the carbonate lenses would be expected to suffer especially, the carbon dioxide being displaced by silica. On the contrary, the present amount of calcite shows a freedom from such action. (3) In the metamorphism of sediments originally containing combined water and carbonates and silica, the silica combines with the bases of the carbonates. Water and carbonic acid are expelled with attendant shrinkage of volume unless their places are taken by infiltrated material. Therefore, if infiltration depended on general porosity some structural or mineralogical evidences of such supposed additions should be expected in those layers which would otherwise suffer shrinkage during the process

[a] Lindgren, W., Metasomatic processes in fissure veins: Trans. Am. Inst. Min. Eng., vol. 30, 1901, pp. 610-611.

of metamorphism. It has been shown that apart from the later fracturing and infiltration there is no evidence of such action. It is concluded, therefore, that *in the first crystallization no additions of material have taken place.*

AGENCY OF HEATED GASES IN CONTACT METAMORPHISM.

In view of the conclusion just stated, it is of interest to note the commonly accepted view as to the direct agency of contact metamorphism. There are two methods by which heat from the igneous mass may be conveyed into the walls—either by conduction through the rock mass without the agency of heated gases, or by an elimination of these gases from the magma, carrying large quantities of heat by convection into the walls. If the approximate initial temperatures of the igneous intrusion and the surrounding rocks are known, the rate of heat dispersion by conduction may be calculated, and it is found that beyond the immediate border the process will be comparatively slow. On the other hand, nothing is known of the rate at which occluded gases escape from an intruded magma, though the quantity and rapidity probably vary greatly in individual instances. That large quantities frequently escape is, however, demonstrated not only by modern volcanic phenomena but also by the study of ancient intrusions now exposed by erosion; it is seen that the metamorphism has been principally on the upper side, that being in the direction of escape for the magmatic emanations.

Nothing is known of the relative efficiency under varying circumstances of conduction and convection, but it would seem probable that conduction might in the case of the larger intrusions be especially influential in the zone of flowage, where the quantity of heat is enormous, the surrounding rocks are without porosity, and the heat is conserved for long periods of time. In the zones of fracture the conditions would seem to favor metamorphism by convection, and this is the commonly accepted view, though the occasional action of dry heat is not excluded.[a]

Acording to Vogt[b]—

> Contact metamorphism is usually referred, in accordance with all probability, to the action of heated steam escaping from the eruptive magma and pressed into the surrounding rocks, where it produces a recrystallization, in most cases without notable addition or subtraction of material. Contact ore deposits form a special class of this metamorphism (involving "ferrization," etc.) and are explained by the presence of metallic compounds in the heated steam.

CONCLUSIONS.

To return to the case in hand and sum up, it would seem that the initial wave of metamorphism, probably due chiefly to water gas above the critical temperature, passed through the rock, resulting in the elimination of most of the interstitial and combined water and part of the carbon dioxide, with some reduction of volume, but under sufficient pressure, aided by recrystallization, to result in a fine-grained homogeneous texture and without accession of material during the process. Following this at a short interval, or perhaps connected with it, compressive stresses fractured the rock closely along several planes of maximum shear and permitted the infiltration of foreign material, probably derived from the granite mass, resulting largely in the

[a] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, p. 489.
[b] Vogt, J. H. L., Problems in the geology of ore deposits: Trans. Am. Inst. Min. Eng., vol. 31, 1902, p. 139.

formation of epidote. Some of the bands of brown garnet in other parts of the district are clearly due to infiltrations of a more ferruginous character, and those mentioned as of occasional occurrence at this place may be of similar origin.

METAMORPHISM FOLLOWED BY EXTENSIVE INFILTRATION.

GENERAL DESCRIPTION.

The metamorphic rocks and intrusions are well exposed along the railroad cut immediately east of Marysville. As shown on the map (Pl. I), three large bodies of quartz diorite, porphyritic on the margins, besides numerous smaller dikes, have broken through the rock of the metamorphic zone and consequently the opportunity for extensive changes has been very favorable. The sedimentaries are banded hornstones, brown, greenish gray, and grayish white, resembling to a considerable degree the series in Drinkwater Gulch just studied. The dip is here steep, 40° to 60° E. At a distance of 400 to 500 feet east of the railroad trestle and about 400 feet from the main batholithic contact the rocks were studied in detail. The general megascopic character of the bands resembles that of those in Drinkwater Gulch; similar brownish-red bands due to the abundance of microscopic mica form the background of the rock mass, the other bands apparently having been largely formed from it either by infiltration or by concretionary segregation. (See Plate XIII.) As before the white, granular laminæ are in few places continuous, but tend to be segregated into lenses separated from the micaceous portions by intermediate greenish-gray envelops.

RELATION OF PARTINGS TO INFILTRATION.

The chief structural difference is in the scarcity of the parting planes oblique to the bedding, which by their infiltration formed such a conspicuous feature of the rocks in Drinkwater Gulch. These are noted here and there, however, and lateral impregnations are seen to have taken place along their paths. This action is very limited where the parting planes cross the mica-bearing bands, but is pronounced where they cross the white granular bands and may extend laterally from the cross fracture for several inches along numerous bedding planes, as shown in Pl. XIII, *A*.

Further observations show that the chief planes of parting and infiltration have here been the bedding planes and that this action has served to heighten the banded nature due to original differences in composition, but as this heightening is parallel with the original structure it requires closer observation to determine that it is due to the secondary cause. The cross fractures are consequently of great value for this purpose.

Occasionally strike faulting of normal character is noticed on the plane of the bedding, indicating that the bedding at one time lay approximately in a plane of shear, and from other considerations it is thought that this is probably related to the ready penetration shown here along the bedding planes. Close observation also shows thrust faulting along the oblique fractures, amounting sometimes to a quarter or half a millimeter. The direction of these two planes of shear would indicate at this point yielding to a more or less vertical thrust and horizontal east-west extension. The predominance of the partings on the bedding planes dipping 40° to

60° E. would also seem to indicate a rotational movement with upthrust greatest on the western side or that of the batholith. This being the reverse of what appears to be the general rule in the district, the local direction of thrust is thought to be related to the intrusion of the batholith, and this is one reason for connecting with some probability the intrusion of the batholith, the development of fracture planes from the local thrust, and the infiltration chiefly along the bedding planes but locally in diagonal directions. Although these rocks are so similar in megascopic appearance to those of the locality in Drinkwater Gulch, already described, under the microscope the mineral changes resulting from the infiltration are found to be very different, the characteristic minerals here being diopside and quartz and not epidote, while no calcite whatever exists within the white lenticular bands.

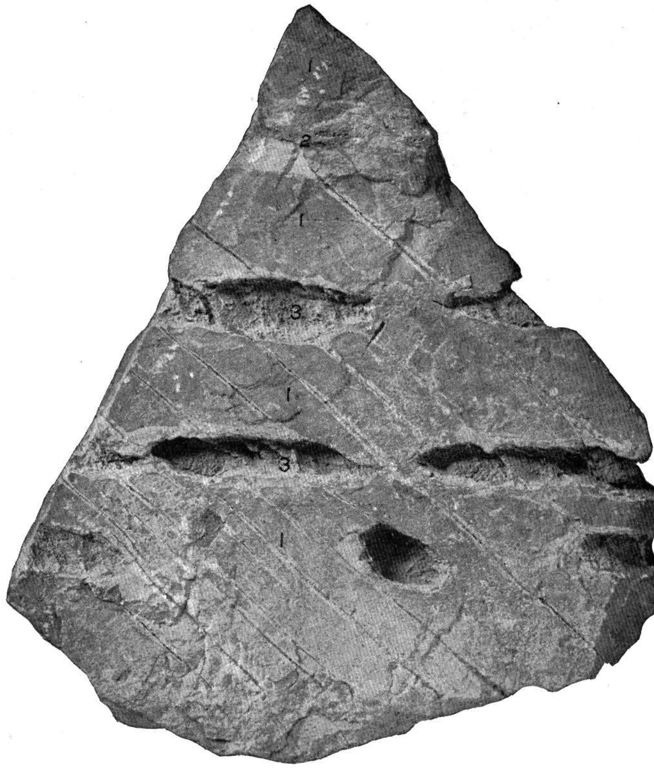
The reddish-brown bands possess the following composition, the percentages being merely rough approximations: Hornblende, in small prismatic crystals apparently intermediate between tremolite and actinolite, 20 per cent; brown mica, probably biotite, in extremely minute tabular crystals of high birefringence, 35 per cent; fine-grained groundmass of quartz with probably some feldspar, the fine-grained allotriomorphic character preventing separation, 45 per cent; pyrite and magnetite accessory in very small amounts.

The gray-green bands show no mica, appearing to consist wholly of about 30 per cent tremolite, the balance being quartz, with possibly some feldspar.

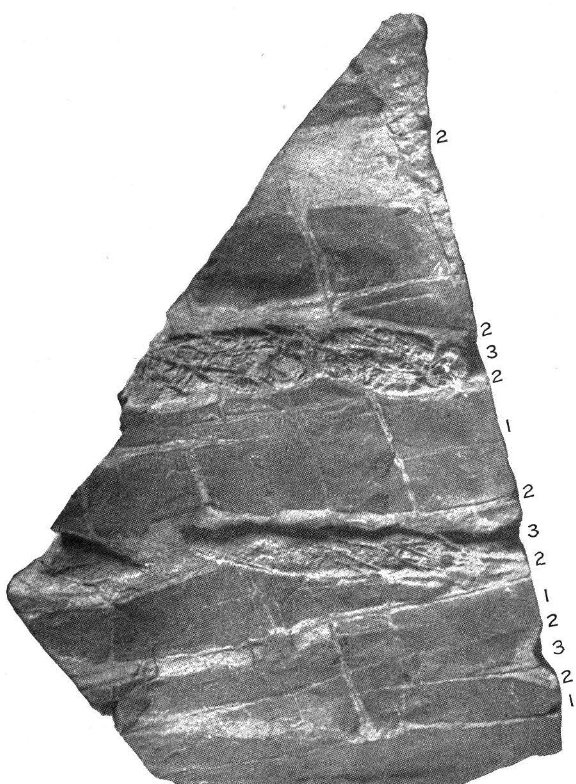
The white lenticular layers, which presumably were originally largely calcite, as in the other locality, show no effervescence on fresh fracture, but do effervesce on weathered surfaces. Under the microscope they are found to consist of diopside and quartz locally with zoisite and one or two undetermined minerals in small amount.

NATURE OF METASOMATIC CHANGES.

Where infiltrated fractures oblique to the bedding cut the several bands the fractures themselves are filled with allotriomorphic vein quartz holding a few prismatic crystals of diopside 0.1 to 0.2 mm. in length. The immediate walls for a depth of 1 or 2 mm. show a fine-grained groundmass principally of quartz but with some diopside, which from its contrast with the true vein quartz is judged to be a metasomatic replacement of the walls. This grades into a finely granular band 2 mm. thick, of diopside with some quartz, beyond which is the normal micaceous and hornblendic hornstone. In the absence of knowledge as to the exact composition and amounts of the several minerals under consideration the statements must be loosely qualitative. It is seen that along the courses of fractures in the red-brown and gray-green bands there has been a metasomatic action by which certain elements of diopside have penetrated farthest and become concentrated in a granular mass of diopside, followed nearer the vein fissure by quartz and diopside. These changes, stated chemically and not mineralogically, show a selective penetration of lime in sufficient quantity to result in the formation of the granular diopside and to a lesser extent of silica. The other chemical elements have of course suffered some changes also, but what they are is not evident from the study of the thin section. In the white bands, it being granted that they were originally calcite, the present mineral composition shows the elimination of all carbon dioxide, the carrying



A



B

BANDED HORNSTONE FROM DRINKWATER GULCH, SHOWING INFILTRATION AND CEMENTATION ALONG PARTING PLANES.

Front and side views of same specimen. Field No. 113.

A

B

BANDED HORNSTONE FROM RAILROAD CUT NEAR GRANITE CONTACT, SHOWING EXTENSIVE INFILTRATION ALONG BEDDING AND JOINT PLANES.

A. Infiltration into reddish-brown biotitic band. Field No. 121.
B. Infiltration into and across an originally calcareous band. On the margins the originally brown biotitic portions have been altered to light-gray siliceous and tremolitic laminæ. Field No. 122.

in of much silica, and the abstraction of some of the lime. The tendency of the metasomatic changes in both cases has been to produce a rock largely diopside, with interstitial quartz.

CONCLUSIONS.

Without intending to draw generalizations from the detailed study of one spot, it still may be of value to point out the chief conclusions. Here again recrystallization due to metamorphism is seen to be distinct from the following metasomatism, but the latter, being more extensive, has masked to some degree the original action. Penetration has readily taken place along bedding planes, probably aided in this instance as planes of penetration by their steepness and the fact that they coincided with a plane of shear. Lateral penetration into the rock mass and accompanying metasomatism have taken place most readily in the calcite layers, resulting in their complete alteration. The changes of the several bands have been such as to tend toward a uniformity of composition, the rocks consisting of dominant diopside with notable quartz. There is but little evidence of additions from the magma, as the characteristic pneumatolitic minerals are wanting and all the lime and at least a part of the silica involved in the formation of the diopside and quartz might come from a redistribution of elements already within the walls. The motive force of these changes must, however, be sought in the exalted temperature of the newly intruded batholith. The circulating medium has doubtless been water, and the formation of diopside shows that this has probably been near or even above the critical temperature. A part, or perhaps all, of this water or water gas may have been original magmatic water. However, the nearly complete silification of the originally calcareous rocks of Drumlummon Hill makes it seem improbable that the necessary silica could have been furnished by the sediments themselves, and it is rather to be looked on as largely an accession from the magma, carried into the walls by the escaping vapors.

METAMORPHISM AT THE IMMEDIATE CONTACT.

GENERAL DESCRIPTION.

A third locality selected for detailed study lies at the granite contact 0.7 mile southeast of the summit of Mount Belmont. Here a cliff of banded, almost horizontal brown and olive-green hornstones rests as a cover upon the granite, the contact plane, conformable with the bedding, being well shown. The gray-green and white bands are not present at this locality.

It will be well to state in advance of the facts the more general conclusions in regard to the sequence of events in order that the bearing of the facts may be perceived as they are presented. Five distinct processes are determined to have taken place, and their sequence is as follows:

First, contact metamorphism, a crystallization of a ferruginous, argillaceous, sandstone into the red-brown, fine-grained micaceous hornstone, apparently without accession of substance.

Second, hornblendic metasomatism, beginning along numerous bedding planes and extending into the walls for small distances, involving the addition of silica, lime, and some magnesia and the abstraction of potash and probably alumina.

Third, epidotization along cross fractures, like the metasomatism penetrating for short distances into the walls.

Fourth, recrystallization adjacent to the granite, seemingly owing to the presence of water vapor from the magma, not changing the mineral species, but enlarging the individual crystals.

Fifth, slight apatitization, tourmalinization, and possibly feldspathization and silicification along the immediate contact.

These individual processes can be studied and separated to advantage here, since the amount of contact action has been small in comparison with many other instances where similar great volumes of magma are brought into contact with surrounding sedimentary formations. The significance of certain of these processes is pointed out in the final summation following the presentation of the detailed facts.

RELATION OF CONTACT TO TEXTURE.

Composition of the rock.—The mass of the rock consists of the brown hornstone, the color being, as before, due to the presence of microscopic mica and similar to that of the two localities already described. Three specimens were taken, one a few feet from the contact (illustrated by Pl. XIV), one against the granite, and the third an inclusion within the granite. In the first, the composition was roughly estimated as follows: Mica, probably biotite, 35 per cent; quartz and feldspar, 65 per cent; epidote and magnetite, accessory, 1 per cent. The average size of the crystals is 0.02 mm., the only ones possessing crystal outlines being those of biotite and magnetite. Under these circumstances it is difficult to separate the quartz and feldspar, but it is believed that considerable of the latter is present.

In the second specimen, at the immediate contact, the same minerals are present and the fabric remains the same, but is about five times as coarse, the average grain here being 0.10 mm. All the minerals, however, hold inclusions of the others, of an average size of 0.01 to 0.02 mm., indicating a selective growth of certain individual crystals after a fine-grained texture, such as shown in the first specimen, had been attained. The composition was roughly estimated as follows: Mica, probably biotite, 25 per cent; quartz, 50 per cent; feldspar, 25 per cent; epidote, magnetite, apatite, and tourmaline, 1 per cent. The feldspars tested by Becke's method were found to be alkaline.

In the third specimen the inclusion is one of a number, all of which lay within 3 feet of the contact, but were not more abundant immediately against it than at a distance of 2 or 3 feet. While some closely resemble the adjacent hornstones and have angular margins, others are coarser grained and show a few larger crystals of feldspar. These latter inclusions may have wavy and ill-defined margins, and megascopically resemble ordinary segregations commonly found in granite masses. The one examined belonged to this class. That it was really an inclusion and not a segregation is determined from the panidiomorphic crystalline texture, resembling that of the hornstones, the biotite crystals especially being indented by the quartz and feldspar. This is easily understood on the assumption that the fragment remained solid during recrystallization, whereas if the crystallization had taken place from a completely fused state the normal order of crystallization would be expected. The mineralogical composition is the same as that of the contact rock, except for the absence of apatite and tourmaline and the presence of some muscovite and scattered idiomorphic phenocrysts of laboradorite near Ab_1An_1 in composition. The feldspar of the groundmass is of two species, being possibly equally divided between plagioclase and a soda othoclase. The average grain of this rock is still coarser than the last, averaging from 0.3 to 0.5 mm., the labradorite phenocrysts, however, reaching a length of 2 mm.

