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TO ACCOMPANY MAP I-381

# GEOLOGY OF THE NORTHERN PART OF THE BOULDER BATHYLITH AND ADJACENT AREA LEWIS AND CLARK AND JEFFERSON COUNTIES, MONTANA

By

Adolph Knopf

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TABLE

## PRECAMBRIAN ROCKS--BELT SERIES

The oldest rocks in the Helena region make up the formations of the Belt Series of Precambrian age. Most of these formations of the Belt were first defined by Walcott (1899) during his pioneer investigations. They are, in ascending order, according to their emended names, Spokane Formation, Empire Formation, Helena Dolomite, and Marsh Formation. These units have been studied in detail and mapped in recent years during the present investigation of the northern part of the Boulder bathylith and adjacent area.

An additional Belt unit, the Greenhorn Mountain Quartzite, was recognized and described by Knopf (1950); it constitutes the uppermost formation of Precambrian age in this part of Montana.

The Belt Series in the Helena region, comprising the Spokane (not separated in the map area) and Empire Formations, Helena Dolomite, Marsh Formation, and Greenhorn Mountain Quartzite, aggregates 12,000 feet in thickness. The rocks are not visibly metamorphosed, except near the Boulder bathylith and its satellitic stocks, notably the Broadwater, Scratchgravel Hills, and Marysville stocks.

### Spokane Formation

The Spokane is the oldest formation of the Belt Series in the Helena region. The type locality is in the Spokane Hills, 15 miles east of Helena. There, the Spokane Formation consists of gray-violet micaceous siltstone and subordinate dark-red argillite_/.

_/ Argillite is used here in the sense suggested by L. V. Pirsson and first used by Wilson (1913, p. 123); compare with Knopf (1947, p. 255).

The siltstone beds range from 2 to 20 centimeters in thickness. Many of the beds are thinly laminated, the laminae being less than a millimeter thick. The siltstones range in density from 2.68 to 2.73; the argillite has a density of 2.73. Thin beds of mudflake breccia occur in which angular pieces of dark-red argillite are enclosed in a gray-violet matrix of siltstone.

Siltstone (density, 2.71) from the type locality of the Spokane Formation is a highly indurated rock composed of grains of quartz and feldspar (both potassium feldspar and plagioclase), detrital flakes of muscovite, and diagenetic white mica.

The uppermost part of the Spokane Formation contains beds of greenish quartzite. The contact with the overlying Empire Formation is gradational and difficult to place, and in the map area the Spokane and Empire Formations have been mapped as one unit.

### Empire Formation

The Empire Formation, named "Empire shales" by Walcott (1899), was defined by him as stratigraphically above the Spokane shale and below the Helena limestone. The type locality was given as the ridge north of the Empire mine, which is on Empire Creek, a headwater tributary of Lost Horse Gulch, in the western part of the Marysville mining district. It would seem hard to have found a more unfavorable place for a type section. It is 40 miles from the type locality of the Spokane Formation; the bottom of the section is the intrusive contact of the Marysville granodiorite stock; and all the rocks are hornfelses, being within the contact aureole, which extends outward and includes the overlying Helena Dolomite here converted to diopside hornfels. According to Walcott, the Empire "is finely exposed in the Drumlummon mine" in the eastern part of the Marysville district, but this was denied by Barrell (1907). In point of fact, the rocks at the Drumlummon mine are tremolite and diopside hornfelses formed by the metamorphism of the siliceous dolomites of the Helena Dolomite.

Barrell (1907), in describing the Empire Formation, preferred to deal with its unmetamorphosed facies as exposed in Little Prickly Pear Valley north of the Marysville stock. On Long Creek, a tributary of Little Prickly Pear Creek, the lower portion of the Empire Formation, according to the writer, consists of pale-greenish hard argillite (density 2.67) alternating with mud-cracked rose or lavender argillites resembling those in the Marsh Formation. Higher up on Long Creek, at an altitude of 4600 feet, the Empire is prevailingly a light-colored argillite, weathering to pale-buff and yellowish tints. It is overlain by the Helena Dolomite, the basal bed of which is a siliceous dolomite (density 2.76).

Probably the best section across the Empire Formation in this map area is in an east-west direction through BM 4457 in the Scratchgravel Hills; it is in the southern half near the north-south center line of section 28, T. 11 N., R. 4 W. The basal member of the Empire is a thin sequence of light greenish-gray quartzite beds and banded ripple-marked quartzite. Three tawny-weathering thin quartzite sequences occur higher in the section. In general, the Empire consists of greenish argillite and purplish-weathering dark-red argillite and siltstone.

The Empire Formation in the Scratchgravel Hills is 1,000 feet thick. In White and Avalanche Gulches in the Belt Mountains, according to Pardee and Schrader (1933) "it appears to be about 1,000 feet thick."

The Empire Formation, being dominantly argillaceous, has yielded cordierite hornfelses in the contact-metamorphic zones. Coarse cordierite hornfelses, some of which are crossbedded, occur in abundance at the head of Ottawa Gulch in the Marysville mining district. Barrell thought that where contact metamorphism has been severe the Helena "limestone" can be distinguished from the Empire only with difficulty, as both turn into hard light-gray or brown banded hornfels. This idea must now be greatly modified. On the detailed geologic map of Helena, Mont., and vicinity by Weed, assisted by Barrell and Griswold (in Knopf, 1913, pl. 7), large areas of diopsidic and tremolitic hornfelses derived from the Helena Dolomite were mapped as Empire Shale. Impressive exposures of these "shales," of hardness of 7 and nearly as tough as iron, occur along U.S. Highway 12, west of Broadwater, a suburb on the western outskirts of Helena. Recognition of their calc-hornfels nature was one of the reasons that led the writer to make a detailed resurvey of the region.

