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THE BOULDER BATHYLITH OF MONTANA*

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ABSTRACT. The Boulder bathylith is a large plutonic mass extending 70 miles along the Continental Divide of the Rocky Mountains from Mullan Pass on the north to 20 miles south of Butte, Montana. The present investigation was begun in 1939 but was interrupted by the war years, and has concerned itself mainly with the northern portion of the bathylith and its enveloping rocks.

The rocks invaded by the bathylith range from Beltian (Precambrian) age to late Cretaceous. The youngest prebathylithic rocks consist of andesitic and potassium-rock silicic lavas (dellenites and toscanites) and associated pyroclastics. In part the volcanics were submarine of Niobrara age and in part were erupted subaerially to form welded tuffs, probably in late Montanan time. Shortly after the final volcanism, the first severe Laramide orogenic crisis in this part of Montana set in.

On the basis of a recent potassium-argon age determination, which gave 87 million years as the most probable age of the granodiorite of the Boulder bathylith, it is concluded that the bathylith was emplaced late in Cretaceous time.

The Boulder bathylith has hitherto been considered to be a one-magma intrusion, but like other large plutonic masses it proves to be of composite construction. The order of intrusion is (1) Unionville granodiorite, a basic hypersthene-bearing granodiorite which itself has developed basic facies of granogabbro; (2) Clancy granodiorite; (3) porphyritic granodiorite; (4) biotite adamellite; and (5) muscovitic biotite granite. Alaskite and aplite are abundant and were presumably (but not yet proved) developed most abundantly during the final stages of bathylithic consolidation. The order of emplacement of the successive intrusives is in the order of increasing silicity.

The Boulder bathylith and its satellitic stocks have exerted extensive contact metamorphism, both purely thermal and pyrometamorphic. Most notably, the Helena dolomite has been transformed into aphanitic tremolite-diopside hornfels to a maximum distance of 10,000 feet from the edge of the bathylith. The highest rank of metamorphism attained is in sillimanite-cordierite-micropertchite hornfels, remarkable rocks that have formed at widely separated localities. In places the magma has reacted with limestone xenoliths with the result that the xenolith is surrounded by an aureole of augite granodiorite in place of the normal hornblende-biotite granodiorite. In other places the evidence appears to demand that the magma in depth had dissolved limestone. By this syntexis alkalic rocks were generated that range from mildly alkalic, such as the Priests Pass leucomonzonite and the syenodiorite of the large stock northwest of Helena, to strongly alkalic, as represented by the nepheline shonkinite occurring east of Montana City.

INTRODUCTION

It is customary in a Presidential address to deal with some general problem by way of critical review and synthesis, but I will beg your indulgence this evening if I break with precedent. I propose to discuss some of the problems that I have met in field work on the Boulder bathylith of Montana during the past ten years. In this work I have been indefatigably assisted by Mrs. Knopf, partly in reciprocity I think for having accompanied her in her field work in the Taconic region of eastern New York, which has been a geologic battle ground for nearly 130 years. The Montana work has been done on my own time and expense, except that some of the chemical analyses have been paid for from the research fund of my Sterling Professorship in Yale University.

* Address of the retiring President of the Peninsula Geological Society, Palo Alto, California, May 3, 1956.

sity. Consequently, whatever I am to say this evening has needed only to have the approval of myself.

The Boulder bathylith of Montana is a large plutonic mass of 1100 square miles area that extends 70 miles along the Continental Divide from Mullan Pass on the north to a point 20 miles south of Butte. It was named in 1897 by W. H. Weed of the U. S. Geological Survey, because the region it occupies is drained by the Boulder River and tributaries and because Boulder, the county seat of Jefferson County, is near the center of the bathylith.

The first geologist to have some broad ideas about the great intrusive mass that later was named the Boulder bathylith was Waldemar Lindgren. In 1883 Lindgren was a member of the Northern Transcontinental Survey, which was sponsored by the Northern Pacific Railway. In the course of his work Lindgren examined the northern end of the bathylith near Mullan Pass, which is where the Northern Pacific crosses the Continental Divide. He (Lindgren, 1886) briefly described the granitic rock and recognized that it resembled the Jurassic granite of Nevada as described by Zirkel, the petrographer of the Fortieth Parallel Survey. Furthermore, Lindgren found that coal-bearing beds considered to be of Laramie age rest on the eroded surface of the granite at Mullan Pass. He concluded therefore that the granite was possibly of Jurassic age. Later, in 1891, he conceded that "The possibility is not excluded however that the granite is of very late Mesozoic age".

Possibly at this time there began to develop in Lindgren's mind a bold idea indeed, an idea that has strongly influenced the thinking of many geologists. In 1915 Lindgren expressed the idea thus: "the fundamental fact in the Cordilleran region is that the igneous activity began along the present Pacific coast line and gradually extended eastward". Twenty years later in referring to the Eocene intrusions of the Black Hills in South Dakota, he (1933, p. 158) said that "it is thought that they hail from the same magma which furnished the Coast batholith, its activities gradually spreading eastward".