Conclusions as to cause of granularity.—The rapid changes in grain without marked change in composition in this rock on approaching the granite seem rather remarkable. The temperature within a few feet of so large a granite mass immediately after the time of intrusion must have been approximately the same as within its margin, and this is further indicated by the holocrystalline texture of the granite against its walls. Therefore, mere differences in temperature can hardly be invoked to account for this change in granularity. Van Hise has shown the importance of interstitial water or water gas in effecting recrystallization, and the greater proportion of this within the magma at the time of the recrystallization of the hornstone may be a possible explanation. If so, it points to an inability of the igneous mass to penetrate readily the fine-grained cover, especially where the bedding of the cover is flat and no edges of the strata are presented to the magma allowing ready penetration. The coarse grain of the granite at its margin shows that the phenomenon is not due to a chilling against the walls.

METASOMATIC ALTERATIONS.

Connected with the study of this contact is the question of possible modification in composition. As the three specimens just described are from successive though similar strata, a direct comparison of their composition is valueless and other features must be considered. It has been shown that in the rock mass as a whole the mica-bearing portion maintains its essential characteristics up to and even within the granite, proving that mere proximity to a granite magma is not able to destroy the mica and produce the mineral changes which have been noted in the localities previously discussed. Nevertheless metasomatic changes are observed here also and will be described.

Possible feldspathization.—In the two specimens in direct association with the granite the mica is not quite uniform in distribution and where deficient in amount the quartz and feldspar are more abundant and of somewhat coarser grain, suggesting that if any changes have taken place they have consisted in a slight addition of quartz and feldspar. If so, such a feldspathization is entirely distinct from simple contact metamorphism and must not be confused with it.

Hornblendization.—In the description of this locality it was noted that the banded hornstones were brown and olive green. The olive-green portions owe their color to crystals of green hornblende averaging 0.25 mm. in length. The smaller of these hornblendic laminæ exist in the form of flat discontinuous lenses 1 to 5 mm. thick and 1 inch to several inches long. While these lenses are parallel to the bedding, they are not arranged on definite surfaces, but are scattered irregularly through the rock. This fact alone suggests that they are due to metasomatic alteration rather than to differences in original composition, a conclusion which is confirmed by the study of the thin section. Under the microscope the central portions are seen to consist of poorly developed pale-green hornblende with a tendency to sheaflike growth, more or less intergrown with quartz. The marginal portions consist of deeper green idiomorphic hornblende crystals, in many places with minute inclusions of the surrounding fine-grained allotriomorphic quartz. Within these laminæ no feldspar is discernible.

The line separating the hornblendic and mica-bearing portions is usually straight and marked by a mica-free white band 1 mm. wide, but for a distance of several millimeters within the mica-bearing portion scattered idiomorphic hornblende crystals are developed, and around them for a distance of 0.1 to 0.2 mm. is a white surrounding zone free from mica, conclusively proving that the hornblende has grown by the absorption of the biotite. The evidence being considered conclusive that at least these scattered outlying crystals of the hornblendic layers have grown by metasomatic reactions, the fact that the process is not observed along any cross fractures is strange and suggests that at the time but few if any such fractures existed. The composition of the hornblendic laminæ was estimated roughly as follows: Hornblende 40 per cent; quartz, no feldspar evident, 60 per cent; accessory magnetite and epidote, 1 per cent.

These changes have started on the bedding planes and spread laterally into the walls. The transformation of the mica into hornblende may not have required either loss or addition of iron, but would involve the addition of silica, lime, and some magnesia and the elimination of potash and probably alumina. In view of the probable presence of some feldspar in the fine-grained groundmass of the original rock and its apparent absence from the hornblendic portion, the mass changes in the rock would appear to be the addition of silica, lime, and magnesia and the abstraction of alumina and alkalies. This process would, therefore, be the opposite of feldspathization. It is needless to say that, owing to the lack of exact data, these results must be regarded as suggestive and not conclusive.

Epidotization.—The hornstones are intersected by a system of transverse cracks hardly continuous enough to be called joints, cutting both the brown and green bands. These cracks run east and west, dip 60° S., and stop at the granite. They are filled with either quartz or epidote. An irregular bleaching is observed to extend 1 to 2 mm. into the walls of those filled with epidote. This bleaching is found under the microscope to be due to a scattered cloud of small anhedral epidote crystals, which are developed in the wall rock and in whose presence the brown mica has been destroyed.

A microscopic examination of the hornstone layer adjacent to the granite reveals scattered grains of epidote running in a line but isolated from each other. Recrystallization of the rock mass after epidotization has been so thorough as to obliterate completely many of the fractures except where preserved by dusty inclusions or crystals of epidote, thus almost concealing a previously shattered condition.

Relative age of the several processes.—As already stated, at this locality five distinct processes have been in operation—first, contact metamorphism, a crystallization of a ferruginous, argillaceous sandstone into the red-brown, fine-grained micaceous hornstone, apparently without accession of substance; second, hornblendic

A

B

METAMORPHISM 10 FEET FROM GRANITE CONTACT. BROWN BIOTITIC HORNSTONE SHOWING INFILTRATION RESULTING IN OLIVE-GREEN HORNBLENDIC LENSES.

A. Hand specimen, showing hornblendic metasomatism with white reaction rims surrounding the hornblendic lenses. Field No. 16.

B. Photomicrograph with analyzer, showing contact of hornblendic *lamina* (below) with biotitic rock mass (above). Field No. 16. Magnified 19 diameters.

metasomatism, beginning along numerous bedding planes and extending into the walls; third, epidotization along cross fractures and extending into the walls; fourth, recrystallization adjacent to the granite, seemingly owing to the presence of water vapor, not changing the mineral species but enlarging the individual crystals; fifth, slight apatitization, tourmalinization, and possibly feldspathization and silicification along the immediate contact, as shown by the composition of the contact rock given on page 128.

The unexpected result is that the first three processes named above appear to be older than the other two, the conclusion being based on the facts that the cracks filled with epidote begin at the contact but are not found within the granite and are masked to some extent by a recrystallization which is closely connected with the granite contact. This recrystallization was doubtless simultaneous with the formation of a little tourmaline and apatite.

The earlier origin of the first three processes may be explained by supposing that the granite did not reach its present limits suddenly and that this locality was within the contact zone long enough for these processes to take place before the final breaking upward of the granite. The implication that the granite gradually ascended to its present limits is so important, however, in connection with the manner of the intrusion, that the conclusion should not be forced on this petrographic evidence alone, which on wider study might be found susceptible of some other interpretation.

CONCLUSIONS.

Apart from the question just touched on the facts observed at this locality call forcible attention to the lack of much direct addition of material from the quartz-diorite magma of the Marysville batholith to its walls where these consist of a somewhat ferruginous and argillaceous sandstone. Although the granite mass is of considerable size the direct contact effects of granitization are much less notable than in some instances which have been studied elsewhere, especially in France.[a] The chief effect has been merely one of recrystallization without fusion or absorption and without destruction of the brown mica, which has given place to other minerals wherever in this region impregnation effects have been noticeable. The presence here and there of small crystals of tourmaline and apatite scattered through the rock near the contact, indicates a limited amount of pneumatolitic impregnation different from the metasomatic reactions, which have been previously discussed.

OTHER CONTACT REACTIONS.

As has already been made evident, the reactions of the immediate contact within this district, in view of the volume of magma concerned, and its probable considerable depth at time of solidification, seem very meager. As a rule the contacts are sharp and with but little apparent chemical modification of either the granite or its walls.

[a] For a discussion of this subject see Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 728 et seq.; also papers by many other writers.

CALCAREOUS CONTACTS.

Specimens were taken at a number of localities where calcite as an original mineral has been involved, which was not the case at the contact just described in detail. The first change in all cases is the entering of silica into combination with the lime, but this action as the result of a direct emanation from the magma permeating the entire wall rock is very limited, probably extending a few feet only, since rocks somewhat calcite-bearing are still found not far from the contact. Beyond this the action appears to be one of infiltration along supercapillary openings. Following the formation of diopside, usually from materials in place, or possibly to some extent from magmatic emanations, has come a metasomatic impregnation of green hornblende and quartz; feldspar may be introduced in smaller amounts. The hornblende forms large idiomorphic crystals 3 to 5 or even 10 mm. in length, holding as much as 40 or 50 per cent of small granular inclusions of quartz and feldspar such as are common to the surrounding groundmass. The diopside granules are in all cases resorbed, showing that the hornblende has grown at their expense. These sharply defined hornblende crystals are apt to form black-green matted surfaces between the granite and the diopside rock. Lines of them penetrate the latter for some inches and isolated crystals may be scattered through the rock for an inch from the general mass. In the case of the wall rocks originally of diopside this clearly indicates an addition of silica, alumina, and iron.

It is not necessary, however, that the wall rocks should be of diopside for this reaction to take place, since it was noted at one place against a biotitic hornstone, in this case the biotite being resorbed; but an originally calcareous nature appears to be favorable for the reaction. This contact impregnation is closely similar to the hornblendization previously described as occurring along sedimentary planes within the red-brown hornstones at a slightly greater distance from the contact at another point, and doubtless the two are genetically related.

In only one instance was the wall rock noted as having any influence on the magma. At the contacts of the large intrusion farthest east from Marysville on the railroad the diorite, porphyritic on the margins, is interfingered with the hornstones. The contact shows tortuous flow lines, and certain dark, fine-grained bands look as if they might belong to either the diorite or its walls. Under the microscope they are found to be rich in hornblende, with some diopside, while quartz and feldspar are segregated through the rock irregularly. It appears to belong to the hornstones, but has been largely modified by the diorite and may have been in part molten.

On the other hand, a narrow margin of the same diorite in one or two places was observed whiter than the normal rock, owing to the substitution of pyroxene for hornblende and an increase in quartz over the normal rock, which is here almost quartz free. The association of as much as 20 per cent of pyroxene with about 15 per cent of quartz is notable and would seem to be most naturally explained by the absorption of lime from the walls. There is, furthermore, over 50 per cent of labradorite and no orthoclase in this contact zone. This apparent reaction between the hornstone and the magma is extremely limited in amount and contrasts with the large degree of marginal assimilation which is thought by many to take place in other regions on the borders of batholithic masses. The wide variation in conditions of intrusion would, as discussed in the introduction to this chapter, seem to provide room for either the presence or absence of marginal reactions and assimilation.

CONTACT REACTION OF APLITE AGAINST DIORITE PORPHYRY.

About 2,000 feet east of the railroad trestle at Marysville the intrusion of diorite, porphyritic near its margins, is cut by aplite dikelets. In this vicinity many of the alaskite-aplites grade into pegmatites, and the latter in places hold vugs which may contain idiomorphic quartz and orthoclase crystals up to 15 or 20 mm. in length. These have been later closed by further crystallizations. They suggest, however, that their intrusion may have been attended with the presence of much water gas, and this possibility should be borne in mind in seeking any explanation for the phenomenon to be described later, of the ferruginous impregnation of the diorite walls from the aplite dikelets. The porphyritic diorite has a fine-grained, dark-gray, microgranitic groundmass holding conspicuous needlelike phenocrysts of hornblende and inconspicuous ones of labradorite. The hornblende needles are green, idiomorphic, and of an original growth, but are surrounded by a bordering ring of small colorless pyroxene granules, the relations of the hornblende and pyroxene being thus the reverse of that which is customary. The groundmass also holds many scattered granules of colorless pyroxene. The question arises as to whether the pyroxene is original or of secondary origin. The probability is that it is secondary, since in places the thinnest needles of hornblende appear to have been entirely destroyed and their places are taken by strings of pyroxene grains. It was noted that on the weathered surface of one block on the borders of the aplite seams the matrix of the porphyritic diorite was of a darker color to a depth of 5 to 10 mm. The thin section showed that this was due to the presence of granular, deep-green hornblende in the groundmass in place of the diopside. The phenocrysts also have a darker tone. The granular hornblende is not only nearer the walls of the aplite dikelets, but is more abundant than the diopside-pyroxene of the groundmass situated farther within the rock.

In view of these relations it would seem probable that on the injection of the aplitic material into these seams there had occurred a selective penetration of iron, lime, and magnesia into the walls, the lime and magnesia penetrating farther; but from the fact that this process was noted only at this one place it does not appear to have been common in the Marysville district. It seems possible, however, that such a process may be important in regions where the intrusion takes place at greater depths and where the water vapor can escape from the walls only with difficulty and the materials have more time to accomplish any reactions which may be favored. Here if the lime, iron, and magnesia were put back into the alaskite dikelet it would become of an intermediate or basic composition. It is suggested that in such magmas holding an abundance of water vapor and intimately injected into a mass still near the temperature of fusion a separation may take place, the basic constituents being readily carried into the subcapillary pores of the rock by the aid of the water vapor and perhaps having a selective affinity for the solid materials of the walls. The acidic constituents, on the other hand, seem to remain in the fissure and to give rise on solidifying to the ordinary alaskite dikelets.

This extension of conclusion from the facts observed at Marysville is suggested by observations which the writer has made in New England, noting the presence in a few places of alaskite dikelets bordered by schistose walls, which close to the dikelets are dark and abnormally rich in biotite.

GARNETIFEROUS IMPREGNATIONS.

In the contact zone of the Marysville batholith, garnet is not a common mineral, and where it does occur it is highly ferruginous and in some cases clearly of metasomatic origin, this being possible also in the other cases where the origin is not clear. At two places within the metamorphic zone narrow contact bands of brown granular garnet were observed occurring between sheets of microdiorite and white marbles. These are clearly reaction bands between the two rocks and probably date from the period of microdiorite intrusions previous to the batholithic invasion. As they lie within the metamorphic zone, however, and no instances were observed beyond it, the exact time of origin is not beyond doubt.

The most noticeable occurrences of garnet not of direct-contact origin are, first, in the prospecting tunnels on Silver Creek, east of Marysville, and, second, along the higher parts of the ridge west of Deer Creek, and also on Drinkwater Gulch. At the end of a tunnel a few hundred feet east of the main contact on Silver Creek the hornstone is observed to give place to an irregular body of a heavy, massive rock consisting of granular green pyroxene and coarse patches of reddish-brown garnet. A small amount of quartz and calcite occur in what appear to have been small open cavities existing after the formation of the other two minerals. A little pyrite is also scattered through the rock. The relations indicate a metasomatic alteration from the adjacent hornstones, with the addition of much iron and possibly some other elements. There are many intrusions in the immediate neighborhood, and this may be near a contact. Near by in the same tunnel is an occurrence of green pyroxene and pyrite, probably formed at the same time, indicating in that case the elimination from the magma of sulphur also.

Along the ridge to the west of Deer Creek there is a continuous exposure of the strata, and for 1,000 feet along the higher part of the ridge occur beds of brown garnet from 1 foot to 5 feet in width intercalated in strata of hard, light-colored hornstones, some of which still hold a small amount of calcite. The garnetiferous bands form from 10 to 15 per cent of the whole series. The southernmost occurrence is a local patch of no great lateral extent, and in this patch free crystal ends project in places into small miarolitic cavities which may once have held calcite. The large amount of iron in these garnet beds and the discontinuity sometimes observed when they are traced along the strike lead to the belief that in all probability they are formed largely or entirely through metasomatic replacement of calcareous rocks.

PYRITIC IMPREGNATIONS.

Under this heading it is intended to treat only those cases of pyritization which appear to belong to the epoch of contact action rather than to a later epoch of hydrothermal metasomatism. Pyrite is the most common sulphide of fissure veins, and where there is any doubt as to the method of origin it is most naturally to be ascribed to aqueous deposition. But it is also believed by many to be deposited within the wall rocks as a direct emanation from magmas, at a time when the temperature is still above the critical temperatures of water and various other volatile substances. Vogt,[a] the leading exponent of this view, classes under this head many important pyrite deposits of Norway, Spain, and other European countries. Lindgren[b] has also called attention in this country to the metasomatic deposit of pyrite among other iron and sulphur minerals in the contact zone of the granitic intrusions of the Clifton-Morenci district in Arizona. As these views, especially the extreme ones of Vogt, have not been completely accepted by many, and as the line between pneumatolitic and hydrothermal action is difficult to draw it is well to call attention to those instances in which the relations seem to point toward pneumatolitic action in close association with the contact.

Two instances were noted at Marysville where the petrographic relationships showed deposition of pyrite in the presence of minerals commonly forming at high temperatures, without noticeable alteration in these minerals. Both occur in prospect tunnels within the contact zone east of Marysville and one has been already mentioned in connection with the garnetiferous deposit of the same locality. At this place poikilitic crystals of pyrite up to half an inch or more in diameter hold the finely granular pyroxene as inclusions. The pyrite shows a slight tendency to crystal boundaries, but in general permeates the pyroxene rock in irregular spongelike growths. In places the composition may be half pyrite. Some patches of hydrous silicates, serpentine, and chlorite are present, but are distinct from the two chief components. Although the pyrite is the younger mineral, the lack of general alteration of the pyroxene, the poikilitic nature of the pyrite, and the close association with the near-by garnet tend to the belief that it formed under conditions in which pyroxene and garnet were stable minerals and that it was associated with their formation.

The second instance is in a prospect about half a mile east of the main contact of the batholith. Here a tunnel 200 feet long driven into the hill on the south side of Silver Creek penetrated a hard, massive, diorite porphyry in the last 100 feet. The entire mass of porphyry is impregnated with pyrite estimated to comprise from 2 to 5 per cent of the rock, a photomicrograph of which is given in Pl. XVI, *B* (see p. 144). Close study shows it to be not an original constituent, but still to have formed simultaneously with biotite which resembles that of the normal crystallization of granite rocks. Under the microscope the rock is seen to consist of about 50 per cent of sharply idiomorphic and strongly zonal labradorite phenocrysts. The groundmass of quartz and feldspar has a granophyric tendency and contains a considerable amount of olive-green mica and pyrite with lesser amounts of calcite, apatite, titanite, and epidote in descending order. Notwithstanding the presence of the pyrite and calcite the rock has a notably fresh appearance, the labradorite phenocrysts showing hardly a trace of alteration, and at first sight the pyrite and calcite have the appearance of original constituents

[a] Vogt, J. H. L., Problems in the geology of ore deposits: Trans. Am. Inst. Min. Eng., vol. 31, 1902, p. 140.