### Helena Dolomite

Overlying the Empire Formation conformably is the Helena Dolomite, consisting of 4,000 feet of mainly siliceous dolomite. This formation was originally named the Helena Limestone by Walcott (1899, p. 207), but it was changed to Helena Dolomite by Knopf (1950), as it was found to consist chiefly of buff-weathering dolomite. This buff-weathering feature had been described by all investigators as characteristic of the formation, but not until 1950 was the dolomitic composition of the formation specifically recognized.

On the weathered surfaces representative rock has a buff chamois-like coating; on fresh fracture it is dark gray, aphanitic, noneffervescent when touched with cold dilute HCl; it is compact and nonporous, and ranges in density from 2.76 to 2.82. Silica, as kindly determined by George Switzer on a sample from the lower part of the section in the Scratchgravel Hills, averages 32.62 percent. A complete analysis from the same sample was made by E. H. Oslund, in the Rock Analysis Laboratory of the University of Minnesota, with the following result:

Analysis of Helena Dolomite

| | | | |
|---|---|---|---|
| $SiO_2$ | 32.88 | $H_2O^+$ | 0.72 |
| $Al_2O_3$ | 3.48 | $H_2O^-$ | .09 |
| $Fe_2O_3$ | .16 | $TiO_2$ | .14 |
| FeO | 1.93 | $P_2O_5$ | .05 |
| MgO | 12.89 | $CO_2$ | 27.71 |
| CaO | 18.42 | MnO | .10 |
| $Na_2O$ | .73 | Total | 99.90 |
| $K_2O$ | .60 | | |

Density, 2.78

Limestone, weathering grayish blue, and mixed carbonate rocks occur in minor amount. Remarkable algal biostromes, of the genus Collenia, from a few inches up to 15 feet thick, occur at numerous stratigraphic horizons from the bottom to the top of the Helena Dolomite. Some are traceable along their strike for thousands of feet. Collenias were said by Walcott (1914) to be abundant from base to top of the Newland Limestone, a formation of the Belt Series stratigraphically far below the Helena Dolomite, and to occur also in the Spokane Shale, but they were not mentioned as occurring in the Helena Dolomite. The presence of Collenia biostromes throughout the entire 4,000 feet of the Helena Dolomite indicates that the dolomite accumulated in a shallow sea never deeper than the depth at which photosynthesis was possible.

### Marsh Formation

"Marsh shales" was the name given by Walcott in 1899 to what he considered to be the uppermost unit of the Belt Series. As the unit contains much interbedded quartzite, Marsh Formation is more appropriate. Its stratigraphic relations with the underlying Helena Dolomite and with the overlying Flathead Quartzite are perfectly exposed on South Park Street at the mouth of Last Chance Gulch in Helena. The Marsh Formation conformably overlies the Helena Dolomite, with which it is connected by a thin zone of passage beds. The Marsh consists of dull-maroon argillite (density 2.66) and mud-flake conglomerate alternating with quartzite beds 1 to 2 inches thick and some limestone; and the Helena here consists chiefly of buff-weathering dolomite, though almost at the top of the formation is a 2-foot bed of siliceous oolitic limestone. Only about 250 feet of Marsh is present, as most of the formation had been removed by erosion before the overlying Flathead Quartzite, of Middle Cambrian age, was laid down disconformably on it.

For a reason not wholly clear, Walcott, having described the new formation from the evidence at Helena, designated as the type locality of the "Marsh shales" the mouth of Marsh Creek, 25 miles northwest of Helena, where, he said, "there is an excellent section on the ridge between Little Prickly Pear Creek and Marsh Creek," about 300 feet thick. This section, which consists chiefly of purplish-red siltstones dipping 25°SW, is really part of the Spokane Formation; the strata are overlain conformably by the Empire Formation, which in turn is overlain by the Helena Dolomite, well exposed west of the mouth of Marsh Creek. Instead of being stratigraphically above the Helena Dolomite as is definitively shown by the exposures in the city of Helena and so recognized by Walcott, the beds of the supposed type Marsh are far below the Helena. The name Marsh is nevertheless retained here for the formation stratigraphically above the Helena Dolomite, but Walcott's type section is abandoned. The Marsh Formation thickens greatly northwestward from its unimpeachable exposure on South Park Street in Helena. Within a few miles it enters the contact aureole of the Boulder bathylith, where it consists chiefly of superb cordierite hornfels, comes out again, and extends to Marysville and the Continental Divide, where the best continuous section, aggregating 3,000 feet, is exposed.

The Marsh Formation has been redefined (Knopf, 1950) as a sequence of argillaceous siltstones and interbedded quartzite conformably overlying the Helena Dolomite and conformably underlying the Greenhorn Mountain Quartzite. The siltstones are generally pale red purple. However, this color does not distinguish these siltstones from similar rocks in the Empire and Spokane Formations. Ripple marks are common; on Parks Creek, for example, are extraordinarily fine exposures that are ripple-marked over hundreds of square feet. Lamination and crossbedding are well-nigh universal. Salt casts were found at two widely separated localities: on the road on the divide between Parks and Skelly Creeks, where the casts are in maroon argillaceous layers, and in laminites south of the Northern Pacific Railway crossing on Greenhorn Creek. The occurrence of salt casts is the only feature so far found in the Belt rocks of the Helena area that is unique to the Marsh Formation.

### Greenhorn Mountain Quartzite

On Greenhorn Mountain a sequence of 1800 feet of quartzite beds rests conformably on the Marsh Formation, and is disconformably overlain by the Flathead Quartzite of Middle Cambrian age.

This quartzite sequence, not previously recognized as a separate unit in the Belt Series, was named the Greenhorn Mountain Quartzite by Knopf (1950). The measured thickness is a minimum, as the top of the section is bounded by the erosion surface on which the Flathead Quartzite rests. The Greenhorn Mountain Quartzite constitutes the country rock of the Continental Divide and makes up the massive bulk of Greenhorn Mountain, 7,500 feet in altitude, the highest summit on the Continental Divide between Mullan Pass and Marysville.

The lower part of the formation is made up of massive quartzite beds, in places showing festoon crossbedding, whereas the upper third is well stratified in beds of uniform thickness ranging from 2 to 5 centimeters. The quartzites as a rule are light gray, but locally are dark red. All are notably feldspathic, the feldspar though dull white on weathered surfaces consisting of clear limpid microcline. The quartzites, which are not porous, range in density from 2.58 to 2.63. In this feature, the result of its content of microcline, the Greenhorn Mountain Quartzite differs essentially from the Flathead Quartzite, which is normally almost entirely quartz and has a density ranging from 2.63 to 2.65.

## CAMBRIAN SYSTEM

### Flathead Quartzite

The Paleozoic sequence begins with the Flathead Quartzite, of Middle Cambrian age. The formation is well exposed in Helena. On South Benton Street it is 86 feet thick, which appears to be its minimum thickness. The topmost 20 feet are interbedded with argillite and constitute passage beds into the overlying Wolsey Formation. The Flathead attains its maximum thickness, 170 feet, southeast of Lenox, a suburb of Helena. It is bedded vitreous quartzite, white on fresh fracture. The quartzite ranges in density from 2.63 to 2.66, the prevalent value being 2.64. It is composed of rounded grains of quartz secondarily enlarged by overgrowths of quartz. It carries some detrital tourmaline and zircon.

In general, the Flathead Quartzite rests in angular accordance on the underlying rocks. Locally, however, as on the west side of Prickly Pear Creek, angular discordance occurs, 10° in strike and 15° in dip. The unconformity between the Flathead Quartzite and the underlying formations of the Belt Series represents an important period of erosion, as indicated by the following evidence. At Greenhorn Mountain on the Continental Divide the Flathead Quartzite rests on the Greenhorn Mountain Quartzite; eastward, it rests at Helena on the Marsh Formation and farther east on the Helena Dolomite; still farther east, in the Belt Mountains, it rests on the feather edge of Helena Dolomite, and according to Mertie and others (1951), it even rests in places on the Empire Formation below the Helena Dolomite. Farther south in the southern Elkhorn Mountains, the Flathead Quartzite rests on the Spokane Formation (Klepper and others, 1957, p. 6). Pre-Flathead erosion therefore removed at least 9,000 feet of strata.

### Wolsey Formation

The Wolsey Formation gradationally overlies the Flathead Quartzite and gradationally underlies the Meagher Limestone. It is best exposed in gulches on the east flank of Mount Helena. On South Howie Street in Helena it is 206 feet thick, and it maintains an average thickness of 200 feet throughout the district.

The typical rock is a micaceous siltstone, of density 2.68; the range is from 2.67 to 2.75. In contact-metamorphic zones some six interbeds of calc-hornfels, from 1 to 5 feet thick, are conspicuous, resulting from metamorphism of siliceous dolomites whose presence is not readily recognizable where the formation is unmetamorphosed.

The typical rock is composed of 80 percent angular grains of quartz and subordinate microcline, 15 percent muscovite and biotite in detrital flakes bent and twisted by compaction, and 5 percent calcite. The abundant mica characteristically gives a phyllitic aspect to rocks fractured parallel to the bedding.

Ripple marks and worm burrows are common throughout the formation. Deiss (1936) found poorly preserved fragments of trilobites in the upper part of the Wolsey Formation in Last Chance Gulch. He lists also fossils found elsewhere in Montana, which serve to determine the Middle Cambrian age of the Wolsey Formation.

### Meagher Limestone

The Meagher Limestone, 640 feet thick, overlies the Wolsey Formation. It consists of two highly contrasting portions: lower thin-bedded siliceous dolomitic limestone, 360 feet thick, and upper massive pure limestone, 280 feet thick. The lower part is generally metamorphosed to diopside-calcite hornfels, weathering brown. The upper limestone is strikingly exposed in the great mural escarpment of Mount Helena in the western part of the city of Helena; and near East Helena it is quarried extensively as a flux for the East Helena smelter.

### Park Argillite

The Park Argillite, 180 to 200 feet thick, lies conformably above the Meagher Limestone and below the Hasmark Dolomite. It consists chiefly of a compact minutely grained dark rock having little or no fissility. Its density ranges from 2.70 to 2.80, the average of determinations on six specimens being 2.76. The argillite has consequently a higher density than that of the granodiorite, the prevailing rock of the adjacent Boulder bathylith. Because of this high density and the lack of fissility, the name shale, which has generally been given to the rocks of this formation is wholly inappropriate. Normal shales have densities from 1.87 or less to about 2.25.

The formation is sparsely fossiliferous, but fossils occur throughout the full length of the mapped extent of the formation. Some fossils found during the present investigation were determined by G. Arthur

Cooper, of the U. S. National Museum (written communication, 1941):

| | |
|---|---|
| Lingulella pentagonalis (Rothpletz) | Middle Cambrian |
| Lingulella cf. L. helena Walcott | Middle Cambrian |

The Park Argillite was readily susceptible to contact metamorphism and striking cordierite hornfelses were formed, but the associated fossils have not all been destroyed and Lingulella shells studded with cordierite crystals have been found.

### Hasmark Dolomite

The Hasmark Dolomite of Late Cambrian age, 450 feet thick, overlies the Park Argillite. It consists of two contrasting parts: a lower dark-gray drab-weathering thick-bedded dolomite, and an upper sequence of light-gray weathering dolomite. The lower dolomite beds show: (a) A dark mottling ranging from simple patterns to highly bizarre; the mottles consist of dark dolomite in a matrix of lighter-colored dolomite; (b) Forms about 6 inches long perpendicular to the bedding and occurring in colonies; unlike the mottles they are white enclosed in dark or black dolomite; and (c) "Twiggy" forms, white crooked tubes which send off branches, probably algae with branching thalli.