[b] Lindgren, W., Genesis of the copper deposits of Clifton-Morenci, Arizona: Trans. Am. Inst. Min. Eng., September, 1904.

of the groundmass. A closer study, however, shows, as is to be expected, that they are not original and that the mica also is a product of metasomatic infiltration. The evidence is as follows: It is noticed that the pyrite and mica are associated and of simultaneous growth, each holding inclusions of the other. The calcite on the whole is younger, but is closely associated with them also. These minerals are not uniformly scattered over the groundmass or even gathered in nuclei, but run in rude lines intergrown with the quartz and feldspar of the groundmass over belts averaging from 0.2 to 0.5 mm. wide. In places the pyrite and mica show idiomorphic tendencies, exist in larger individuals, and spread more widely over the groundmass than in other places. The calcite is found chiefly in such centers and locally has the appearance of being partly hemmed in by mica plates. The feldspar phenocrysts remain intact, though many of them are partly enveloped by a string of pyrite grains as if a fracture line admitting the material had readily followed part way around their perimeter. This is well shown in Pl. XVI, *B*, by holding the plate at some distance and letting the eye dwell on the general appearance of the section rather than the detail. In rare instances lines not over 0.1 mm. in width penetrate the feldspars and are filled with feldspar, mica, pyrite, calcite, and apatite. That this feldspar is secondary is evident from its slightly different composition, though it is a regrowth from the parent crystal. The shape of the secondary feldspar areas suggests that mica may have once occupied the whole space and that then by a reversal of the metasomatic action it has suffered partial destruction, its place being occupied again by feldspar. This inference can not, however, from the nature of the evidence, be certain. In the case of the fractured feldspars the inner and most basic portions have suffered some degree of recrystallization and sericitization.

This description emphasizes the conclusion that after the rock was solid it was closely fractured, the groundmass suffering rather than the feldspar phenocrysts; this was followed by an extensive infiltration of at least iron and sulphur under conditions of temperature at which the plagioclase feldspars were stable minerals, conditions favorable also for the formation of the olive-green mica, which is presumably biotite. The infiltration resulted in metasomatic action, with considerable recrystallization of the groundmass. Lime, carbonic acid, and chlorine or fluorine were also brought in or partly supplied by the materials of the groundmass.

As previously stated, there is no accepted absolute criterion for the distinction of metasomatism under pneumatolitic conditions. Lindgren[a] notes that while biotite is rare in fissure veins, it still occurs, in one instance associated with quartz, garnet, tourmaline, actinolite, and zinc blende; and the ability of pyrite to form small, sharp crystals in fresh original quartz, feldspar, hornblende, and pyroxene is well known. Nevertheless the description of this rock strongly suggests that with the exception of the calcite the action has taken place at a high temperature, probably above 365° C., and therefore under pneumatolitic rather than hydrothermal conditions.

The conclusion of most importance, perhaps, is that the infiltration, even at high temperatures, depends on a fractured condition of the rock in the absence of a

[a] Lindgren, W., Metasomatic processes in fissure veins: Trans. Am. Inst. Min. Eng., vol. 30, 1901, pp. 609-616.

naturally porous texture, the distance to which the solutions have penetrated into the solid walls being very slight.

Another instance which might be mentioned in this connection is a sheet of pyritized microdiorite nearly 3 miles north of Marysville penetrated by the workings of the Big Ox mine. The region has suffered severe metamorphism, which in connection with a dike of porphyritic quartz diorite leads to the belief that a considerable body of igneous rock is present not far below. The microdiorite is extremely altered, the rock now consisting largely of secondary greenish-brown mica, hornblende, calcite, and quartz, only the lathlike crystals of plagioclase appearing to be original. The pyrite occurs to some extent as crystals through the rock, but chiefly in a system of parallel joint planes. The evidence of an early origin is here not so clear, but the rock is interesting as being associated with the metamorphic zone and probably over a still uncovered body of igneous rock, suggesting its derivation from the latter.

METAMORPHISM OF THE MICRODIORITES.

DESCRIPTION.

The appearance of the microdiorites where they have suffered changes within the metamorphic zone has already been partly described. The original rocks are gray-black in color, in places fine grained, in other places with conspicuous hornblende phenocrysts. Where altered by contact action shades of reddish brown are assumed where the groundmass becomes filled with flakes of brown mica, or greenish gray where the alteration has been to fibrous hornblende. The groundmass is the first to suffer alteration, the change being usually to a mass of mica flakes which form a veil over the entire rock.

In the more severe alterations the hornblende phenocrysts are also completely destroyed and their places taken by a matted mass of green fibrous hornblende, locally mixed with the brown flaky mica. The plagioclase is relatively stable. In some of the most highly altered specimens quartz and calcite also appear.

With two exceptions the microdiorites showing alterations of this nature were clearly within the metamorphic zone. The exceptions are two sheets noted on the railroad cut in Sawmill Gulch at a distance of a mile from the batholith and half a mile from the limits of the strongly metamorphic zone. Here, besides idiomorphic crystals of biotite upward of 0.5 mm. in length, are flaky aggregates scattered more or less freely over the section. Within polygonal patches replacing some earlier mineral a considerable amount of calcite occurs with orthoclase with flaky biotite in places and more rarely pyrite and ilmenite.

On the other hand alterations of this character are not universal within the metamorphic zone. Two specimens, showing under the microscope a fresh appearance and the original crystallization, were collected within 500 feet of the main batholithic contact, one being cut by dikelets of the Belmont porphyry. A third, used for analysis, was collected at Bald Butte in close association with other specimens which showed extreme alteration.

ORIGIN.

That the metamorphism is not due to mere elevation of the temperature is indicated by the freedom from recrystallization here and there in proximity to the batholith, by the presence of it in two associated instances at some distance beyond the intensely metamorphic zone, and especially by the unusual severity of the alteration at Bald Butte in connection with the mineralization of the large dike of Belmont porphyry and the adjacent hornstones, veinlets of quartz and fluorite cutting the porphyry, the hornstones, and some of the microdiorite sheets. Again, alterations of this character are not observed at great distances from the batholith, the microdiorites being there either unaffected or altered to calcite, sericite, and chlorite, mineral changes which might readily result from surface actions. These relations are best explained by the view that the alteration has been due to thermal waters, perhaps approaching pneumatolitic conditions, holding solvents derived at least in part as emanations from the still heated magmas, rising toward the surface and finding certain of the microdiorite dikes and sheets favorable channels for penetration.

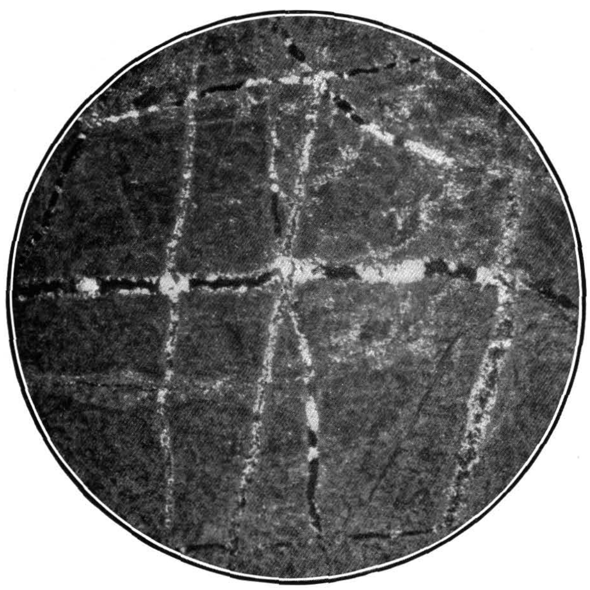
The formation of secondary biotite, hornblende, and orthoclase doubtless indicates an elevated temperature, as these minerals are characteristic of the primary crystallization of igneous rocks and are relatively uncommon in fissure veins. As to whether the temperature necessary for metasomatic changes of this character is above the critical temperature of water there is no information.

HYDROTHERMAL METAMORPHISM OF THE HORNSTONES AT BALL BUTTE.

The hornstones of Bald Butte are distinctly banded and differ in appearance from those of other parts of the Marysville district, the colors varying from light to dark greenish gray, with narrow laminæ almost white, the shades of brown and red being absent. Under the microscope the darker bands are seen to consist of small crystals of splintery actinolite and flakes of green mica set thickly in an exceedingly fine-grained microgranitic groundmass which appears to be wholly of feldspar. The light gray-green bands consist largely of tremolite set in feldspar, and the white bands almost wholly of feldspar. Scattered through the entire rock are minute rough grains, judged to be epidote, and very small crystals of apatite are fairly common.

A clue to the possible origin of this mineral arrangement is found in places on the western slopes of Bald Butte. Here a diopside hornstone, shown in Pl. XV, holding some quartz and possibly feldspar, has been thoroughly and closely shattered, the seams varying from 0.1 to 0.2 mm. in width, being filled first with quartz and later with fluorite as shown in the photomicrograph. On the walls the diopside is turned to a mass of bluish-green hornblende crystals tending to stand at right angles to the fractures, the original nature of the rock showing only in the nuclei between, as seen in the view of the hand specimen. The presence of the quartz and fluorite in the fractures connects the alterations with those of the dike of Belmont porphyry, which were accompanied by the infiltration of quartz and fluorite into the open fractures, and in places by the complete transformation of the porphyry into these same minerals plus muscovite. It has been shown that the same action has converted the adja-

A



B

SHATTERING, INFILTRATION, AND HYDROTHERMAL METAMORPHISM OF DIOPSIDE HORNSTONE OF BALD BUTTE.

A. Hand specimen, showing light-colored, unaltered diopsidic nuclei and the development of green hornblende on the margins of the cracks.
B. Photomicrograph with analyzer, showing shattered rock with cracks infiltrated first with quartz and then with fluorite. Magnified 11 diameters.

cent microdiorites into greenish-black rocks in which the original hornblende has been recrystallized into a mass of hornblende fibers and the groundmass is sifted over with hornblende fibers or mica flakes.

An inspection of the map (Pl. I) shows that Bald Butte owes its prominence to a superior hardness of the rocks adjacent to the dike of Belmont porphyry. These several reasons lead to the belief that the rocks of Bald Butte as a whole have suffered hydrothermal metasomatism, possibly approaching pneumatolitic conditions, and that the brecciated zone of the Belmont porphyry dike offered a favorable channel for the escape of heated waters from below.

RELATIONS OF MICA, HORNBLENDE, AND PYROXENE.

INTRODUCTORY STATEMENT.

In the preceding pages it has been stated that sometimes diopside is formed through contact actions, sometimes hornblende. Instances have been cited also where hornblende has replaced diopside, and one where diopside has replaced hornblende. It will be well to sum up the relations which have been observed to exist in this district between these minerals, and to disentangle and coordinate, if possible, the apparently contradictory facts. By so doing some general principles may be derived in conformity with what has been or may in the future be noted elsewhere, and in this way the mineralogical relationships observed here may be utilized for reaching solutions in regard to other problems.

Mica, hornblende, and diopside-pyroxene are all observed to form as a result of simple contact metamorphism and also from metasomatic reactions. Therefore it is the rock composition which determines the resulting mineral, since any one of the three can form under the physical conditions of the contact zone.

This chemical difference is expressed by the following formulas of common species of these groups:

Biotite.................................... $Si_6(AlFe)_6(KH)_6O_{24},Si_6(MgFe)_{12}O_{24}$.[a]
Tremolite.................................. $CaMg_3Si_4O_{12}$.
Diopside................................... $Ca_2Mg_2Si_4O_{12}$.[b]

The most distinctive chemical features of these minerals are the low silica and high alkali of the mica group, the high magnesia or ferrous iron of biotite and tremolite (actinolite), the equal molecular ratio of lime and magnesia in diopside, and the absence of appreciable alumina and ferric iron in tremolite and diopside. In the micas there is no lime, in tremolite 13.4 per cent of lime, in diopside 25.9 per cent.

The conditions under which these minerals occur within the contact rocks of the Marysville district are noted in the following paragraphs:

RELATIONS OF BIOTITE AND HORNBLENDE.

Mica is extremely abundant in the hornstones as the result of the simple metamorphism of argillaceous and slightly ferruginous sediments containing a notable proportion of comminuted but not decomposed feldspar. It is not so abundant, however, as a result of metasomatic change, doubtless because the ready solubility of the alkali allows its abstraction, and under those circumstances hornblende is fre-

[a] Tschermak's formula. [b] Double the usual formula.

quently developed at its expense. This is contrary to the reaction which Bischof has noted as taking place in surface weathering, where if water impregnated with alkaline carbonates comes into contact with calcareous silicates the alkalies are deposited and the lime removed, the replacement being explained on the supposition that the alkalies in their nascent state form new combinations with the other silicates present, while the lime combines with the carbonic acid. The nearest approach to this opposite reaction is observed at Bald Butte, where hornblende phenocrysts of the microdiorites have been recrystallized into a matted mass of hornblende fibers, locally intermixed with brown mica, presumably biotite. These reactions must not, of course, be confused with the original crystallization of biotite or other micas from magmas.

To sum up the foregoing statements, it is found in the Marysville district that—

First. Mica may crystallize as a primary mineral either from a magma or in a contact rock offering a suitable composition. If sufficient iron is present the species will be biotite.

Second. Near the batholithic contact biotite is not a stable mineral under metasomatic conditions, but by the loss of potash and water and the addition of lime and silica tends to be transformed into hornblende. Considerable alumina is doubtless eliminated also. This, then, is a mark of pneumatolitic metasomatism.

Third. At a greater distance biotite and hornblende are about equally stable, and the partial or complete transformation of hornblende into biotite may therefore be regarded as a mark of hydrothermal metasomatism, tho perhaps at a temperature but a little lower than under the more intense conditions closer to the contact.

Fourth. At still greater distances and under conditions of hydrous metamorphism such as exist in the outermost belt of the crust biotite itself tends to break down into more hydrous forms, such as chlorite. This is in agreement with the rarity of biotite in fissure veins, as pointed out by Lindgren,[a] who concludes from the structural relations that in the instance where he notes it as occurring the mineralization followed pretty closely the consolidation of the rock. It is seen that the same relations of the development of biotite of metasomatic origin to the time of metamorphism and igneous intrusion hold true for the Marysville district. It seems probable, therefore, that the hornblende-biotite-chlorite series of metasomatic minerals may be one of the best measures of the physical conditions under which a rock has taken on its final crystalline form, where one of these minerals is found to have replaced another of the series.

RELATIONS OF HORNBLENDE AND DIOPSIDE.

The preceding descriptions of the contact phenomena show that either hornblende or diopside may develop as a result of primary crystallization from a magma or by the metamorphism of the wall rocks, and in the latter case they may occur in either the inner or outer zone and therefore under either pneumatolitic or hydrothermal conditions of temperature, but hydrothermally only as a result of simple metamorphism and not of metasomatism. They may also originate as a result of pneumatolitic metasomatism, either mineral being transformed into the other according to the character of the solutions involved.

[a] Lindgren, W., Metasomatic processes in fissure veins: Trans. Am. Inst. Min. Eng., vol. 30, 1901, pp. 609-610, 644.

A diopside may be changed into a hornblende, crystallizing on a coarser scale if much iron or magnesia is introduced in the presence of the necessary amount of silica. As a rule there appears to be always sufficient silica either present in the rock mass or brought in with the bases. On the other hand, if lime is introduced a hornblende may be transformed into a diopside, crystallizing, however, on a finer scale. Apparently in this region neither mineral tends to form by metasomatic replacements in the zone of hydrothermal metamorphism, as is shown, indeed, by their conspicuous absence from ordinary fissure veins.

Of the two changes, that from diopside to hornblende appears to be the more common and would seem to imply that iron-bearing emanations from the magma are more usual than calcareous emanations. Where there is evidence of the latter within the Marysville district it may perhaps be true that the excess of lime has been acquired by the emanations in their passage through calcareous wall rocks, rather than by an original derivation from the magma.

As a partial exception to the above statements must be noted the tendency of pyroxene to pass over into the fibrous hornblende known as uralite as a more stable form. This may apparently occur with little addition or abstraction of material from the rock mass, but rather by a breaking up of the original mineral molecule with a partial separation of lime as finely divided calcite or epidote. According to Rosenbusch[a]—

> It is in general absent from the younger augite rocks, but occurs in those whenever they have been subjected to the same mechanical processes which the Paleozoic masses have undergone.

The same author says elsewhere:

> All augite of diabase weathers very readily with the formation of * * * chloritic substances or of serpentine that are nearly always mixed with pistacite or calcite. * * * Where the diabase occurs in strongly folded rocks or in the contact zones of abyssal rocks the augite is very often transformed into uralitic hornblende.[b]

It appears, then, that under dynamic metamorphism in the zone of anamorphism hornblende is a more stable mineral form than pyroxene; but to judge from the phenomena of the Marysville district, where rock mashing is absent, the formation of the one or the other is determined by the chemical composition of the rock, and either may form in contact metamorphism, even within the zone of fracture or by pneumatolitic metasomatism, depending on the character of the solutions.

RELATIONS OF EPIDOTE TO THE CONTACT.

Wherever epidote occurs in this district as well developed and individualized crystals, either scattered as an impregnation mineral within the walls of joint planes or filling these planes with matted crystals, it is in close relationship to the contact. Where it occurs as an alteration product, no close relationship is indicated. At one place in the inner contact zone it has been developed in the cracks of a crackled wall rock which has later lost the appearance of shattering by a recrystallization of its mass.

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[a] Rosenbusch, H., Microscopical Petrography of Rock-making Minerals (Iddings's translation), p. 271.
[b] Rosenbusch, H., Elemente der Gesteinslehre, 1898, p. 322.

These relations suggest that epidote as a filling of open spaces is characteristically associated with magmatic emanations under pneumatolitic and not under hydrothermal conditions. As an alteration product from other minerals no such relationship holds, and it probably develops frequently from hydrothermal actions. Lindgren[a] notes that "it occurs chiefly in basic rocks containing labradorite and similar soda-lime feldspars and may form pseudomorphs after orthoclase, plagioclase, hornblende, or augite. These are the conditions under which it was observed to occur as an alteration product in association with the gabbro areas in the northern portion of the Marysville district.