The dolomite beds, of both the lower and upper parts, are remarkably pure, the density averaging 2.84. Twenty-nine analyses of dolomites from Grizzly, Nelson, and Colorado Gulches made by the U.S. Geological Survey in 1943 confirm the high-grade nature of the dolomite.

Equivalent rocks in the neighboring Elkhorn Mountains are assigned to the Pilgrim Dolomite (Klepper and others, 1957) and in the Spokane Hills and Big Belt Mountains to the Pilgrim Limestone (Mertie and others, 1951).

### Red Lion Formation

The Red Lion Formation of Late Cambrian age, approximately 160 feet thick, overlies the Hasmark Dolomite. The lowermost part is generally not exposed, except where it has been altered by contact metamorphism, there consisting of 20 feet of thin-bedded calc-hornfelses (density, 2.98). Above them are 45 feet of hard argillites, as a rule metamorphosed to cordierite hornfels. Above the argillites are 100 feet of interbedded limestone and dolomite. Distinctive of this upper belt is a zone 25 to 50 feet thick containing crinkly filaments of chert which anastomose irregularly roughly parallel to the bedding. The filaments weather in strong relief and make the zone a valuable aid in mapping. The top of this "marker" zone consists of mottled dolomite reminiscent of fucoidal rocks or so-called tapestry limestones.

A highly fossiliferous slab of blue limestone traversed by numerous crinkly filaments of chert was found in the "marker" zone by E. B. Knopf on Squaw Gulch, a tributary of Grizzly Gulch in the outskirts of Helena. Preston E. Cloud reported on these fossils (written communication, 1942) in part as follows:

"Of described species of Billingsella your specimens from the Red Lion Formation at Squaw Gulch, Montana, are nearest to B. plicatella but are probably specifically distinct. The two forms are similar to one another and unlike other described Billingsella in the pronounced convexity of the ventral valve and in the tendency of the ribs to bundle and fade out posteriorly. The ventral valves in your collection are more strongly convex medially and the ribbing is much less well defined than in B. plicatella. One of the dorsal valves collected by you probably represents another species, differing in being prominently and completely ribbed and more transverse than either B. plicatella or the new species B. aff. B. plicatella. Stratigraphically this means that your specimens are Upper Cambrian, and, in view of their similarity to B. plicatella, the rocks in which they occur may be tentatively correlated with the zone of B. plicatella, commonly referred to the Dry Creek shale."

Between the overlying Jefferson Formation and the supposed top of the Red Lion Formation are 30 feet of poorly exposed thin-bedded limestone and red siltstone, which have been mapped with the Red Lion Formation but possibly represent the Maywood Formation of Late (?) Devonian age.

## DEVONIAN SYSTEM

### Jefferson Formation

The Jefferson Formation of Late Devonian age, roughly 750 feet thick, consists of dolomites alternating with limestones. All dark-gray and blackish beds are dolomites, generally highly fetid; light-colored beds are mainly limestones. Some very black dolomites are as black on weathered surfaces as on freshly fractured surfaces.

The dolomites in this area are in places highly porous, the outcrops being so full of small holes as to be pseudo-vesicular, the result of removal by weathering of periclase and brucite formed by contact metamorphism. The density has thereby been reduced from 2.80 to 2.00.

## DEVONIAN AND MISSISSIPPIAN SYSTEMS

### Three Forks Formation

The Three Forks Formation, 350 feet thick, of Late Devonian and Early Mississippian age, conformably overlies the Jefferson Formation. In ascending order, the Three Forks Formation comprises green shale, 240 feet thick; limestone, 25-50 feet thick; blue-black shale, 35-90 feet thick; and 50 feet of massive aphanitic white or light-bluish-gray scapolite-diopside calc-hornfels, possibly the contact-metamorphic equivalent of the Sappington Sandstone Member.

The green shale is fossiliferous. A collection made 65 feet above the base of the formation on Dry Gulch, a few miles southeast of Helena, was examined by G. A. Cooper, who reported (written communication, January 1942) as follows:

Schizophoria sp.
Cyrtospirifer monticola (Haynes)
C. sp.
Leiorhynchus ventricosum (Haynes)
Camarotoechia cf. C. contracta Hall
Cleiothyridina devonica Raymond
Actinoptera sp.
Leptodesma sp.
Schizodus sp.
Age: Three Forks (Devonian)

Schindewolf (1934) has shown from an examination of the Three Forks fauna that it belongs to the Platyclymenia Stage, the fourth of the six of the Late Devonian--that is, it is of late but not latest Devonian age. Cooper and others (1942) concur with that assignment.

The green shale has generally been metamorphosed to cordierite hornfels, but nevertheless an astonishing number of specimens of the hornfels on being broken open yield well-preserved brachiopods, generally Cyrtospirifer. In contrast, the upper shale, which is of highly distinctive blue-black color, has resisted metamorphism and is generally unaltered. The overlying hard massive calc-hornfels, which is presumably the metamorphosed form of the Sappington Sandstone Member, in the 25 miles along which it has been mapped is nowhere in its unaltered state--siliceous dolomite. It is a notable feature of the areal geology, and moreover, because of its resistance to erosion, is a great aid in geologic mapping.

## MISSISSIPPIAN SYSTEM

### Madison Group

The Madison Group, 1,300 feet thick, comprises a lower unit 300 feet and an upper unit 1,000 feet thick. The lower unit consists of thin-bedded dark limestone, which on weathered surfaces is drab blue gray. It contains numerous beds of crinoidal debris, and black chert is abundant, including chertified fossils. The upper unit is thickly stratified in beds probably 3 to 6 feet thick, but in many places its outcrops show no bedding. It is predominantly a snow-white marble which yields massive domelike outcrops.

The lower unit is doubtless the Lodgepole Limestone of Early Mississippian age, and the upper unit is the Mission Canyon Limestone of Early and Late Mississippian age.