SPECIAL STRUCTURES IN METAMORPHIC ROCKS.

On the hill slopes of Drinkwater Gulch northwest of the batholith the topography is determined by the varying resistance of a series of hard, white hornstones, limestones, and limy hornstones, the first named being the most resistant. Within these rocks various forms of mineral segregations have arisen during metamorphism. These can be most clearly distinguished in the purer limestones, since in these rocks the metamorphic minerals do not occupy so large a proportion of the whole. For the growth of these minerals the material must be brought together from a certain small distance and concentrated upon the surface of the growing crystals It will be desirable, therefore, to discuss first the limits of molecular travel as found at this place, and for this purpose the phenomena observed in the purer limestones will be described.

One bed typical of many others consists of a blue crystalline limestone filled with clusters of radiating skeletal tremolite needles upward of half an inch in length. These show conspicuously on the weathered surfaces, but not on fresh fractures, and comprise perhaps half the rock mass. Between the clusters of tremolite needles, themselves holding much calcite, are channels of pure blue limestone. There is no evidence that infiltration has caused the differences between the various beds, and on the assumption that the siliceous material was originally uniformly distributed through the stratum the width of the channels free from tremolite is a measure of the power of the molecules of silica to travel in the rock toward the places of crystallization. Here it is in few places over an eighth of an inch. This rock could have resulted from a dolomite carrying about 25 per cent of silica.

A molecular power of travel toward points of crystallization is nothing unusual; in fact, it is necessary. In a fluid magma the molecules can slowly work toward the centers of crystallization without great difficulty if the magma be not too viscous and sufficient time be granted, but in a solid rock the problem is of a different nature and interstitial water is considered to be the agent which by holding small amounts of the elements in solution gradually passes the uncrystallized material over to the growing crystals. The object in mentioning the present instance is, as previously noted, to show the distances of molecular travel in this particular case and to illustrate the tendency of the individual crystals to bunch together, a feature which is frequently observed and is here particularly clear.

[a] Lindgren, W., Metasomatic processes in fissure veins: Trans. Am. Inst. Min. Eng., vol. 30, 1901, p. 611.

About 50 feet stratigraphically below the bed just described there is a stratum of hard grayish-white diopside hornstone, some of whose layers remain without crevices where exposed to the weather, while other beds show a rude system of cracks which, looked at on the bedding plane, resemble sun cracks in drying mud. From the side, however, the cracks are seen to be very irregular, crumpled, and discontinuous, resembling worm burrows in wood. This same structure was observed in two localities, and in both cases massive solid strata adjoin those holding the openings.

A study of thin sections showed that the solid stratum shown in Pl. XVI, *A*, consisted essentially of diopside, that mineral forming as much as 90 per cent of the rock, with some quartz or feldspar, some epidote, and a small amount of calcite, estimated at 1 per cent. Scattered narrow lenticular areas show a coarser crystallization of diopside and are judged to have been the filling of spaces originally open or filled previously with other minerals. In the adjoining open stratum the cracks were formerly filled with calcite, which is now dissolved by weathering. The rock between the cracks is composed of diopside, but contains more calcite than the solid stratum above, the amount being estimated at about 10 per cent. The cracks are usually not more than 3 to 5 mm. in width and from a fraction of an inch to a couple of inches apart.

The previous study of the tremolite limestone suggests that here also there has been a tendency of the siliceous material to segregate, and that where the resulting lime silicate does not constitute the whole rock mass there is formed a series of fractures resembling shrinkage cracks from cooling, but more irregular. The calcite has segregated into these fractures without the necessity of their ever having been open spaces until exposed to surface weathering.

On the supposition that no elements have been added from without, the solid stratum, consisting almost entirely of diopside, would result from the metamorphism of a dolomite carrying about 40 per cent of impurities, mostly silica. On the other hand, the stratum holding the cracks, having been a somewhat purer limestone, would on metamorphism lose less carbonic acid and shrink less. Under these conditions the absolute shrinkage of the massive or diopside stratum during metamorphism would be the greater, and therefore these cracks in the less siliceous stratum can not be looked on as due to differential shrinkage, since they occur in the stratum which has shrunk least. Their crinkled character perpendicular to the bedding does suggest, however, that a considerable thinning of the beds, resulting in diminution of volume, has taken place after they first originated.

FACTORS DETERMINING EXTENT OF METAMORPHIC ZONE.

EFFECT OF COMPOSITION.

As has been stated on page 102 in discussing the faulting marginal to the batholith, some sedimentary members suffer metamorphism much more readily than others, so that hard hornstone beds may be encountered surrounded both above and below by softer and comparatively unmetamorphosed beds, while in strata of the same composition the metamorphism fades out gradually. These features make it difficult in places to draw sharply defined boundaries to the metamorphic zone.

EFFECT OF UNDERGROUND EXTENSIONS OF THE MAGMA.

On the southwest the metamorphism is continuous to the boundary of the area mapped, over 2 miles from the batholith, while immediately south of the batholith it does not attain more than a quarter of a mile in width. Difference in composition of the strata does not appear to offer a solution of this great variation, and a more natural explanation, suggested by the structural relations of the contact already discussed on pages 79–81, is that underground extensions of the batholith brought the magma comparatively near the surface in regions where the metamorphism is intense.

EFFECT OF MAGMATIC EMANATIONS AND SHATTERED WALL ROCKS.

As has been stated, the accepted view of the origin of contact metamorphism is that it is due to gases, especially water gas, escaping from the magma, carrying heat and, locally at least, various substances into the wall rocks. Ordinary dry conduction would also operate, but it is probably, at least in the zone of fracture, a slower process and therefore not the primal agency in the metamorphism. While the relation of the two is unknown, it has been shown that in the Bald Butte region the dike of Belmont porphyry and the brecciated zones on its walls have acted as channels for escaping substances which have caused great metasomatic changes of the dike and filled the open fissures with quartz and fluorite. These effects would be ascribed to hydrothermal action, possibly approaching pneumatolitic conditions, the gas-aqueous emanations of Weed's classification,[a] yet they have produced effects in the wall rocks which are similar to those of contact metamorphism and have resulted in a conspicuous recrystallization and induration.

It has been shown that in all cases in this district where metasomatism could be proved the action was greatly favored by a brecciated or fissile character of the strata, and it is seen that along such zones metamorphism may extend to unusual distances. This is no more than is to be expected, since the channels of readiest escape are sought out by gases as well as by fluids, and would permit metamorphic effects to greater distances than in other portions of the contact zone.

CONCLUSION ON THE EXTENT OF METAMORPHISM.

The foregoing considerations make it evident that no exact statement can be made as to the distance to which metamorphism has extended. Laterally it may not have strongly affected the walls in places for distances of over 1,000 feet. Vertically it is supposed to have extended far higher, the topographic relief indicating strong metamorphism for at least 1,000 feet in all cases, and a conservative estimate of the maximum distances reached would be at least two or three times that figure.

EXTENT AND CHARACTER OF METASOMATIC INFILTRATION.

From the preceding studies it has been shown that, especially in the inner half of the metamorphic zone, infiltration has occurred at many places, resulting in the formation of hornblende, diopside, garnet, epidote, and quartz under conditions which are judged to have been pneumatolitic. In a few cases biotite and pyrite have

[a] Weed, W. H., Ore deposits near igneous contacts: Trans. Am. Inst. Min. Eng., vol. 33, 1903, p. 719.

been formed under conditions not clearly demonstrable as pneumatolitic but apparently quite different from those connected with hydrothermal actions in fissure veins. Lastly, quartz, fluorite, muscovite, some biotite, and hornblende have been formed in connection with fissure veins and therefore presumably by hydrothermal rather than pneumatolitic action, tho the presence of fluorite, biotite, and hornblende, minerals common to contact metamorphism, suggests close relationships to pneumatolitic conditions.

The problem presented is, first, to what extent is infiltration, either pneumatolitic or hydrothermal, resulting in changes in chemical composition, connected with metamorphism; and, second, to what extent have such processes operated in the Marysville district? As pointed out in the introduction to this chapter these are important questions, and the criteria may be summed up as follows:

First. The original metamorphism shows no evidence of infiltration, thin concretionary bands of calcite still existing between siliceous bands. Yet calcite, both here and elsewhere, is found to be a mineral which readily suffers change in the presence of siliceous or sulfurous solutions.

Second. In the outer portions of the metamorphic zone a considerable amount of calcareous hornstones and smaller amounts of marble are present, a composition which, contrasted with that of the inner parts of the zone, is evidence that metamorphism without metasomatic infiltration has been the prevalent process in the outer portions.

Third. In strata consisting of alternating hornstone and marble laminæ the hornstone laminæ and associated hornstone beds are observed to show a compact, fine-grained, homogenous character, giving no evidence of varying composition or crystallization such as might be expected in metasomatic additions.

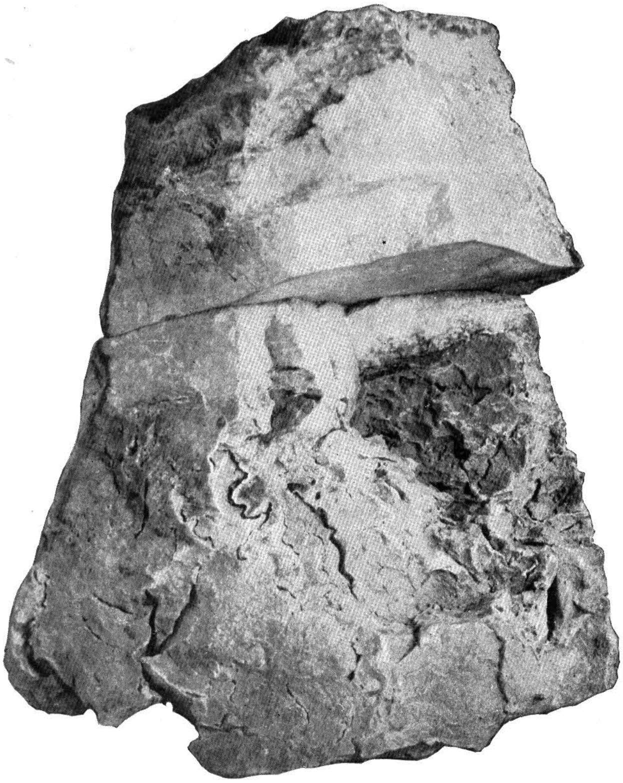
Fourth. These same laminæ of hornstone are formed of diopside, tremolite, actinolite, biotite, muscovite, quartz, feldspar, and in many places small amounts of calcite. These mineral compositions are such as would result from the simple metamorphism of the Empire and Helena formations, which are of a mixed sedimentary character.

Fifth. Minerals of characteristic pneumatolitic origin are wanting in these strata.

Sixth. In all cases where simple metamorphism and metasomatic infiltration are observed occurring together, the latter is seen to take advantage of brecciated or fissile structures, either following the brecciation or accompanying it, but penetrating only slightly into the rock.

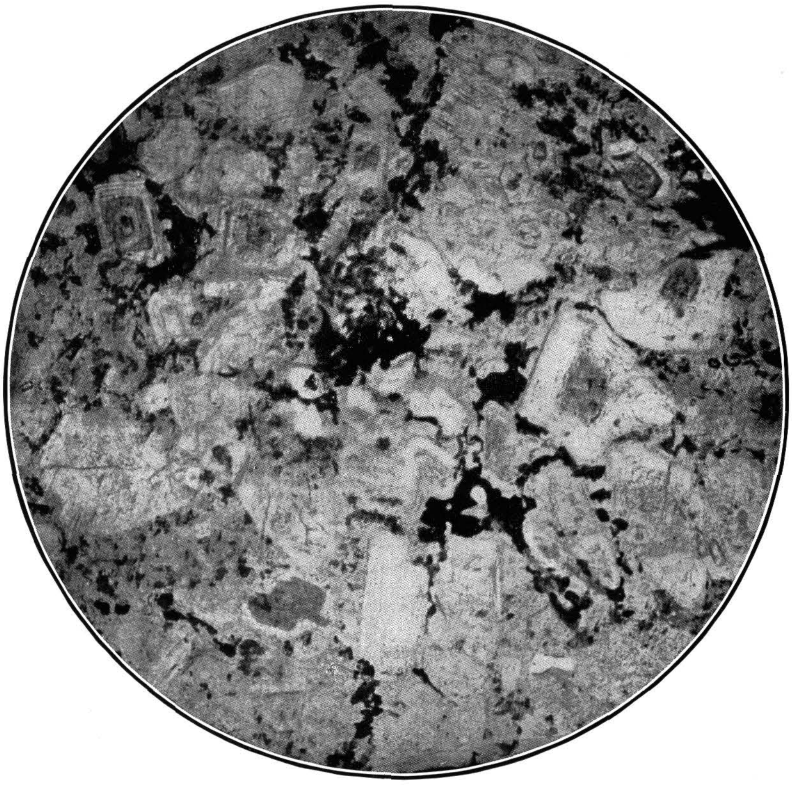
Seventh. A brecciated or fissile state appears to be a common but transient stage in the metamorphism. This may be due to any or all of the following factors: The regional brecciation and block faulting due to the structural changes accompanying the invasion of the magma; the effects of heat expansion; volume changes during metamorphism; or to the expansive force of crystallization of minerals developed in the rock mass from the permeating gases or fluids.

Such a brecciated state is favorable to metasomatic infiltration and probably also to a further advancing outward of the metamorphic zone. Completion of the infiltration process with recrystallization of the entire rock mass may completely or almost completely destroy the evidence of the once brecciated or fissile state.



A. DIOPSIDE HORNSTONE WITH CALCITE SEGREGATIONS.

Lower half shows cavities formed by recent solution of former crinkled calcite segregations. Unweathered fragments still show the calcite undissolved. The upper portion of the specimen is, however, a diopside hornstone without segregations. For the significance of these crinkled segregations see pp. 143, 148–150. Specimen from Gould, 12 miles northwest of Marysville, Mont. Field No. 41, *A* and *B*.



B. DIORITE PORPHYRY IMPREGNATED WITH PYRITE UNDER PNEUMATOLITIC CONDITIONS.

Photomicrograph without analyzer. Magnified 11 diameters. Contact metamorphic zone, Marysville, Mont. See page 135. Field No. 146.

Eighth. Infiltration along the bedding planes by selective action is apt to heighten the laminated appearance and produce a ribbon structure narrower and more marked in color than the original sedimentary laminæ.

THE PROCESS OF METAMORPHISM AND POSSIBLE SEQUENCE OF EMANATIONS.

As stated in the introductory portion of this chapter, contact metamorphism in the zone of fracture is supposed to be dependent chiefly on gaseous emanations from the magma which carry the heat with them into the surrounding rocks. The question arises as to how this process can take place without being universally accompanied by metasomatic infiltration. The answer may lie in the following facts: By far the most abundant gases given off by magmas, as illustrated by volcanic phenomena, are water gas, carbon dioxide, and nitrogen. These in themselves could add nothing to the wall rocks, as water can form hydrates of the anhydrous minerals only under hydrothermal conditions and not in the presence of dry steam;[a] carbon dioxide is unable to replace silica at high temperatures; and nitrogen is inert. The changes, then, must depend on the elements which these gases carry in solution. To judge from the varied effects around intrusive bodies the kinds and amounts of these elements vary greatly, and in magmas of similar character they probably undergo a secular change with the cooling of the magma.

If it is granted that in the case of the Marysville batholith moderate amounts of silica, iron, and sulphur, with lesser amounts of other elements, have been given off, it remains to be seen why the metasomatism was not coextensive with the metamorphism. The answer may be partly in the fact that the wall rocks exercised a straining or precipitating action on the solutions leaving the magma, the silica and other substances combining with the walls, and the inert gases, not yet robbed of their heat, passing farther into the rock and carrying forward the work of simple metamorphism.

To pass to a still more speculative side of the subject, it is to be noted that around the batholith metamorphism is universal. Siliceous infiltration is confined to the inner portions of the metamorphic zone, but is not universal, since here and there beds of marble remain intact to points within comparatively short distances of the magma, as on the northern slopes of Mount Belmont. Ferruginous and sulphurous additions, represented by garnet and pyrite impregnations, are still more local and confined to the intensely metamorphosed zone. Lastly, the quartz, calcite, fluorite, and sulphide deposits in the fissure veins and the metasomatic additions to their walls are localized as a result of the structure and were derived from a considerable depth at a time when the adjacent portions of the magma were solid.

This series of emanations, each successively more localized, appears to correspond roughly with their order in time. The later ones, as shown by their peculiar composition, must have drawn their materials from a wider zone and concentrated them into more localized deposits at greater distances from their source. This concentration has probably been governed in part by the gradual gathering of emanations from a depth into the channels of least resistance in a manner similar to the junction of many underground feeders of meteoric water to form a spring.

[a] Van Hise, C. R. (following Delesse and Barus), A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, p. 493.

This sequence of eruptive after effects suggests that in the magmatic emanations the earliest, eliminated immediately after intrusion of the magma to a higher zone with a corresponding relief from internal pressure, may have been the freest from elements producing metasomatism and may have been chiefly instrumental in the primal metamorphism. It is needless to say that this is merely a suggestion

VARIATIONS IN THE EASE OF METAMORPHISM OF DIFFERENT STRATA.

Where foreign substances are not added to the rock, contact metamorphism may be defined as a noticeable crystallization of amorphous substances or a recrystallization and possibly new combinations of substances already present, with an elimination of those which are gaseous or fluid. Judged on this basis, the evidence of the Marysville district shows that certain beds suffer metamorphism much more readily than others.