Because of the widespread effects of contact metamorphism, the lower unit generally contains abundant needles of actinolite. This feature is particularly well displayed in Dry Gulch, where the lower unit, dipping 35° S., consists of highly actinolitic beds 2 to 3 inches thick alternating with less actinolitic beds 4 to 6 inches thick.

## PENNSYLVANIAN AND PERMIAN SYSTEMS

### Quadrant Quartzite and Phosphoria Formation

The Quadrant Quartzite, which overlies the Madison Group accordantly, is 370 feet thick, as measured in Holmes Gulch, southeast of Helena. The lower part includes rocks assigned to the Amsden Formation in neighboring areas.

Section of Quadrant Quartzite in Holmes Gulch

Jurassic and Cretaceous Systems:

Sandstone; cement is contact metamorphosed to tremolite, bytownite, and calcite.

Erosional unconformity.

Pennsylvanian System:

| Quadrant Quartzite: | Thickness (Feet) |
|---|---|
| 6. Calc hornfelses and quartzites | 160 |
| 5. Forsterite marble | 5 |
| 4. Quartzite | 35 |
| 3. Dolomite | 35 |
| 2. Quartzite | 5 |
| 1. Calc hornfelses and tremolitic quartzites | 130 |
| Total thickness | 370 |

The Phosphoria Formation, because of its thinness, was mapped together with the underlying Quadrant Quartzite. It is best seen in Holmes Gulch, where it is not more than 20 feet thick. Some phosphate-bearing rock occurs here as float, carrying ooids of chalk-white phosphate 1 to 5 millimeters in diameter. Some of the phosphate-bearing rock resembles siliceous calc-hornfels. Under the microscope it was found to consist predominantly of grains of detrital quartz, along with calcite, apatite, and diopside of contact-metamorphic origin. The identity of the phosphate as apatite was confirmed by an X-ray analysis by R. A. Gulbrandsen, of the U. S. Geological Survey. Similar phosphate rock was found also as float, north of Park City, at the contact of the Quadrant and overlying Jurassic and Cretaceous sequence.

## UNDIFFERENTIATED JURASSIC AND CRETACEOUS

Disconformably above the older formations is a sequence of highly metamorphosed rocks, several thousand feet thick and generally unfossiliferous. It comprises sandstones, the original cement of which is now diopside, tremolite, or calcic plagioclase; quartzites; hornfelsed shales; white calcic hornfelses, and blue limestone.

East of the mapped area unaltered fossiliferous rocks of Jurassic age (Ellis Group) and of Cretaceous age (Kootenai Formation) occur. Above the Kootenai beds is a sequence of black shales and sandstones of Colorado age, 2100 feet thick, containing two thick sills of diorite porphyry. Above the Colorado beds are 910 feet of sandstone and lapilli-tuff, as measured by Klepper and Freeman and assigned by them (Klepper and others, 1957, p. 28) to the Slim Sam Formation of late Niobrara age. In this section marine Niobrara fossils had been found by the writer and his associate in 1947. J. B. Reeside, Jr. reported on these fossils (written communication, 1948) as follows:

Ostrea sp., small single species
Inoceramus stantoni Sokolow
Acteon sp.
Baculites cf. B. codyensis Reeside
Age: upper Colorado (Niobrara)

Volcanic rocks interlayered with the sedimentary rocks are mainly of three kinds: plagiophyric andesite (density, 2.82); basaltic andesite (density, 2.89), carrying pyribole phenocrysts prominent on weathered surfaces; and light-colored rhyodacite (density, 2.62).

Because the Jurassic and Cretaceous rocks in the map area are generally highly metamorphosed they have not been subdivided.

## QUATERNARY

### Morianal deposits, high-level gravel, and alluvium

Morainal deposits thick enough and continuous enough to conceal the bedrock geology have been mapped near the Continental Divide northwest of U. S. Highway 12. A notable feature of the morainal deposits is the immense size of their granite boulders, as large as 15 by 15 by 4 feet.

In addition to the gravels in the beds of the existing streams, whose placer gold led to the discovery of the mineral wealth of the region beginning in 1864, older gravel deposits occur at many places. They are exceptionally well shown in the lower part of the city of Helena, near 11th Avenue. The gravels are coarse, containing boulders up to 5 feet long. Boulders of granite are thoroughly rotted. The gravels rest on yellow, much weathered Helena Dolomite, altered to a depth of at least 20 feet. Such decayed gravels occur at many other localities, but no special study of them has been made. Remarkably, they occur also below the auriferous gravels of the Last Chance alluvial fan, on the northern outskirts of Helena, where they have become visible in deep cuts made during gold-dredging operations. In these gravels the granite boulders have also been altered to pseudomorphs consisting of thoroughly rotted rock.

## PREBATHYLITHIC IGNEOUS ROCKS

### Gabbro

Gabbro occurs as sills as much as 400 feet thick in the formations of the Belt Series of the Scratchgravel Hills. A coarse-grained black rock of density 3.00 to 3.13, and pigeonitic locally, it is unlike any of the other gabbros in the area mapped. It is cut at many places and metamorphosed by the syenodiorite stock and also by granodiorite porphyry related to the Boulder bathylith. Because the gabbro occurs only in Belt strata, its age is probably Precambrian as suggested by Pardee and Schrader (1933).

### Andesite, basalt, and rhyodacite

The principal rocks that formed the roof under which the Boulder bathylith was emplaced comprise lavas, tuffs, and breccias of andesitic, basaltic, and rhyodacitic (dellenitic) composition. Some of the rhyodacites are rich enough in potash to be called toscanite (Knopf, 1957, p. 84, 87). The rhyodacites are commonly flow-banded with conspicuous laminae a millimeter or less in thickness. The andesites average about 2.78 in density, the basalts about 2.91, and rhyodacites 2.65. These three types are generally closely associated as successive flows.

A continuous mass of potash-rich rhyodacite (toscanite), an analyzed specimen of which contains 6.07 $K_2O$, extends from MacDonald Pass several miles northward along the Continental Divide. It consists largely of breccias and welded tuffs, apparently of constant chemical composition, and has no associated andesites and basalts. The presence of tuffs welded (agglutinated) by viscous deformation shows that these eruptions took place subaerially, whereas volcanics in other parts of the mapped area are locally interlayered with water-laid sedimentary rocks.

The volcanic rocks that make up most of the remnants of the roof under which the Boulder bathylith was emplaced have been assumed by all previous investigators, beginning with Weed (1902, 1912), to be of one age. However, field evidence in the Helena area suggests that there has been more than one episode of volcanic activity late in Cretaceous time. Klepper and others (1957) named the volcanic roof rocks in the Elkhorn Mountains on the east side of the bathylith the Elkhorn Mountains Volcanics and determined them to be of Late Cretaceousage. However, this age assignment cannot be extended to the Helena area without more conclusive evidence than is now available.

### Diorite porphyry

Stocks, sills, and dikes of diorite porphyry, in part prebathylithic and in part synbathylithic, occur throughout the region. The most notable stock of prebathylithic age forms the hill in Helena on which Carroll College stands. It intrudes the Helena Dolomite. It is a rudely schistose porphyry (density, 2.69), carrying 40 percent of white andesine phenocrysts and a few inconspicuous crystals of hornblende or biotite enclosed in a microcrystalline groundmass.

The porphyry of the prebathylithic sills and dikes is of the same general character as that of the stock at Carroll College. It is, as a rule, darker and seems to be more mafic, but this is an illusory effect, the result of abundant fine flaky biotite disseminated throughout the porphyry by the contact-metamorphic activity of the Boulder bathylith. In general, the prebathylithic dikes are more "altered" in appearance than those that were emplaced during the intrusion of the bathylith.

The diorite porphyry intrusives are doubtless in part underground correlatives of the volcanic extrusives of Late Cretaceous age.

## SYNBATHYLITHIC INTRUSIVE ROCKS

Shortly after the youngest of the prebathylithic volcanics had been erupted, the rocks of the area were folded, powerfully enough so that the youngest volcanic rocks now stand vertically, as is well shown on U.S. 12 west of the Continental Divide. The Boulder bathylith then began to be emplaced. The bathylith, as shown by field evidence, was emplaced in at least five stages. The successive magmas arrived according to the well-known rule, in the order of increasing silica content.

### Unionville Granodiorite

The earliest major intrusive is dark granodiorite, well exposed south and southeast of Helena. The name Unionville Granodiorite has been given it, after a village 4 miles south of Helena (Knopf, 1957, p. 91). It is an augite-biotite-hornblende granodiorite, generally containing some hypersthene. Its density ranges between 2.75 and 2.82, the type rock analyzed being 2.78.

In places, as at Park City and east of Montana City, the Unionville Granodiorite has a basic facies of hypersthene granogabbro; in the chemically analyzed sample from Park City the plagioclase is labradorite ($An_{55}$) and the density is 2.84. Some parameters of the Unionville Granodiorite and its hypersthene granogabbro facies, as well as of other rocks of the Boulder bathylith are shown in table 1.

### Clancy Granodiorite

The second intrusive is the Clancy Granodiorite, so named (Knopf, 1957, p. 91) from the Kain quarry on Clancy Creek, less than a mile west of Clancy, a town 12 miles southeast of Helena. It is a coarse-grained hornblende-biotite-granodiorite of density 2.71, in which quartz is conspicuous; it is light gray, in contrast to the dark gray of the Unionville Granodiorite. The Unionville Granodiorite had already solidified and was cut by dikes of the younger magma, as is well shown on the summit of Colorado Mountain. The Clancy Granodiorite shows no perceptible chill selvage against the Unionville Granodiorite, which indicates that not much time elapsed between the two intrusions.

Two potassium-argon age determinations have been made on the biotite of the Clancy Granodiorite from the type locality: 82 million years as determined at the University of Alberta (Baadsgaard and others, 1961), and 81 million years at the University of California at Berkeley (Evernden and others, 1961). The intrusion took place therefore very late in Cretaceous time, the Cretaceous, so far as now known, having ended about 70 million years ago.

### Porphyritic granodiorite

The third intrusive is a porphyritic granodiorite. It is characterized by abundant orthoclase phenocrysts an inch long and half an inch across. It is more constant in composition (table 1, no. 3) than any other intrusive mass making up the composite body of the Boulder bathylith. Its average density is 2.68, the range being from 2.71 to 2.65. The plagioclase is zoned from $An_{35}$ in the core to $An_{20}$ in the outermost zone. Granodiorite of this kind extends to Mullan Pass, the northernmost limit of the Boulder bathylith.

The porphyritic granodiorite is known to intrude a more basic granodiorite, but its position as the third member in the intrusive sequence is partly inferential, being based on stage of evolution indicated by the differentiation index, 71.9, as given in table 1.

### Biotite adamellite

A fourth intrusive is admellite, so called to emphasize that its plagioclase content is approximately equal to its content of potassium feldspar. It definitely intrudes the Clancy Granodiorite. It intrudes also the Unionville Granodiorite, against which it has developed an easily perceptible chill border not over a few inches thick. It is higher in silica (71.3 percent), much higher in quartz, and is lower in density (2.65) than the earlier intrusives. In terms of the ferromagnesian minerals, the admellite magma had progressed so far in stage of evolution that only biotite was crystallizing from the magma.