On the northern slopes of Trinity Hill unmetamorphosed limestones and shales are interbedded with light-gray hornstones of varying degrees of hardness which effervesce either slightly or not at all on applying hydrochloric acid. An examination with the microscope shows that these hornstones consist largely of diopside, with lesser and varying amounts of tremolite, muscovite, and calcite. In the process of metamorphism silica has displaced carbon dioxide and given rise to the present mineral combinations. The same features may be noted on Silver Creek near Sawmill Gulch, but the most striking instance occurs 1 mile north of Drinkwater Gulch. Here prominent cliffs of light-gray diopside hornstone about 50 feet thick may be traced for a third of a mile. The dip is less than 10°, and typical Helena limestone is found stratigraphically both above and below. This flat dip and the lack of evidence of direct association with faults, as well as the presence of the unmodified rock both above and below, negative the idea that the diopside is here the result of the infiltration of siliceous waters. The rock is scratched with some difficulty and possesses a very even and fine-grained texture, with an irregular semiconchoidal fracture somewhat resembling that of a quartzite. Under the microscope it is found to consist largely of diopside, estimated at 85 per cent, in irregular granular crystals, whose individual boundaries are to be distinguished only between crossed nicols, with small amounts of tremolite in thin rods and still smaller amounts of calcite and muscovite. There is little if any quartz, and the maximum diameter of the crystals varies from 0.05 to 0.10 mm. There is no evidence of minute brecciation with infiltration of silica along a multitude of crevices, such as is found at Bald Butte. Thus both structural and petrographic evidence indicates that the present mineral character is not due to infiltration.

It may be concluded, therefore, that siliceous limestones are the strata most readily metamorphosed, the silica displacing the carbon dioxide and combining with the lime and magnesia set free. The same conclusion is reached from a study of the tremolitic limestones. One of these, interbedded between strata of diopside hornstones, has previously been described. The weathered surface shows conspicuous radial clusters of tremolite needles up to half an inch in length, while the blue limestone, which forms the matrix, is only finely crystalline and not even to be designated as a marble. This shows the readiness and coarseness of the crystallization of the lime-magnesia silicates.

This action is directly the opposite of what Lindgren[a] finds to be true of the Clifton-Morenci district of Arizona, where the greatest contact effects have been produced in almost pure limestones and the metamorphism was attended by extensive infiltration of sulphur, iron, copper, and zinc, and probably also of silica and magnesia, the infiltration having taken place to distances up to 2,000 feet from the contact and between almost unaltered Devonian and Cretaceous sediments. It is obvious that the difference is to be found in the extensive metasomatism which occurred in the Arizona locality.

MASS AND VOLUME CHANGES IN CONTACT METAMORPHISM.

GENERAL STATEMENT.

In the preceding pages a detailed discussion has been given to show to what extent simple contact metamorphism has taken place and to what extent there have been metasomatic changes. It has been shown that both processes have been involved, the metasomatism reaching some importance near the magma or along channels favorable for the escape of gases or fluids. The question now arises as to what mass and volume changes are involved in these processes.

In 1902, the year after the field work in the Marysville district was done, the writer published a paper dealing with the mass and volume changes involved where no accessions were received during metamorphism.[b] In this paper it is shown that in pure siliceous or calcareous sediments no changes took place except a reduction in porosity with consequent slight diminution of volume. In pure clay stones a considerable loss of volume takes place, both from loss of porosity and combined water and from the formation of minerals of greater density. In sediments of a mixed calcareous nature, however, these changes reach a maximum, the water and carbonic acid being eliminated by the combination of the silica and alumina with the lime and magnesia and in special cases the rock losing 50 per cent of its volume.

In the process of metasomatism accompanying metamorphism no general basis exists for calculating the mass and volume changes taking place, for not only are certain elements brought in, but others are taken out. If any one element existed in unchanged amount both before and after it would give a standard to which the others could be compared; but as there is no certainty that any element does so remain in unchanged amount calculations on such a basis are liable to error. However, as an extreme condition let it be considered that in the formation of the simple lime or lime-magnesia silicates none of the lime or magnesia of the original rock is carried away and all the silica is brought in. The volume changes resulting have been calculated by Van Hise,[c] and the results in the two cases may be tabulated as follows:

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[a] Lindgren, W., Genesis of the copper deposits of Clifton-Morenci, Arizona: Trans. Am. Inst. Min. Eng., September, 1904.

[b] Barrell, J., The physical effects of contact metamorphism: Am. Jour. Sci., 4th ser., vol. 13, 1902, pp. 279–296.

[c] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 239–241.

Changes of volume in metamorphism and metasomatism.

Metamorphic mineral.	Formed from—	Changes in volume (per cent).	
		SiO_2 original.	SiO_2 added.
Wollastonite ($CaO.SiO_2$)	Calcite	—31.5	+10.8
Diopside ($CaO.MgO.2SiO_2$)	Dolomite	—40.1	+ 2.0
Tremolite with calcite ($CaO.3 Mgo.4 SiO^2$)	do	—25.2	+ 9.9

In the metamorphism of the calcareous beds of the Marysville district diopside and tremolite have been the two minerals of commonest formation. It is desirable to apply the test of these calculated volume changes and observe how the results conform to the conclusions previously reached as to the relations of metamorphism and additive metasomatism.

ZONE OF SIMPLE METAMORPHISM.

A well-marked locality from which detailed studies were made is the hill on the north side of Drinkwater Gulch. Here on the higher slopes tremolitic limestones are interbedded with diopsidic hornstones, from many of which carbonic acid has entirely disappeared. Under the supposition that no accessions of silica have taken place the strata have shrunk in varying degrees from 10 to more than 40 per cent. As the original composition of the formations involved (the Helena and Empire) would result in such shrinkages, the only way in which they could be avoided would be by the addition of an equal amount of material from extraneous sources. Consequently it is very evident that in strata of a suitable composition to produce diopside about 40 per cent of foreign minerals should be added, unless the added material were itself diopside. Infiltration to such an extent would be also expected to attack the interbedded limestones, which if transformed into diopside would suffer almost no change of volume. Therefore, in additive metasomatism sufficient to produce no changes of volume in the Helena and Empire formations during their metamorphism there should be expected an abundance of diopsidic or tremolitic hornstones interbedded with others showing up to 40 per cent of quartz, pyrite, or other minerals characteristic of magmatic emanations. Of course theoretically any gradation between no infiltration and complete infiltration may occur, but the strata of the outer parts of the metamorphic zone give no indication of such action in any degree. On the other hand, the strata consisting of 90 per cent or more of diopside with small amounts of other silicates interbedded with fairly pure limestones not only agree in character with the unmetamorphosed series, but are in themselves an indication on the side of no infiltration.

In spite of this conclusion but little structural evidence of the shrinkage remains, a result which is probably due to recrystallization proceeding at an equal pace with the metamorphism and shrinkage. Among the meager evidences which may be due to this cause, but may also be explained in other ways, are the following:

First. In diopside-calcite strata it was noted that in those beds which held the most calcite and therefore had shrunk the least, the calcite was largely segregated in lenses not parallel to the bedding planes. These lenses were ascribed primarily to the segregative tendency of the diopside. They were probably formed in planes of tension at right angles to the line or lines of least pressure and are crumpled in a manner which suggests shortening of their surfaces after their formation. The direction of shortening would agree with the supposition of their formation as planes of tension.

Second. In the diopside strata surfaces of coarse and freer crystallization are apt to occur at angles to the bedding, suggesting the filling of crevices, and in hornstones of all varieties evidences are sometimes found of a brecciation which may be revealed only by bead-like strings of some other mineral, recrystallization having otherwise obscured it. This of course in itself is no evidence of shrinkage.

Third. In a few places puckered and shortened strata of limestone were observed between others of diopside or tremolite hornstone, but such relations are sometimes observed in limestone formations which have been neither crushed nor metamorphosed and are therefore inconclusive.

In conclusion it must be said that the evidence of shrinkage in the metamorphic zone is entirely indirect, but is considered by the writer to be none the less conclusive.

ZONE OF PNEUMATOLITIC INFILTRATION.

In the inner portion of the metamorphic zone but few marbles are found and these not in immediate contact with the granite. With this exception the hornstones appear to be largely of the same types in both the inner and outer portions. The change of greatest magnitude, therefore, and one which has been studied in the detailed examples, is the replacement of carbon dioxide by infiltrated silica and the resulting transformation of dolomite into diopside. Under the extreme case of a pure dolomite suffering no loss save the carbon dioxide there would result an expansion of 2 per cent on its transformation to diopside. As these conditions are, however, never realized, the process of diopsidization would also result in some shrinkage, which, however, may be prevented or even overbalanced by the infiltration of additional substances. In the studies of infiltration it was noted that quartz is a common accessory with diopside in what were originally the carbonate lenses, and it is suggested that its infiltration may have been due to a porosity accompanying the metasomatic alteration of the carbonate.

The most conspicuous metasomatic action, therefore, does not appear to have resulted in any noticeable change of volume.

The minor changes which were noted, such as the replacement of biotite by diopside, or either of these by green hornblende, and the impregnation of the immediate contacts by green hornblende and quartz, have not taken place on a scale sufficiently large to produce notable results. They do not, however, appear to have resulted in any dimunition of volume, but on the contrary, have probably produced some expansion through the addition of more material than has been carried away.

The pyritic and garnetiferous impregnations appear to have produced not much change in volume, at least no shrinkage, the pyrite either having idiomorphic boundaries and growing through other minerals without apparently disturbing them, or filling crevices and cavities.

To sum up these statements, it appears that within the inner or metasomatic zone simple metamorphism has resulted in the same shrinkages as farther from the magma, but that the following pneumatolitic or semipneumatolitic impregnations have not produced marked changes of volume, the tendency being for infiltration to compensate fully for any losses which would otherwise take place. On the whole, slight expansions may result.

CHAPTER V.

METHODS OF IGNEOUS INTRUSION IN THE MARYSVILLE REGION.

INTRODUCTION.

METHODS OF BATHOLITHIC INVASION.

In the preceding pages the facts relating to the geology of the Marysville district have been presented with only such inferences as seem not to be open to serious question, even those which were given having been made distinct from the facts on which they are based by being placed under separate headings. However, not only is there a variety of causes and methods of igneous invasion undoubtedly occurring in nature, but the geologic relations of a single igneous body have been frequently interpreted in two or more ways opposed to each other. This diversity of view among geologists renders it desirable to describe accurately and in great detail the characteristics of typical intrusions in various localities and after the description is completed to append such interpretations as seem warranted.

A century ago this diversity of geologic opinion centered chiefly on the aqueous or igneous origin of basalts, but since these belong to the volcanic series a part of the process by which they finally come to place can be actually observed, and but a small amount of geologic observation was needed to explain their origin through igneous activity at the surface of the earth. Again, a generation ago, when Gilbert and Holmes brought the nature of laccoliths before the scientific world, there were not wanting well-known European geologists who, governed by preconceived opinions and ignoring certain facts, gave other interpretations to the phenomena. Thus the history of the development of knowledge concerning igneous geology points to the necessity of, first, accurate and complete observation; second, presentation and classification of the facts; and third, a separate statement of the conclusions indicated by the facts.

In the case of intrusive bodies the possible methods of making room for the magma may be classified under a few heads. In the simplest forms the intrusive may wedge apart more or less vertical walls, as in dikes, or lift the superior formations, giving rise to sills and laccoliths. In regard to these there is a general agreement of opinion, but there is no common belief as to the mode of origin of the large, and in many cases irregular, igneous bodies, commonly described as stocks, plugs, bysmaliths, bosses, and batholiths. Yet in even the most complex cases the displaced material must either have made room for the magma by being forced upward, sidewise, or downward, or have been absorbed into the magma, each of these fundamentally different views having been proposed by various geologists to explain especially the origin of batholiths. Where such opposite theories are so confidently advanced, it is to be anticipated that more than one and possibly all may contain elements of truth, one process having possibly been dominant in one locality, another process elsewhere, and in many places two or more methods concurring.

The question of the origin of invasive granitic masses is one of fundamental importance in igneous geology for several reasons. Their surface area is most extensive, including in the United States alone great portions of the Sierra, northern Cascade, and Rocky Mountain regions, the Black Hills, the Lake Superior region, the New England province, and the metamorphic districts of the southern Appalachians, and representing intrusions at various periods from the pre-Cambrian into the Tertiary.

Their volume is enormous, since they originate only as plutonic rocks, bared by long ages of erosion, and it is to be concluded that many occurrences are not yet exposed to observation, and others which have been formerly exposed have become again concealed beneath sedimentary deposits. When this conception of their horizontal extent is combined with the fact that they are of great but unknown thickness, no bottoms to the larger areas being anywhere revealed by erosion, it is seen that the volume of the batholithic masses is far greater than that of all the extrusive materials, even though the latter in the western part of the United States must be measured by hundreds of thousands of cubic miles.

The correct understanding of the nature of batholithic intrusion is important also since it leads one step downward into the internal regions of the earth—regions which must be forever concealed from observation, and which exist under chemical and physical conditions so different from those familiar at the surface of the earth that even deductions from known chemical and physical principles can be made only with reservation and with hesitancy. With this introduction, the discussion may pass to a consideration of the various hypotheses which have been proposed, a few of which are largely wrong, but many of which may be largely true.

HYPOTHESES AS TO MODE OF INVASION.

MAGMATIC FILLING OF VACANT CHAMBERS.

The term batholith was first proposed by Suess, who supposed great empty chambers to be prepared for the magma by the bodily subsidence of lower portions of the crust, the magma later welling into the cavity.[a] From what is known of the strength of rocks and the size of the batholithic masses it is clearly impossible that any vacant cavities a fraction of the size of the batholiths could have sustained themselves, but provided that the magma welled in as the bottom sank the roof would be continuously sustained, and the hypothesis is not impossible. In a highly modified form, where the rock which is displaced is supposed to sink not as a unit but in fragments, this becomes the "stoping" hypothesis suggested first by Brögger and Lawson as applicable in a small way and later developed by Daly.[b]

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[a] Suess, E., Das Antlitz der Erde, vol. 1 (English translation), p. 168.

[b] Daly, R. A., The mechanics of igneous intrusions: Am. Jour. Sci., 4th ser., vol. 15, 1903, pp. 269-298; vol. 16, 1903, pp. 107-126.

METAMORPHISM OF SEDIMENTS IN SITU.

Although Hutton recognized the intrusive nature of Scottish granites, granitic rocks in general came to be customarily looked on by a later generation as merely the last term in the metamorphism of sediments, the transformation from rock to magma thus taking place in situ and the eruptive contacts being explained on the supposition that slight eruptive movements on the margins of the fused mass might lead to dike and sheet intrusions.[a] A more accurate knowledge of the petrography and form of batholithic masses showed the untenableness of this view, which in the last twenty years has become generally abandoned by those geologists most familiar with the facts of the field.

MARGINAL ASSIMILATION

The preceding discussion leaves several hypotheses in the field, of which the first to be noted is that of marginal assimilation, held especially in France, where Michel Lévy, Lacroix, and others consider that a large body of magma lying below the zone of fracture and of sedimentary formations may melt its way upward and incorporate these overlying rocks, the form of the intrusion thus being pyramidal and broadening downward to unknown limits. This implies some amount of diffusion or current action, but it has been maintained by the advocates of the hypothesis that this has not been so complete that the marginal portions of the igneous rock may not still show in places a chemical modification toward the composition of the invaded formation. In America this view has been maintained by Lawson and Emerson, but by the majority of American geologists it is considered as still open to doubt as a competent explanation of such invasions. It would seem, however, that such a process might vary within wide limits, becoming important in the case of superheated magmas coming from deeper regions of the crust and confined for long periods of time at considerable depths, where the excess heat slowly passing into the wall rocks might raise them to the point of fusion. On the other hand, it is doubtful if marginal assimilation ever plays a noteworthy part in the more superficial intrusions into the zone of fracture, even where the magma may be of great volume.[b]

LACCOLITHIC NATURE OF BATHOLITHS.

The first of the two preceding hypotheses involves merely a physical change of metamorphism with softening and slight mixing to attain homogeneity; the second involves a chemical change necessitating the addition of foreign material and a greater mixing to maintain the heat supply and the approximate homogeneity of the resulting magma. In contrast to these may be described the theories as to the mechanical methods of possible invasion. Under these theories the magma is a distinct and foreign body, invading the outer crust from below either actively or

[a] Dana, J. D., Manual of Geology, 1895, pp. 810-811.

[b] Some references on this hypothesis of invasion are the following:

Lévy, A. Michel, Contributions à l'étude du granite de Flamanville et des granites français en général: Bull. Services carte géol. France No. 36, vol. 5, 1893.

Lacroix, A., Granite des Pyrénées et ses phénomènes de contact: Bull. Services carte géol. France No. 64, 1898.

Duparc, Louis, Recherches géologiques et pétrographiques sur le massif du Mont-Blanc: Mém. Soc. phys. et d'hist. nat. Genève, vol. 33, No. 1, 1894.

Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 728-736.

Daly, R. A., Secondary origin of certain granites: Am. Jour. Sci., 4th ser., vol. 20, 1905, pp. 185-216.

passively. The first of these hypotheses to be noted is that of Brögger,[a] who argues strongly for the laccolithic nature of batholithic granites, stating that, since the occurrences of laccoliths have been made known, the granite bosses are to be conceived of as laccoliths laid bare by erosion. Although the granites and other abyssal rocks are observed to be of not exactly analogous form, yet they have so many features in common that according to Brögger it hardly appears hazardous to regard them as of an essentially related origin. The chief difference he believes to be in the depth at which the intrusion solidified. The form of the intrusive mass, whether as a typical laccolith or as more irregular masses, Brögger regards as relatively unessential.[b] Thus he conceives the form to be essentially laccolithic, the cause a purely mechanical pressing out or injection of the granite; tho in the case of the Drammenfjord batholith of the Christiania region he explains the irregular nature of the upper contact surface by the breaking away and subsidence of numerous fragments.[c] While Brögger[d] maintains the high liquidity of granitic and other deep-seated magmas, Becker, on the other hand, believes that it is highly probable that the magmas of the granular rocks are not liquids but stiff emulsions, comparable with modeling clay.[e] The physical condition of the magma, whether fluid or pasty, would of course have a vital bearing on the mechanics of intrusion. That even the larger magmatic bodies have come to place, at least partly by intrusive processes, seems to be usually true, but the physical nature of the magma and the depth and nature of the surrounding rocks must govern so thoroughly the resulting form, that it is doubtful if in any case batholiths should be confused with laccoliths. They are certainly normally much more irregular.

ROCK FLOWAGE AND CRYSTALLIZATION OF WALLS.

The second hypothesis of mechanical invasion to be considered is that proposed by Van Hise[f] to explain especially the relations of the granitic core of the Black Hills to its walls and extended by him to apply in general to igneous intrusion in the zone of anamorphism, combined to a certain extent with other processes of invasion. He conceives that the magmas are sufficiently fluid to transmit thrusts according to the laws of hydrostatics, and that they make their way by raising up and pushing aside the material previously occupying the space without necessarily breaking through it on a large scale. Thus the space is made by pushing the invaded rock to one side as well as by lifting it upward, and the work is accomplished largely through recrystallization of the wall rocks, with a resultant schistosity parallel to the igneous contact.

In this respect the theory differs essentially from that of Brögger, but the difference is such as one would expect to find between theories based on movement in the zone of flowage and in the zone of fracture, respectively, and therefore the two are not necessarily antagonistic. While Van Hise's theory would seem to apply very

[a] Brögger, W. C., Der Mechanismus der Eruption der Tiefengesteine: Die Eruptivgesteine des Kristianiagebietes, vol. 2. 1895.
[b] Op. cit., pp. 118, 119.
[c] Op. cit., pp. 133, 134.
[d] Brögger, W. C., Die Eruptivgesteine des Kristianiagebietes, vol. 3, 1898, p. 336.
[e] Becker, G. F., Present problems of geophysics: Science, vol. 20, 1904, p. 550.
[f] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 708-710.

well to certain batholiths which were presumably intruded in the zone of flowage, it can hardly be applicable in any measure to batholiths covering thousands of square miles which break across the surrounding rocks with highly irregular contacts, developing no schistosity in them—batholiths which have apparently come to rest in the zone of fracture and which can be demonstrated in some cases to have approached within a mile of the surface at the time of intrusion. For these cases Van Hise would himself doubtless consider such a method of invasion as inapplicable.

BYSMALITHIC INTRUSION BY MARGINAL FAULTING.

A third hypothesis of mechanical invasion differing somewhat from those already given is that proposed by Iddings to explain the intrusion of the Mount Holmes igneous body of the Yellowstone National Park. Since this more or less circular stock is bounded by walls approximately vertical, and has apparently not pushed aside the surrounding rocks, Iddings considers that the intrusion lifted its cover by marginal faulting, acting as a punch to drive the material upward by shearing it around the margin. The bottom of the magmatic body is supposed to rest upon the Archean basement.[a] But as the cover, if once present, has been completely removed, and as the bottom is not exposed, this explanation is seen to cover only one of several possibilities.

SUBSIDENCE OF ROOF BLOCKS.

The mechanical methods of invasion thus far discussed, as well as various minor modifications of them, all postulate an active intrusion, the internal pressure of the magma being greater than the external resistance of the walls, and the walls yielding by one method or another. Another theory of mechanical invasion yet to be considered is essentially different from any of these. This is the hypothesis of batholithic invasion by the breaking free and sinking of fragments from the roof, thus allowing the magma to passively rise and fill the place as the blocks sink away. By a continuation of this process it is conceived that a great body of magma may rise comparatively near the surface. In fact, the difficulty of the hypothesis is found in limiting the process in order that the surface shall be preserved, since there is no geologic evidence that great bodies of magma have ever broken upward completely to the surface by the foundering of the crust.

This theory of invasion has been ably presented by Daly, but was first proposed by Kjerulf a quarter of a century ago as an accessory process accompanying assimilation. From the review which Brögger gives of Kjerulf's work,[b] the latter conceived the Drammenfjord batholith to broaden downward into a magmatic reservoir and to be, in fact, a foundation granite whose method of advance had been by "a tearing to pieces and swallowing up," this being characterized in many other places as a "melting in or assimilation." Details of the method do not appear to have been given, but it is spoken of by Brögger as essentially the same as the marginal assimilation theory of Michel Lévy, so that it may be considered that Kjerulf held that melting in place rather than subsidence was the fate of any loosened

[a] Iddings, J. P., Mon. U. S. Geol. Survey, vol. 32, pt. 2, 1899, p. 16 et seq.
[b] Brögger, W. C., Die Eruptivgesteine des Kristianiagebietes, vol. 2, 1895, pp. 119, 120.

crust blocks. In 1882 Brögger disproved for this batholith the presence of marginal assimilation, and Kjerulf himself never sought later to maintain this view.

Brögger, on the other hand, presents a strong argument in favor of the laccolithic nature of the occurrence. Recognizing, as Kjerulf has done, the irregular nature of the contact of the Drammenfjord batholith, the granite breaking across the strata, he explains the fact that portions are missing by supposing them to have sunken to a floor and believes them to be still existent in the depths beneath the granite. To the extent that these blocks have sunken the magma has been pressed out, the whole mechanism of eruption being, according to him, an extremely simple equation of hydrostatic equilibrium.[a]

This is the first clear presentation of the process of subcrustal stoping, but the idea appears to have lain dormant until Daly, in 1903, showed by a discussion of the relative specific gravities of magmas and rocks that with all except the more basic magmas subsidence of roof blocks was possible and used this theory to explain the coming to place of the Mount Ascutney stocks and later extended it to apply to batholiths in general.

THE PRESENCE OF STOPING IN MONTANA.

The writer was first brought into touch with these questions in 1899, when, as a field assistant of the United States Geological Survey, he spent four months in geologic study under the direction of Mr. W. H. Weed in the region between Helena, Elkhorn, and Butte, Mont., all lying within or at the contacts of the Boulder batholith.

The observations of that summer showed the inadequacy of marginal assimilation as the method of coming to place for this batholith and suggested that the method of invasion had been chiefly by the subsidence of crust blocks and the passive rise of the magma. The writer's views on this subject were put in form in April, 1900, but as they were in many respects novel and it was desirable to test them with more conclusive evidence he was advised to withhold them from publication until more complete studies could be made. This opportunity arrived in 1901, when a detailed study of the small outlying batholith which forms the center of the Marysville mining district showed that the nature of the contacts were well adapted to test this hypothesis of invasion.

It is believed that the contact relations at Marysville indicate with reasonable certainty that stoping or subsidence of roof blocks has been a dominant process at this locality and presumably over the region of the Boulder batholith also, but it does not by any means follow that the same holds true of other regions. In fact, as previously noted, a variety of processes should be expected, depending on the conditions of temperature and pressure existing in the magma and its walls, as well as the fluidity of the one and the rigidity of the other.

The adjustment between methods may be somewhat as follows: In general, superheated magmas confined at great depths should show a maximum of marginal assimilation. Magmas in the zone of flowage may be able to crowd their walls aside with the development of a peripheral schistosity, while those breaking up into the

[a] Op. cit., pp. 133, 134.

zone of fracture may make their way by forcing the strata apart, producing dikes, sheets, and laccoliths; or by rupture and subsidence of roof blocks they may work upward by stoping; or if confined within narrow limits and possessing great expansive force they may break their way to the surface, giving rise to the phenomena of volcanism. In any case the action must follow the paths of least resistance and be subject throughout to determinable, if not determined, chemical and physical laws. The diversity of views in regard to the method of massive igneous intrusions is doubtless founded on a diversity in nature and requires that many localities shall be studied with an open mind and that the contact phenomena shall be described with reference to the zone of intrusion, the character of the magma, and other similar factors.

METHODS OF IGNEOUS INTRUSION AT MARYSVILLE.

INTERMITTENT AND SUDDEN NATURE OF DIKE INTRUSIONS.

At Marysville there is one set of dikes and sheets, the microdiorite of Bald Butte, preceding the invasion of the batholith and the formation of the zone of contact metamorphism. Another set, the Belmont diorite porphyry dikes, is closely connected with the batholithic invasion in point of time, but whether immediately before or after it is not settled. The batholith itself has granitic dikes and sheets as outliers, mostly of more acidic composition. Later than the batholith are those pegmatites cutting the granite, the Drumlummon porphyry, and the rare basic dikes. For all except the pegmatites the evidence of the sudden and intermittent character of their intrusion is summed up in the following paragraphs.

EVIDENCE FROM COMPOSITION.

Each of the above-mentioned series of dikes is distinct from the others, no transition stages difficult to classify being found, indicating either that distinct magmas had been tapped by the fissures and their contents injected into the same locality and series of strata or (the much more probable explanation according to present views) that owing to slow variations in the character of that part of the supplying magma, intrusions widely separated in time showed a dissimilarity of composition.

EVIDENCE FROM AGE.

Giving force to the preceding statement is the fact that the age relations are well defined, all the microdiorite dikes of Bald Butte belonging to an earlier stage, all those of the Belmont diorite porphyry to a later stage. In no place where they cut each other are their relations reversed.

To follow the same argument, the dikes later than the batholith, and cutting it, show that when they were intruded consolidation had proceeded to a considerable depth during a length of time sufficient to supply highly differentiated products from the fluid remnants of the original magma, if such was the cause of the variation in the magma.

EVIDENCE FROM HEAT RELATIONS.

The previous arguments have pointed to the intermittent character of the intrusions. The argument from the heat relations, on the other hand, bears on the suddenness of the separate intrusions and requires also more detailed analysis.

Doelter[a] has shown that the common magmas in passing from solidity to fusion undergo a state of viscidity which lasts while the heat is raised from 30° to 90° C., the temperature of fluidity with various magmas varying from 1,010° to over 1,290° C. It is generally accepted that at times of intrusion the magmas are reasonably fluid, this being especially true of dike intrusions, since a state of viscidity would destroy the ability of the fluid sheet to transmit pressures, and consequently the power of penetration to distant points would be lost.

It will be well to begin the argument by supposing a case most favorable for slow dike intrusion, since if slow intrusion is found impossible for this case it may be dismissed for those less favorable.

Suppose that a fluid and not viscous magma lay quiescent at a certain level until an even temperature gradient had become established from its limits to the surface of the earth; dikes penetrating for a certain distance would be maintained viscously fluid indefinitely, the limit being where the temperature in the wall due to the presence of the near-by fluid magma was that which would hold the same magma in a viscid state. Beyond this limit intrusions, especially if of small volume, would congeal with a rapidity dependent on the coolness in the walls. To illustrate, assume that a magmatic body at the rather high temperature of 1,500° C. lies at a distance of 10 miles from the surface, the mean surface temperature being zero, and that the upper limit of viscosity for this magma is at a temperature of 1,200° C. Thin dikes in advance of the main body would then be maintained fluid indefinitely for a distance of about 2 miles. At a distance of 5 miles below the surface the normal temperature in the wall rocks would be 750° C., and a sudden thin injection at this level would find itself in the presence of rock 750° colder than itself; the drop through 300°, producing viscosity, would then be made rapidly. It is seen, therefore, that dikes would be able to penetrate much farther in a fluid condition if the work were done quickly, giving less time for the loss of heat. That the limits of dike injection in other regions have not been in general confined to any zone of indefinitely long fluidity is evidenced by the contact phenomena, the local metamorphism of the walls, and the absence of metamorphism at a distance from the walls, as in the Newark rocks of the eastern United States, indicating that the country rock was comparatively cool at the time of injection and was locally heated by the intruded magma.

These considerations show that the extended dike intrusions resemble volcanic eruptions in that both take place in an intermittent and paroxysmal manner. On the other hand, it is readily seen that a zone of indefinite fluidity of a dike would vary directly with the superheating of the magma and the depth from the surface and may be a very important factor in the methods of invasion of batholithic bodies. With the passage of time, allowing a general cooling of the batholithic reservoir, and the possible encroachment of the magma toward the surface, giving a sharper tempera-

[a] Doelter, C., Tschermak's Min. u. petrogr. Mitth., vol. 20, 1901, p. 232.

ture gradient in the walls and cover, this zone of indefinite fluidity would decrease in width and finally disappear when the margin of the batholith itself became viscid. Whether or not such a zone occurs remains, however, to be proved.

RELATION OF DIKES TO THE BATHOLITH.

The poverty of the intrusive phenomena preceding the batholithic invasion is in contrast to the conditions in the near-by Elkhorn district, only one series of dikes and sheets distinctly older than the batholith being found at Marysville, indicating that at least a small outlying batholith may reach its final limits with very little or no antecedent eruptive phenomena.

Those dikes which are closely related to the batholith in chemical composition are also close to it in point of distance. For example, the Belmont porphyry is confined to the zone of contact metamorphism and the Drumlummon porphyry to one portion of the batholithic contact. Further, the quartz-diorite and granite offshoots from the batholith do not penetrate very far from the magma body into the country rock. Where occurrences at a distance are found, as in Eldorado Gulch and at the Big Ox mine, the amount of surrounding metamorphism is so great as to lead to the conclusion, previously pointed out, that larger bodies of the magma lie at no great depth.

METHODS OF BATHOLITHIC INVASION AT MARYSVILLE.

LACK OF MARGINAL ASSIMILATION.

GENERAL STATEMENT.

As previously noted, marginal assimilation, by which a magma is supposed to dissolve or melt up large quantities of the wall rocks, has been urged by a number of observers as a dominant method of batholithic invasion. The process should depend for its efficiency on the volume and temperature of the magma, its depth from the surface, and the composition both of the magma and its walls. As the Marysville batholith is closely associated with the large Boulder batholith, exposed over about 2,000 square miles, it is to be presumed primarily that the conditions for marginal assimilation were not unfavorable and the problem of invasion must first be examined from that side.

This subject was studied in detail for the Boulder batholith, but as the paper on that region is still uncompleted certain statements will be abstracted and condensed from it.

CRITERIA FOR DISTINGUISHING MARGINAL ASSIMILATION.

The difference of the marginal portions of a magmatic body from the main mass may be due to three possible causes.

First. There may be a differentiation of the magma by which the marginal portions may become either more acidic or more basic than the main mass. Although there are many theoretical difficulties in the way of differentiation, as Becker has shown,[a] yet the field evidence of such a process is considered so strong by the majority of petrographers that it is generally believed to have taken place.

[a] Becker, G. F., Some queries on rock differentiation: Am. Jour. Sci., 4th ser., vol. 3, 1897, pp. 21-40.

Second. The magma before intrusion may have been unhomogeneous, giving rise to variations of composition simulating differentiation after intrusion. While this might explain the phenomena exhibited in many cases, it is extremely difficult to account in this manner for many others, including such as those which Pirsson has described as occurring in the laccoliths of the Highwood Mountains, Montana.[a]

Third. Marginal assimilation may be a possible cause of marginal variations in the magma, this being distinguished from assimilation of inclusions after they have sunk to a great depth in the magma, as urged by Daly.[b]

The present discussion deals only with the possibility of marginal assimilation. The criteria may be summed up as follows:

First. In magmatic differentiation there is a considerable body of each product. Each is fairly homogeneous within itself, and the transition from the one to the other is in no case at the immediate contact of the walls. In a reaction zone between the magma and the invaded formation, on the contrary, the transition is sharpest at the immediate contact and fades out on each side. The study of the inclosing rocks will ordinarily show that, even if they exist as inclusions, they are distinct from the magma, and therefore, if they are surrounded by a narrow zone, which exhibits its greatest transition at the contact, this is concluded to be a reaction zone between the magma and its walls, with consequent assimilation.

Second. The above discrimination has been based on the assumption that the changes both of differentiation and assimilation had taken place after the magma had come to rest. It is, however, quite probable that slow motions in the magma would accompany either process. In the case of differentiated material the two complementary products might become mixed into a ropy fluid of uneven composition, such as is occasionally seen in dikes. If magmatic currents in larger reservoirs exist, on the other hand, in moving past the inclosing walls they would remove any dissolved material and tend to break loose small fragments, which, floating free in the magma, would be further acted on and would reproduce in miniature the effects previously described as shown on the walls. If the current were fast, compared to the speed of solution, the assimilated material would make but little showing, becoming more thoroughly mixed through the general mass; but in proportion as the speed of the current increased the manner of eruption would be rather by intrusion than by absorption, and the quantitative effects of the mixing would be small.

Third. The surest criterion for separating the two processes lies, however, in a study of the chemical compositions. Parts of a magma modified by contact will show an enrichment in those elements and those only which constitute a higher percentage of the rock walls than of the magma. These changes will ordinarily not be the same as those resulting from differentiation, since in the modified zone the added elements will not be grouped together in those relations characteristic of the differentiation process. Thus the internal evidence of the magma and the external evidence of the walls will mutually assist the investigator in arriving at a conclusion in any specific instance as to which process has been in operation.

[a] Pirsson, L. V., Petrography and geology of the igneous rocks of the Highwood Mountains, Montana: Bull. U. S. Geol. Survey No. 237, 1905.

[b] Daly, R. A., The mechanics of igneous intrusion: Am. Jour. Sci., 4th ser., vol. 15, 1903, pp. 269-298; Secondary origin of certain granites: Idem, vol. 20, 1905, pp. 185-216.

Fourth. Marginal assimilation, if a method of invasion, should show certain relations between the form of the intrusion and the chemical nature of the walls, since sandstones, shales, and limestones are neither equally soluble nor fusible.

APPLICATIONS TO THE MARYSVILLE DISTRICT.

As previously stated, this subject of the possibility of marginal assimilation was examined in considerable detail for the near-by Boulder batholith, and it was found not only that there was no evidence of such assimilation as a method of invasion at the present limits of the batholith, but that it could hardly have acted appreciably even during the encroachment of the magma through the last 3 or 4 miles below its present level. It will only be necessary, therefore, to summarize the evidence briefly so far as it relates to the Marysville district.