### Muscovite-biotite granite

The fifth intrusive is a medium-grained biotite granite low in plagioclase ($An_{30}$). Muscovite, probably deuteric in the main, is generally present. This granite (density, 2.61 to 2.62) forms relatively small masses in comparison with the great volumes of granodiorite. According to the field evidence it is clearly younger than the Clancy Granodiorite. Its relation to the biotite adamellite, however, has not yet been established by field evidence. It is generally tourmaliniferous, and in places it is crowded with tourmaline nodules and with tourmaline developed along fractures. These features are spectacularly displayed near Montana City, in Prickly Pear Valley southeast of Helena.

### Alaskite and aplite

Alaskite, a coarse-grained, hypidiomorphic granular rock of alkali feldspar and quartz, forms a few small stocks, but many dikes. Aplite, the minutely grained and panidiomorphic equivalent of alaskite, is immensely more abundant than the alaskite. Dikes of aplite cut all the phanerites of the Boulder bathylith as well as the adjacent invaded rocks. Most are thin, but some are as much as 100 feet thick.

### Intrusive rocks of undetermined genetic affilitions

Graphophyre.--In the high mountainous portion of the Boulder bathylith southeast of Helena is a large mass of darkish granitic rock (density, 2.68) that to the unaided eye resembles the Unionville Granodiorite. It was discovered under the microscope to be a graphophyre, or "granophyre" as such rocks are commonly called in error, containing phenocrysts of labradorite and clinopyroxene in a well-developed groundmass of micropegmatite. No rock mass of this kind has previously been reported from the Boulder bathylith.

Nonporphyritic granodiorite and undivided granodiorite.--Large masses of granodiorite, shown on the map as "nonporphyritic granodiorite" are mainly the equigranular equivalents of the porphyritic granodiorite.

The designation "granodiorite undivided" is used to show on the map a large body of granodiorite whose field characteristics are not distinctive enough to indicate its relationship to the other units of the bathylith. Granodiorite of this kind is extraordinarily well displayed on the MacDonald grade of U.S. Highway 12, as the ascent to MacDonald Pass from the east is called. The average rock has a density of 2.68 and a plagioclase of composition $An_{45}$. On the lower part of the MacDonald grade the granodiorite is dark gray and consequently seems to be more mafic than indicated by its density of 2.68; higher up, at altitude 6,160 feet at the Montana State Road Maintenance Station, it apparently grades into a white granodiorite (density, 2.69).

### Aberrant intrusives

The five intrusives, beginning with the Unionville Granodiorite and ending with the muscovite-biotite granite, appear to constitute the normal stages of the evolving bathylith. They were emplaced in the order of increasing silica content and their differentiation index increases progressively from 58.1 to 79.7 and higher. Other plutonic masses of comparatively small volume occur, however, which do not fit into the normal scheme of magmatic differentiation. They are therefore here called "aberrant intrusives"; their aberrancy is thought to be the result of the assimilation of limestone (Knopf, 1957).

Priest Pass Leucomonzonite.--One such mass is at Priest Pass, near the Continental Divide. It is of monzonitic composition, is nearly devoid of quartz, and contains about 9 percent hornblende and biotite. It was named Priests Pass Leucomonzonite (ibid., p.95), but is here emended to Priest Pass Leucomonzonite.

Syenodiorite of the Scratchgravel Hills Stock.--(described under "Satellitic stocks").

Shonkinite.--Shonkinite occurs at four localities. It was first found at a limestone xenolith enclosed in granogabbro east of Montana City; the xenolith is cut by thin dikes of shonkinite and nepheline shonkinite and much larger masses of orthoclase gabbro. Shonkinite is notably developed as dikes 1 or 2 feet thick that cut a diopside tactite on the south side of the highway extending east from Montana City. The striking shonkinite at this place is made up of augite poikilitically enclosed in glassy alkali feldspars an inch and a half long. Dikes of shonkinite cut also a vesuvianite mass 50 feet thick on Grizzly Gulch, near Helena.

The largest body of shonkinite is half a mile west-northwest of Austin, the only locality where it has been found in a mass large enough to be shown on the geologic map.

### Satellitic stocks

Twenty or more stocks occur near the Boulder bathylith in the mapped area. The largest forms the Scratchgravel Hills, which rise prominently northwest of Helena out of the Helena Valley. The Marysville granodiorite stock, 6 miles north of the Boulder bathylith, is the most famous. The problem of its relationship to the Boulder bathylith, namely whether it is an outlier of one of the component bathyliths, or is a satellitic mass, or is unrelated to the bathylith (Knopf, 1950), has finally been solved by determining the absolute age of the stock by the K-Ar method on biotite, which shows it to be 78 million years (Baadsgaard and others, 1961, p. 699), indicating that the stock was emplaced contemporaneously (within the limits of experimental error) with the Clancy Granodiorite of the Boulder bathylith. In default of absolute age datings of the other stocks, the relationship of these stocks to the bathylith is not definitively established.

Olivine-orthoclase gabbro of the Knapp stock.--The most mafic rock in the area makes up the Knapp stock, 15 miles southeast of Helena. It is an olivine-orthoclase gabbro, ranging in density from 2.87 to 3.20; it is ideally fresh, and is rich in ferromagnesian minerals--olivine, hypersthene, augite, hornblende, and biotite. It preceded the Unionville Granodiorite and granogabbro adjacent to it.

Bytownite gabbro and syenodiorite of the Scratchgravel Hills stock.--Syenodiorite (density, 2.76) consisting of plagioclase ($An_{35}$), microperthite, augite,
gravel Hills stock.--Syenodiorite (density, 2.76) consisting of plagioclase ($An_{35}$), microperthite, augite,
and hornblende, makes up the large stock of the Scratchgravel Hills. Bytownite gabbro (density, 3.16) occurs on the north border of the stock; it was emplaced before the main body of syenodiorite.