Detailed chemical relations of granite and walls.—The Marysville batholith shows two types of rocks, but the difference is largely a question of texture, a finer grained, less hornblendic, and possibly slightly more acidic type being found at some places but not associated with the margin. On the other hand, some of the marginal intrusions from the batholith are more acidic and others more basic, but the basic are richer in iron than the mass of the batholith, while the wall rocks are, as a rule, richer in lime. There is unusually little variation throughout the batholith and its apophyses compared to that shown in many other intrusions of the kind, and such variations as are found have no relation to the composition of the wall rocks.

General chemical relations of earlier and later intrusions.—The microdiorites represent an earlier and more basic series of dike and sheet intrusions, before the batholith and its contact zone were present. The batholith in its invasion has therefore displaced a large amount of siliceous, aluminous, and calcareous sediments, after the intrusion of the microdiorites. If the microdiorites are taken as giving some indication of that earlier magma, then the modification in composition which has taken place between the time of the earlier intrusions and that of the batholith is not due to any notable assimilation either at the present limits or at a greater depth, since the variation in composition has not been a raising in the percentage of silica, alumina, and lime, but rather an increase of silica, alumina, and alkalies, with a decrease of lime, iron, and magnesia. The variation is therefore not in sympathy with the invaded formation, either in detail or in a broad way.

Form of margin.—Around both the Boulder and Marysville batholiths the contacts are in all cases sharp and distinct. They cut at all angles across both sedimentary and igneous formations, now horizontal and again vertical. Here and there large V-shaped bays from the batholiths enter into the walls for a few hundred feet or for a mile or more, without disturbance of the strata or indications that the contacts are later fault planes. In many places the contact shows a blocky character and the larger outline is in many ways but a greatly magnified form of these details. Locally satellitic chimneys are found adjacent to the main mass, but these have not originated by selective action confined to any one rock; on the contrary, they exhibit the same irregular margins as the parent mass. It is to be concluded, therefore, that marginal assimilation has not played a noticeable part in the intrusion of the Marysville batholith.

INSUFFICIENCY OF HYPOTHESIS OF FAULTING.

As already stated, the structure of the Mount Holmes bysmalith of the Yellowstone National Park has been explained by Iddings[a] as due to an upward lifting of a laccolithic roof to the extent of 2,000 to 4,000 feet, with encircling faults which account for the nearly vertical contacts. Brögger,[b] on the other hand, speaks of the Krogskoven crust block sinking 400 meters, tilting the neighboring crust block to the west and acting as a cause for the pressing out of the adjacent Drammenfjord batholith. In the one case faulting has been produced by the direct upward thrust of the magma; in the other by the down sinking of a neighboring crust block. The possibility of such actions must therefore be considered in the present instance.

In the details which have been given of the batholithic contact at Marysville it has been shown that at numerous places the surface passes under the sedimentary cover at a flat angle and with a character proving that the cover has not been shoved over the granite by thrust faulting. There remains to be discussed, however, the possibility that the general outline has been produced by an irregular laccolithic intrusion, subjected later to cross faults which could account for the high, steep walls exposed by the workings of the Drumlummon mine. It has also been shown that such steep walls probably exist to a limited depth in the contact crossing Edwards Mountain and running along Drinkwater Gulch. The possibility that these steep contacts have been produced by faulting is negatived by the fact that the actual contact at a steep angle with granite and hornstone interlocked can be observed in the western part of the Belmont mine and at places in the Drumlummon mine. (See Pls. IX and X.) Furthermore, in the Drumlummon a flat cover of sediments which overlies the granite exposed in the main tunnel appears to be a horizontal projection from the steep wall and not to be cut off from the wall by a fault plane.

It is to be concluded, therefore, that while small faults may in a few places form the contact surface, they do not in any measure account for the general form of the intrusion.

INSUFFICIENCY OF LATERAL THRUST.

Batholithic intrusions in regions of foliated and metamorphic rocks have commonly penetrated along the planes of foliation and have made room for themselves by a separation and a thrusting aside of the walls, even if the intrusion is complicated by other methods of action. That such a method of invasion by lateral thrust has not acted here is readily seen on stating the evidence.

First. No schistosity is developed in the surrounding rocks parallel to the walls and therefore there is no evidence of rock flowage caused by lateral thrust from the magma, as noted by Van Hise in the Black Hills.

Second. The flatness and irregularity of much of the contact surface if made by lateral thrust of the magma would involve continuation of these flat surfaces as thrust planes in the walls. On the contrary, as may be observed in the sections of the Drumlummon mine, such thrust planes are not observed and as mentioned in a pre-

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[a] Iddings, J. P., Mon. U. S. Geol. Survey, vol. 32, pt. 2, 1899, pp. 16 et seq.

[b] Brögger, W. C., Die Eruptionsfolge der Triadischen Eruptivgesteine bei Predazzo in Südtyrol: Die Eruptivgesteine des Kristianiagebietes, vol. 2, 1895, pp. 146, 147.

vious paragraph the horizontal projection of hornstone over the main tunnel appears to be in stratigraphic continuity with the steep portion of the walls at a lower level.

Third. In the larger batholiths which have approached near the surface, as the Boulder batholith, lateral thrust would involve an enormous horizontal movement from 50 to 100 miles in some cases. In such an event a cover from half a mile to a mile in thickness or even thicker could not retain its continuity, but would be stretched and broken. A thin cover over a batholith would be an impossibility under such conditions, and yet portions of such a cover still remain bordering the Marysville and Boulder batholiths and probably exist as remnants at some places over the interior of the Boulder batholith.

Thus the evidence contravenes such an idea of intrusion in the localities under discussion, and there are the strongest of reasons for holding that such a method has not been operative. The evidence is drawn partly from the Marysville and partly from the Boulder batholith, but on account of their close relationship what is true regarding the intrusion of the one applies with considerable force to the other.

INSUFFICIENCY OF HYPOTHESIS OF LACCOLITHIC ORIGIN.

THE LACCOLITHIC PROCESS.

The typical laccolith splits the sediments along their bedding planes, a thick series of shaly strata being the most favorable for its formation. The roof in all cases is domed, having been lifted by the hydraulic power of the penetrating magma. In the case of the Marysville batholith, however, only in a few places does the contact surface conform to the bedding planes, normally cutting across them at an angle, indicating that the simple form of laccolithic intrusion certainly does not apply here. Yet from the form of the simple ideal laccolith many departures are observed, giving rise to such terms as asymmetric laccoliths and compound laccoliths. As previously noted, Brögger ascribes a laccolithic nature to the Drammenfjord batholith, meaning that an invading magma has lifted bodily a cover from a floor and that the depth of the batholith is presumably small in comparison with its horizontal extension. The form of the intrusive mass, whether that of a typical laccolith, or of a more irregular body, Brögger regards as relatively unessential.[a]

Although there is a proper tendency to limit the term laccolith to the more typical form and to group these larger and more irregular bodies under a separate division as batholiths, yet the present discussion turns on whether the Marysville batholith can or can not be accounted for by a mere lifting of a roof from a bottom, complicated, it is true, by an irregular parting of the roof with the injection into it of dikes and sheets. The process may be essentially of a laccolithic nature, according to Brögger, even if the form of the roof is further modified by the breaking free and sinking of roof blocks, as he believes to have occurred in the case of the Drammenfjord batholith. Such a conclusion may at first sight be entertained when it is noted that a considerable degree of doming has occurred, as indicated on the structural plate (Pl. XI) and cross sections (Pl. II) and as discussed on page 87.

Doming is indicative of an internal pressure within the magma by virtue of which it may be able to penetrate the wall rocks in dikes and sheets or lift its cover,

[a] Brögger, W. C., Der Mechanismus der Eruption der Tiefengesteine: Die Eruptivgesteine des Kristianiagebietes, vol. 2. 1895 pp. 118, 119.

or break out to the surface as a volcanic effusion. In the case of a simple laccolith the doming of the cover is sufficient to account for the entire intrusion, but a detailed consideration of the present instance will show that it can not account for the character of the walls nor in any great measure for the volume and nature of the intrusion.

FORM OF ROOF AND WALLS.

Along Drumlummon Hill the contact on the whole is steep, as shown by the workings of the Drumlummon mine and as inferred by the narrow zone of contact metamorphism along the southern part of the hill. In the Drumlummon mine this approximately vertical wall goes down for over a thousand feet, and the physiographic indications, as discussed on page 86, indicate that it was steep for upward of another thousand feet above the present limits of the outcrops along this hill. Yet over the main tunnel of the mine and at another point three-fourths of a mile to the south flat projections extend over the granite from the steep wall. These show that there are reentrant angles in the contact, so that the contact surface steps downward like the side of an irregular pyramid in a rude giant stair. Here the vertical wall of the step far exceeds the horizontal.

Indications of a similar nature are found elsewhere. At the Belmont mine the tunnel which passes under the arm of hornstone projecting into the granite encounters a vertical wall of hornstone at its end. Again, in the Cruse mine, while the granite appears to underlie the entire workings, yet some vertical contacts are found, showing an irregular steplike margin. The end of the flat hornstone peninsula is also cut off vertically, as may be seen at an exposed contact immediately south of the Cruse mine. At most places around the batholith, mine workings do not expose the underground extensions of the contact, and an understanding of their nature depends on various lines of reasoning which have been developed earlier in the paper (pp. 79–81) under the heading "Underground extensions of the batholith." It was shown that while the well-exposed contact immediately north of Silver Creek is steep and blocky, the contact metamorphism and intrusions indicate an eastward extension of the magma at no great depth. Thus the indications everywhere point to a pyramidal and stairlike contact, though the "treads" or flat surfaces as a rule exceed the "rises" or vertical portions, from which it is concluded that the general slope of the batholithic surface is presumably flatter than 45°.

OUTLYING INTRUSIONS FROM THE BATHOLITH.

It has been shown that at various places, as in the Drumlummon mine on Silver Creek, and north of Drinkwater Gulch, there are intrusions of the same magma which are forced into the strata as dikes and sheets and which dip away from the batholith. On the northern slopes of Mount Belmont, however, is an outlier in close relation to the main body, which is not of this nature. Only a few hundred feet from the main contact, which is here nearly horizontal, the outlier has a rudely circular outline and shows indications of having been once covered by a flat roof. It has not perceptibly disturbed the flat-bedded hornstones either to the south or north of it, and has been interpreted as an upward hollow in a flat and irregular roof.

CONCLUSIONS ON LACK OF LACCOLITHIC NATURE.

For the intrusion to be of a laccolithic nature, even of so irregular a form as Brögger has maintained for the Christiana region, the surface of splitting by which the cover would have been lifted from the bottom must have been rudely that of a flat pyramid. The highest part of this surface should be concealed at no great depth beneath the town of Marysville. Not only must the surface have been in general pyramidal, but it must have borne minor pyramids upon its sides, one of which would account for the small outlier on the northern slopes of Mount Belmont.

When it is considered that a laccolithic intrusion splits the invaded formation along a flat surface of least resistance and differs from a sill only in that the magma is intruded in considerable volume and in lenslike form, it is seen that the contact surface of the Marysville batholith can not be regarded as in any sense due to a mere parting of cover from bottom and a lifting of the cover.

If it is maintained that the nature is essentially laccolithic but that the sinking of crust blocks has also taken place, giving rise to the flatly pyramidal and steplike character of the contact surface, it may be answered that the contacts which are explained in this way would account for the greater part of the invasion of the Marysville batholith. The doming, it is true, simulates a feature of laccolithic intrusion, but it may be shown that any body of magma lighter than the crust which it supports will exert a vertical thrust on it. The doming, therefore, is no proof of laccolithic nature, but a necessary consequence following the intrusion in large volume of any magmas of less specific gravity than the sedimentary rocks. While the doming would allow a greater volume of intrusion and a greater consequent depth, it is here a secondary effect and not sufficient to account for any large part of the intrusion. The insufficiency of the laccolithic hypothesis may, however, be better shown by discussing the larger batholith on the south in connection with the question of the cover, and attention will next be given to that feature of the problem.

RELATION OF THE MARYSVILLE TO THE BOULDER BATHOLITH.

The Marysville batholith, as has been shown, is in reality a small outlier of the far greater Boulder batholith, covering over 2,000 square miles to the south. The arguments which have been used for the Marysville area in regard to the method of intrusion apply throughout to the contacts of the Boulder batholith. The contacts of both are at some places flat, at other places steep, with reentrant angles in the bottom of the cover and in the sides, without evidence of later faulting to account for all of these irregularities.

COVER OF THE BOULDER BATHOLITH.

The additional evidence obtained from the Boulder batholith is, however, derived chiefly from the nature of the cover. In the Elkhorn district and at other places bordering the batholith is found a series of andesite tuffs and extrusive lavas which probably attained a maximum thickness of several thousand feet. These were poured out in latest Cretaceous or early Tertiary time upon a land surface perhaps as irregular as that of the present day, consisting of folded and eroded Paleozoic and Mesozoic strata.

At Elkhorn the granite of the batholith has been intruded at a later date and in places immediately underlies the earlier extrusive andesites. The contact is followed here by a sheet of acidic granite which has penetrated between the quartz monzonite or normal rock of the batholith and the andesites. The age relations are clearly shown, the acidic granite having a close relationship to the normal rock of the batholith, being considered an associated later aplitic product. The intrusive rock sends stringers into the andesite, which, with the associated sedimentary formations, shows a great deal of contact metamorphism. As further evidence pointing to the same conclusion the aplitic granite shows under the microscope a finer grain and a poikilitic texture adjacent to the andesite—indications of a chilling against the extrusive mass.

At other localities also, especially at Whitehall, as noted by Mr. Weed,[a] the andesite shows a great amount of alteration and exists as marginal fragments in the rock of the batholith. It is therefore concluded that the granite, which is younger than the andesites, where it lies immediately under them, as on Elkhorn Mountain, was covered at the time of its intrusion by the andesite formation only.

In the central parts of the batholith there are still large areas of andesite, whose age, whether older or younger than the granite, has not been determined with certainty, but remnants of sediments have nowhere been detected. A consideration of these facts indicates that at Elkhorn, on the margin of the batholith, the granite was covered by not much over 2,000 feet of andesite rocks, or perhaps less, and that elsewhere it is probable that the cover was largely formed of this andesitic series. Erosion has since bitten deeply enough to have removed the greater part, it being presumed that where absent it once existed. On account of this erosion, also, if sediments anywhere formed the cover or if the magma reaching the surface solidified in glassy or porphyritic forms, no evidence of such remains. It is seen that the batholithic invasion reached a point comparatively near the surface of the earth, far within the zone of fracture, and that portions of a superficial covering still remain, disproving the necessity for profound erosion to reveal this widespread granitic body. A very similar instance of a batholith covered at the time of its intrusion by a series of extrusive andesites only has been noted by Smith and Mendenhall in the Cascade Mountains.[b]

Hague also has shown that large stocks in the Absaroka Range, some of them 3 miles or more in diameter, were intruded into the volcanic breccias which, with the lava flows, form the uppermost formations of that rugged region. He states that he is more or less skeptical as to the need of an immense thickness of overlying material to develop the so-called plutonic rocks; and that large intrusive bodies came to a standstill without any surficial manifestations in the Absarokas is, he thinks, fairly well determined.[c] This evidence of the occasionally superficial nature of batholithic intrusions presents a conception quite different from that of the deeply abyssal nature which is usually considered as belonging originally to granitic masses exposed

[a] Oral communication.

[b] Smith, G. O., and Mendenhall, W. C., Tertiary granite in the northern Cascades: Bull. Geol. Soc. America, vol. 11, 1900, pp. 223-230.

[c] Hague. Arnold, Early Tertiary volcanoes of the Absaroka Range: Presidential address, Geol. Soc. Washington, 1899, pp. 23, 24.

only through miles of later denudation. It is a conception which must have an important bearing on hypotheses of invasion and its significance in this respect will next be considered.

RELATION OF COVER TO LACCOLITHIC NATURE.

The only remnants of a cover existing over the Boulder batholith are patches of older extrusive andesites and, as shown at the margin, not more than a few thousand feet of erosion have been necessary at the most to lay bare the granite. If the granite, then, had been intruded in the form of a great laccolith it would be necessary to hold that the parting on the surface of intrusion took place over an area of more than 2,000 square miles, everywhere within a few thousand feet of the surface and largely at least between a superficial blanket of volcanic materials and the erosion surface of sedimentaries upon which this blanket rested. The dissimilarity of such a broad and superficial but very thick intrusion to anything which is known in nature and its general improbability are good reasons for dismissing the laccolithic hypothesis as strained and untenable. There are, then, not only no evidences of a laccolithic nature, but to make it even a probable view some evidences of a bottom would have to be found—one which presumably should match the surface of the original cover. No trace of such a bottom has been uncovered by the deepest erosion.

DEPTH SHOWN BY EROSION AND ITS CONSEQUENCES.

At Elkhorn, on the margin of the batholith, the granite rises to an elevation of nearly 9,000 feet, while in the Boulder Valley only 6 miles away the same granite, of a markedly similar character, and belonging to the same common area, is found at an elevation of 5,000 feet, giving a vertical depth of 4,000 feet exposed by erosion. On the assumption of a laccolithic form, if this thickness of granite existed near the present margin it was doubtless thicker in the center, so that 7,000 feet may be assumed as a minimum. If the bottom does not subside at an equal rate with the intrusion the latter would raise the surface of the batholith from 4,000 to 7,000 feet, as a minimum above the surrounding country. But the cover at Elkhorn was certainly much thinner than this, and there is no reason to regard the thinness there as exceptional. This leads to the idea of a magmatic reservoir whose top would be some thousands of feet above the surrounding country and which would be retained by cracked and broken walls thinner than the thickness of the laccolith. If the magma were fluid this would result in a welling forth of great lava floods pouring over the older andesites, but no remnants of such lavas are found, altho the andesites still exist in great quantity. If, on the contrary, the magma were a soft solid it can nevertheless hardly be conceived to have been of as great a rigidity as ice. Yet an ice cap covering over 2,000 square miles whose center was 7,000 feet above its margin would presumably spread outward by viscous flow even if mantled by a broken rock cover half a mile thick. While the assumption of a highly viscous nature might account for an absence of fluid lava flows, it could hardly account for the formation of so huge a laccolith over so great an area so near the surface of the earth. Therefore, if it be supposed that a laccolithic body could have invaded all of this area at so slight a depth without breaking through and flooding the surface, the only saving clause to the whole hypothesis is that instead of doming up the cover to the entire thickness of the intrusion in usual laccolithic form, here the bottom subsided and prevented in that way the surface of the laccolith from being lifted above the surrounding region.