### Plutonite porphyries

Porphyry dikes and sills as much as 100 feet thick emplaced during the growth of the Boulder bathylith are common throughout the region. The dikes not only cut the presumable parental igneous rocks, but the dikes and related sills have invaded the adjacent country rocks. They have a wide range in composition, from tonalite porphyry, through granodiorite and adamellite porphyry to granite porphyry. In density they range from 2.69 to 2.59. Many of the porphyries are conspicuously porphyritec, with large phenocrysts of plagioclase, orthoclase, and quartz in fine-grained or microcrystalline groundmasses. As it is impossible to name plutonite porphyries accurately without the aid of chemical analyses, the dikes are shown on the map as granodiorite porphyry, the term being used in an essentially noncommittal way.

Many porphyries in the region are disconcertingly granitoid in appearance. The unaided eye is not able to distinguish a porphyry in which the groundmass is less than 25 percent. Thus a rock near the Big Indian Mine on the upper reaches of Holmes Gulch that appeared to be a normal granodiorite proved under the microscope to be a hypersthene-augite granodiorite porphyry (density 2.70). A supposed white granodiorite on the Mike Renig trail at the Continental Divide was found to be a graphophyre (density, 2.69).

The fact that the Boulder bathylith is a composite mass of at least five major intrusives makes the genetic interpretation of the dikes much more complex. In theory, each of the major intrusives might have been accompanied by its own retinue of aschistic and diaschistic dikes.

## POSTBATHYLITHIC IGNEOUS ROCKS

During and after the emplacement of the Boulder bathylith late in Cretaceous time, erosion began to strip off the roof rocks, and to uncover the granodioritic rocks. After the bathylith had been partly uncovered, dacites were erupted in considerable volume; later rhyolites also were erupted and olivine basalt in minor amount.

Table 1.-Parameters of the Boulder bathylith phanerites and associated alkalic rocks

| | $SiO_2$ (percent) | Density | An in plagioclase | Normative | | Differentiation index | Normative color index (weight percent) |
|---|---|---|---|---|---|---|---|
| | | | | Plagioclase | Quartz | | |
| 1 Unionville Granodiorite | 61.14 | 2.78 | 47 | 44 | 15 | 58.1 | 21.6 |
| 1A Granogabbro | 54.63 | 2.84 | 55 | 56 | 8.6 | 41.8 | 28.9 |
| 2 Clancy Granodiorite | 65.49 | 2.71 | 44 | 39 | 22 | 67.3 | 15.0 |
| 3 Porphyritic Granodiorite | 66.14 | 2.70 | 40-20 | 34 | 22 | 71.9 | 10.4 |
| 4 Adamellite | 71.28 | 2.65 | 40 | 29 | 33 | 79.7 | 5.8 |
| 5 Granite | n. d. | 2.61 | 30 | n.d. | n.d. | n.d. | n.d. |
| Syenodiorite | 56.01 | 2.76 | 35 | 31 | 3.0 | 57 | 21.8 |
| Priest Pass Leucomonzonite | 64.13 | 2.66 | 37 | 24 | 11.8 | 79 | 8.7 |
| Nepheline shonkinite | 57.95 | 2.93 | | | | 44 | 48.1 |

### Dacites

Dacites are common throughout the region, chiefly as lavas, dikes, and sills. A mass of biotite dacite vitrophyre (density, 2.37) east of Lenox, characterized by vertical flow structure throughout, is apparently the stump of an old volcano.

The dacite dikes and sills are notable because they generally have black vitrophyric margins. Such margins are as much as 2 feet thick on dikes only 15 feet thick. Most impressive of all is a vertical dike 10 feet thick cutting the Jefferson Formation in Weed siding on the Northern Pacific Railway--it is vitrophyric across its entire thickness.

The dacites contain some thin gold-bearing veins. More important gold veins occur in the thick series of dacites on Lowland Creek (Knopf, 1913), 30 miles southwest of Helena.

No geologic evidence on the age of the dacites, other than that they are postbathylithic, has yet been found. However, the dacites have been correlated with the dacite occurring in the neck of the volcano that makes up Bib Butte at Butte (idem). Dacite from the summit of Big Butte, recently examined by the writer, is an ash-gray rock carrying innumerable small phenocrysts of high-temperature plagioclase ($An_{33}$), quartz, and biotite, which are embedded in a glassy groundmass. Two potassium-argon age determinations on biotite from the dacite have recently become available, one by Baadsgaard and others (1961, p. 697) and the other by Evernden and Curtis; both are 51 million years. This determination, if sustained, would indicate an age about the middle of the Eocene for the dacite eruption at Butte.

### Rhyolites

Rhyolite is widely distributed throughout the region, generally in small masses. The northern end of the Boulder bathylith and the Continental Divide north beyond the bathylith are capped by rhyolite lavas of striking appearance. They are ash-gray rocks carrying phenocrysts of coal-black quartz along with sanidine, sparse plagioclase, and less biotite. The plagioclase is a high-temperature variety of composition $An_{11}$. At the clay pit west of Mullan Pass on the Continental Divide, the rhyolite overlies clay beds of Oligocene age.

Rhyolite breccia has broken through the Flathead Quartzite a few miles east of Helena, where it was formerly quarried as a building stone. The breccia is quite constant in character; it is made of angular fragments; generally 2 to 3 inches long, of flinty blue-gray felsitic rhyolite in a reddish matrix more or less opalized.

Rhyolites are well represented south and east of Montana City as flows, pyroclastics, and plugs. The 4,560-foot peak southeast of Montana City is capped by rhyolite 150 feet thick; the lower part is perlitic obsidian carrying sparse crystals of high-temperature plagioclase ($An_{17}$).

It has been usual to regard all rocks in the region called rhyolite to be contemporaneous, but no proof has been offered that such an age assignment is true.

### Olivine basalt

Olivine basalt occurs at five localities in very minor amount. Glassy olivine basalt (density, 2.78) occurs in two very small areas south of U.S. Highway 12 between Helena and East Helena. A dike of olivine basalt (density, 2.88), 80 feet thick, cuts the Unionville Granodiorite in the low col between Tucker and Holmes Gulches. These examples will suffice.

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