For this to happen as fast as the magma was intruded the bottom would have to be relatively thin and have fluid support. This, then, postulates merely a deeper batholith in continuity with a magmatic reservoir, with a laccolith on top—a complication of theory which breaks beneath its own weight.

PROBABLE THICKNESS OF BATHOLITHIC BODIES.

In any individual instance the depth of the intrusion can be proved only to be at least equal to the difference of elevation shown between the highest hilltops and the deepest valleys, mines, or borings. Yet a bottom has frequently been assumed as existing at some moderate depth below the present level of erosion, and the assumption that batholiths are of laccolithic nature may be defended in regard to any particular one by saying that nowhere within it is a bottom exposed because the level of erosion has not yet sunk deeply enough. Since man can not wait while nature performs this task, this argument would put an end to the discussion were it not that in various terranes from the Archean upward are exposed broad granitic areas, some of which must naturally have suffered erosion to a depth of from 2 to 5 miles or more, yet in no case has evidence of a bottom been detected for the larger areas. Since, as shown above, laccoliths of such thickness could not be expected to occur, the universal absence of the exposure of bottoms to the larger batholiths may be taken as evidence that in all probability no bottoms exist in this class of invasions, but that, on the contrary, they extend downward into depths never reached by erosion and possibly maintain throughout equal if not larger horizontal dimensions.[a]

LACK OF CRUSTAL REMOVAL BY VOLCANIC OUTBURST.

The conclusions on the nature of a geologic act are always based on inference except where that or exactly similar work is observed to be done. In many cases, however, the conclusion is none the less sure on that account. In the present instance the rock which has been displaced by the Marysville batholith is not visible, so that whether it has been carried upward or downward is a matter of inference. That the removed sedimentary material has not been carried upward is indicated by the conclusion that a flat roof still covers large portions of the Marysville batholith and by the physiographic evidence that such a roof was once much more extensive. This would leave but comparatively small vents through which an enormous volume of sedimentary rocks would have to be swept by outrushing floods of lava. It would be equivalent to the discharge of a flat pyramid through its apex, requiring within the earth strong horizontal currents in the lava toward the opening and on the outside of the earth volumes of lava containing the sedimentary breccia, whose complete removal by erosion during the time which has since elapsed can hardly have been possible. Such an arrangement would also require that the sediments should be carried out as relatively small inclusions in a lava sufficiently viscous to pluck them from their seat and hold them suspended. No such inclusions are observed.[b]

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[a] At some localities in New England and elsewhere some broad sheets of granite have foot walls exposed, yet these sheets are traceable into larger granite areas and are in the nature of outliers.

[b] It is to be noted that where, as in the Absarokas or on the margins of the Boulder batholith, great quantities of fragmental extrusives preceded the rise of the plutonic masses, the extrusive materials are nearly all of igneous origin and hold proportionately but a small mass of sedimentary fragmental material.

It is concluded, therefore, that at Marysville there is no such evidence of the removal of the sedimentary material upward as would be expected under the volcanic hypothesis, and that, on the contrary, the general form of the intrusion was such as to render this method of removal impossible. The batholith, therefore, is not related in its nature to a volcanic stock.

PASSIVE INVASION BY SINKING OF ROOF BLOCKS.

GENERAL STATEMENT.

A review has been given of various methods by which granite magmas are supposed to work toward the surface in large volume, giving rise to batholithic masses. In many cases the evidence is good that a variety of processes has taken place; in other cases the proposed method of invasion rests on assumptions which may be unprovable and some of which are improbable. It has been seen, however, that none of these methods account for the facts of the Marysville district nor for the adjoining Boulder batholith. By a process of exclusion, therefore, the method of passive invasion by the subsidence of roof blocks has been reached.

The possibility of such a method has been amply shown by Daly unless the magma be conceived to be a soft solid of so high a degree of viscosity that blocks of heavier rocks, even of large size, are unable to settle through it. Such a degree of viscosity is as yet unproved as a general proposition, though possibly true in individual instances, and many able geologists, such as Brögger, hold that it does not exist. The only safe method, therefore, is to appeal to the facts of the field as indicating a fluid or semifluid state of the magma at the time of the intrusion.

DEGREE OF LIQUIDITY OF THE MARYSVILLE MAGMA.

A considerable degree of liquidity is indicated by the dikes and sheets, almost identical in composition and texture with the main batholith, which are found dipping away from it on the hill north of Drinkwater Gulch and which occur at other places at considerable distances, as at the Big Ox mine. These sheets and dikes are all thin, extended bodies, whose penetration involved the transmission of pressure for some distance from the larger mass to the point of intrusion. Such a transmission of pressures could occur only in a fairly fluid medium, since one of high viscosity would absorb the pressure by internal friction and result in limited lens-like and not sheetlike intrusions. The fact that the composition and texture of the outlying dikes and sheets are approximately the same as those of the batholith, and that they do not exhibit a pegmatitic nature indicate that they have not had any special degree of fluidity due to an excess of water vapor.

INFERENTIAL EVIDENCE OF SUBSIDENCE OF ROOF BLOCKS.

The plan of the foregoing argument has been one of exclusion of all other possible methods and then a consideration of the possibility of this. It is now appropriate to show to what extent the field evidence indicates a subsidence of roof blocks and conforms to what may be anticipated in such a case. The statements which have been made in regard to the nature of the roof and walls, and the lack of inclusions or assimilated material in the magma, may be applied to this discussion without detailed repetition. It is sufficient to state here that the evidence may be considered on a small or a large scale, the latter being the most convincing, since the geologic relations on a broad scale are the least open to doubt. On a small scale, it is seen that walls of the reentrant and steplike character shown in fig. 6 suggest the breaking away of individual blocks not necessarily more than 20 to 50 feet in diameter and possibly smaller. On a large scale, on the other hand, are to be noted the highly irregular form of the body, large vertical and horizontal contacts breaking across the sedimentary structures in a manner unlike the roof of any known laccolith; the fact that it has not made room for itself by pushing the walls to one side, setting up a peripheral schistosity as in the Black Hills and elsewhere; the fact that the granite mass broadens below as far as observation can reach; and the fact that the sediments in large part act as a cover which was certainly once somewhat more extensive and was possibly originally continuous.

These facts, while disproving other methods of invasion, are at the same time suggestive of the rifting away and subsidence of large individual blocks. Such evidence is of an inferential nature and necessarily so, since under the terms of the hypothesis the loosened blocks have sunk to depths beyond the reach of erosion; but taken in connection with the inability of all other methods to account for the magmatic invasion it is sufficient to carry a considerable degree of conviction.

GENERAL DETAILS CONNECTED WITH STOPING.

Under the preceding heads the evidence which bears on the method of invasion has been considered. It is now appropriate to mention some details which do not bear on the truth or falsity of stoping, or the subsidence of loosened roof blocks through the magma, but which, that being accepted as the general method of invasion, concern the manner of action.

ABSENCE OF INCLUSIONS.

It is to be noted that there is a striking absence of inclusions throughout the mass of the batholith. This is true of both the Marysville and Boulder areas and has been mentioned by Daly as true of igneous massifs in general. Along the borders of these Montana occurrences there is even less of a zone of injection and marginal inclusions than has been frequently noted elsewhere; only at a few places within the main area of the Marysville batholith are any chips and bowlders of the wall rocks found, and these are apt to be confined to a belt within a couple of feet of the walls. In view of the stoping hypothesis it may be questioned why such inclusions are not observed in all stages of disruption from the walls. The answer has been suggested by Daly and was independently arrived at by the present writer in April, 1900, in an unpublished paper on the contact at Elkhorn, which, as noted previously, was withheld from publication until fuller data should be obtained. A quotation from that paper is as follows:

> The contact is in its larger proportion a broken and irregular surface slanting beneath a sedimentary cover, and it is probable that at no great depth the granite underlies the greater part of the district. If the granite merely broke through and involved the original rocks of the area it now occupies, their entire absence from it as inclusions is remarkable; if they had been carried away by fresh accessions from

below they should be found as inclusions in certain localities preserved from erosion. On the supposition that they have sunk as fast as freed, the absence of inclusions may be readily explained. If, on the other hand, the batholith were an intrusive mass of limited thickness, its bottom should somewhere be exposed with the heaps of roof blocks resting upon it. As a matter of fact, no indications of a bottom have been observed anywhere within this batholithic area, and, although the evidence is negative in character, it must be taken as confirming to a certain degree the hypothesis that practically there is no bottom.

According to these views, the few small inclusions close to the margin are those last detached and prevented from sinking by the increasing viscosity of the cooling liquid. A block once well away from its original position would not be held stationary, since the greater heat and liquidity at short distances from the borders would permit a freer fall.

ZONE OF MARGINAL INTRUSIONS.

Surrounding the batholith, for distances up to half a mile from the contact, sheets and dikes related to the main mass commonly occur. In many cases, as in some of the dikes of the Drumlummon mine, these intrusions are more acidic than the quartz diorite and are probably later than the invasion of the batholith and therefore do not enter into the problem of stoping. In many other cases, however, the similarity in rock type is so close as to leave no reasonable doubt in regard to the connection of these intrusions with the main mass of the batholith. In certain instances this connection can be traced, and it is found that they are parts of the general intrusion and were fluid at the same time, as indicated by the crystallinic continuity. In the marginal intrusions of this type many of the vertical dikes and dikelets have shown considerable power of penetration, as exhibited in the character of the contacts and in the general form. The contacts show tongues forced irregularly into the sediments, and where the two are intimately interlocked a slight amount of crumpling may be developed. In general form some of the intrusions are of lenticular cross section and end rather bluntly, as shown east of Marysville. (See figs. 4 and 5, pp. 70, 71.) In deforming the wall rocks to permit intrusions of this character considerable work must have been involved, implying an excess of hydrostatic pressure within the magma and an ability to force its way. At other places, however, the dikes emanating from the batholith are narrow in proportion to their length and penetrate to considerable distances, and, in regard to the flatter or sheetlike intrusions especially, the evidence of intrusive power is not so marked; the contact may for considerable distances be parallel to the bedding without disturbing it. The same distinction may be noted in the character of the batholithic contacts where they are well exposed. On the hypothesis of stoping this relation would be explained by the supposition that the intersection of dikes and sheets caused the separation of roof blocks from their moorings and permitted their subsidence. The dikes being forced into the roof would possess a greater excess pressure, as may be shown mathematically, and would also meet a greater resistance to horizontal expansion. Sheets, on the other hand, would meet with much less resistance to their intrusion.

In many places these dikes and sheets dip away from the batholith. Their confluence, therefore, would lead to the separation of blocks, giving a pyramidal form to the whole intrusion. Distinct from either the intrusive dikes or sheets is the satellitic chimney on Mount Belmont, where an oval outcrop of granite several hundred feet in diameter has come to place without any noticeable disturbance of the flat strata. This fact, together with its close association with the main mass, leads to the view that its presence is due to stoping and that a slightly greater erosion would serve to connect its outcrop with that of the larger area.

SIZE OF STOPED BLOCKS.

But little evidence in regard to the size of the sunken roof blocks is to be had within the limits of the district, since no detached blocks remain visible. The nature of the contact where well exposed, however, as on the north side of Silver Creek, suggests, from the size of the reentrant angles, that blocks not more than 10 to 20 feet in diameter may have been removed, while the larger features of the contact, as shown by the maps and sections of the Drumlummon mine, suggest that the detached blocks may have been from 100 to several hundred feet in diameter. On the margin of the Boulder batholith, however, marginal inclusions are present, though sparingly. South of Helena these range from 10 to 20 feet in thickness as the smallest size, while at Elkhorn one was noted 65 feet wide by 100 feet long and several hundred feet from it a larger one about 200 feet in diameter.

The process of stoping, then, appears to be carried on by the separation of blocks from 10 to 200 feet or more in thickness and of considerably greater length. The small flakes of wall rocks which are found locally in the marginal portions of the magma do not appear to represent the work of the stoping process; since their volume is insignificant with respect to these larger fragments, and the general shape of the contact does not indicate the rounding and peeling that would be characteristic of exfoliation on a small scale into the magma. These indications from the walls and the inclusions are in conformity also with the theoretical conclusion that the ease of subsidence of blocks through the magma should vary directly with the diameter. This is seen when it is considered that in the case of similarly shaped blocks differing in size the viscous resistance, depending on the amount of the surface, varies with the square of the diameter, while the weight, which is the force tending to overcome the resistance, varies as the cube of the diameter. The same principle is illustrated by the speed of subsidence of detritus through water, the coarser particles reaching the bottom first.

In the earlier stages of the invasion the average size of the stoped blocks may have been different from what it was in the later stages, as the size must be dependent on many factors, some of which, as the viscosity of the magma, were doubtless changing.

PROBLEM OF THE COVER.

The greatest theoretical difficulty in the way of accepting stoping as one method of batholithic invasion, and perhaps a dominant method when the magma has encroached into the zone of fracture, is the fact that it apparently ceases without finally breaking through to the surface with crustal foundering over the limits of the batholithic reservoir. Such a caving in of the surface would presumably lead to enormous outpourings of acidic lavas from the granite batholiths—outpourings which find no suggestion in nature. This difficulty is somewhat diminished if it is granted that the batholithic magmas are never fluid, but are of the nature of soft solids. And yet a closer examination shows that even this view presents its difficulties, since in that event the act of intrusion could be effected only by a great internal or hydrostatic pressure of the magma which would raise it above the general level of the country and break up a cover as thin as that which existed over the Boulder batholith, with resulting lateral viscous flow. To avoid this difficulty it may be supposed that the bottom was pushed down by the magma as the magma was prest in—a supposition which postulates a weak bottom resting upon a readily yielding base. This is an approximation toward the stoping hypothesis, save that possibly the bottom is supposed to go down as more or less of a unit and the magma to be forced in above. The one view represents wholly an active intrusion, the other a passive rise as the blocks subside through their own weight. Apparently, then, the maintenance of a thin cover, say from half a mile to a mile thick, over some thousands of square miles is a problem under any theory of igneous invasion and a priori ideas in regard to this subject can not be urged as an argument against the hypothesis of stoping, but the presence or absence of this method of invasion must be determined rather from the facts of the field. Nor can laboratory experiments be urged as either proving or disproving the hypothesis, since it is impossible to reproduce in miniature the same ratio of temperature, pressure, viscosity, and structure as is found in nature.

It is seen, therefore, that the preservation of a cover is a separate problem to be attacked after the field investigation has shown that the cover was present at the completion of magmatic invasion and that the method of invasion was by stoping. This report is not the place to discuss the problem, as it is designed to present here only the facts of the field with such inferences and conclusions as may readily be drawn from them. The problem of the cover, on the other hand, requires a theoretical treatment of the hydrostatics of a viscous magma supporting an irregular roof lighter than itself. It need only be said that the permanence of the cover appears to depend on many factors, of which six may be singled out as chief. First, there is a great difference in temperature between the upper and lower surfaces of the cover. Second, a siliceous magma nearing its solidifying point attains so great a degree of viscosity that dikes and sheets are intruded with increasing difficulty and blocks set free are less able to subside. As the magma nears the surface the fall of temperature within a short distance in the rocks surrounding the magma is more marked, intrusions are more quickly chilled, and thus the magma tends to seal up fissures as they arise. Third, when a broad body of magma lies near the surface it possesses less power to find explosive relief through any single vent, since the restraining force which gives it the eruptive power is due primarily to the weight of the superincumbent crust restraining the lava and its occluded gases. For this reason as the crust becomes thin over a wide area the power of injection becomes weak, and the viscosity of the apophyses is all the more effective in preventing any fissure from being forced widely open with catastrophic outrush of the magma. Fourth, when certain tracts tend to subside through unequal weight or unequal support the movements are along normal fault planes, as exhibited in the structure of the Great Basin. This tends to wedge the blocks tightly and prevent the ready opening of fissures. Fifth, if any crust block is unusually thick and hangs pendent within the magma, such a block on account of its greater weight would have a greater tendency to subside and allow the magma to well forth in its place at the surface. It may be shown, however, that any mass hanging within the magma is peculiarly liable to have the pendent portion split off by lateral intrusions of the magma and that this tendency is in that way prevented from reaching a completion disastrous to the cover. Sixth, in case the magma encroaches upward by stoping to a higher level over limited areas, giving rise to satellitic chimneys or batholiths, as that of Marysville is satellitic to the Boulder batholith and as the small outlier on Mount Belmont is a satellite of the second order, it may be shown that stoping in this manner tends to terminate itself before reaching the surface, on account of a vertical roof pressure which the magma exerts the higher it rises above the mean upper level of the surrounding mass—a pressure which tends to dome the roof upward, as is observed at Marysville, and to prevent the subsidence of roof blocks. Again, in such limited chambers the chilling of the magma would go forward more speedily and be likely to terminate the possibility of stoping. The tendency in such satellitic chimneys would be to favor vertical injection, with perhaps surface overflows whose violence would depend on the depth of the general magmatic body from the surface. It is thus seen that in such ways the cover tends to be preserved, and yet it would seem that in spite of these factors there should be a high probability of its disruption and engulfment were it not that the facts of the field lend no plausibility to that view. Although depending on many factors, the key to the permanence of the cover appears to lie in the difference in temperature between the cover and the magma and in the viscous nature of the magma when cooled nearly to the point of solidification.

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