The first modern geologic work on the bathylith was done by the U. S. Geological Survey near the close of the nineteenth century in connection with studies of the mining districts by S. F. Emmons and especially by W. H. Weed and his assistants, notably Joseph Barrell, at Butte, Elkhorn, Helena, and Marysville. It was soon discovered that the youngest rocks invaded by the bathylith consist of a series of andesitic lava flows and breccias, which form its cover or roof. The andesites were thought to be Eocene and therefore the bathylith was considered to be Miocene. In the first flush of enthusiasm the exciting fact was announced that the intrusive mass had reached within a thousand feet of the Earth's surface (Weed, 1902, p. 452). But greater familiarity with the region destroyed this early confidence and less definite estimates were later reached.

Weed (1899) termed the rock that makes up the bathylith a quartz monzonite, which he regarded as being of very uniform composition throughout its entire area, except at contacts especially with limestone where it is basic. He regarded the bathylith as the result of an intrusion of a single magma, which has locally developed facies. In his final report on the Butte

district, Weed (1912) developed these ideas in somewhat greater detail. These ideas remained the general concept of the Boulder bathylith until the present investigation, which has shown that, like most other great bathyliths, it is a composite mass made up of successive intrusions of differing composition.

In 1911 Dr. Lindgren, who was then Chief of the Metalliferous section and became Chief Geologist of the U. S. Geological Survey in that year, assigned me to a field project in Montana; namely, to make a map of the Boulder bathylith and surrounding area from Marysville on the north to Butte on the south and to prepare a report on the ten mining districts in the region. I was given also a field assistant, Henry G. Ferguson, something I had never had during my five years service on the Alaskan Division; and to have attained to this high privilege gave a great lift to the morale of a young aspiring geologist. At any rate the report was completed early in 1912 and was issued by the Survey in 1913 (Knopf, 1913b).

In retrospect the field season of 1911 has always seemed particularly interesting for a number of reasons, not the least of which was the exhilaration of field work in the summertime of Montana. In 1938 I decided to examine the Boulder bathylith as a possible problem in the mechanics of intrusion. A rapid reconnaissance indicated that its granitic rocks show no density stratification; for example, granodiorite from the top of Colorado Mt. at 7400 feet altitude has a density of 2.71 and similar granodiorite from a depth of 3600 feet in the Stewart mine at Butte has a density of 2.72. It became apparent that in order to begin to understand the bathylith it would be necessary to map it petrographically, which had never been done, and furthermore to determine the stratigraphy of the surrounding strata, their structure, and their contact-metamorphic alteration. The ingrained belief that the Boulder bathylith is a quartz monzonite mass and that therefore all the rock that makes it up and all its satellitic stocks is quartz monzonite has led to the result that on extant maps gabbro, granogabbro, tonalite, granodiorite, adamellite, granite, graphophyre, alaskite, leucomonzonite, syenodiorite, and hornfelses diorite porphyry are all shown as "quartz monzonite". To distinguish these different rocks and to map them is a difficult and time-consuming task and has often proved to be highly frustrating, but if our understanding of the Boulder bathylith is to be increased the task must be done.

In carrying out this mapping a specific gravity balance by which the density of hand specimens could rapidly be determined proved to be indispensable. The specimens collected each day were weighed and their densities determined, and the results served as valuable checks on the field determinations. This was true not only for the igneous rocks but also for the contact-metamorphic and the sedimentary rocks.

THE STRATIGRAPHIC COLUMN

The rocks invaded by the Boulder bathylith range in age from Precambrian to late Cretaceous. The oldest beds are of Beltian age, the Helena region containing many of the type localities of the Belt series as named by Walcott (1899) in his pioneer studies.

The oldest Beltian unit in the Helena region is the Spokane formation comprising argillite and argillaceous siltstone, with sandstone interbeds, generally of some pronounced red color—maroon, brick-red, Indian red, or lavender rose. Presumably, but not surely, four Beltian units occur below the Spokane formation, as the Helena region is 60 miles west of where the Neihart quartzite, the lowermost Beltian formation, crops out.

Above the Spokane is the Empire formation, also named by Walcott; it is 1000 feet thick and consists of pale-green argillites alternating with mud-cracked rose or lavender argillites.

Overlying the Empire formation is the Helena dolomite (Knopf, 1950, p. 837-838), originally named Helena limestone by Walcott. It consists mainly of 4000 feet of buff-weathering siliceous dolomite. A chemical analysis of a representative sample of the dolomite is given in table 1. Limestone and mixed carbonate rocks occur in minor amounts. Remarkable algal reefs up to

TABLE 1
Analyses of Helena Dolomite and Other Rocks
from the Helena Region, Montana

	I	II	III	IV	V
SiO ₂	32.88	71.81	65.50	70.15	65.09
Al ₂ O ₃	3.48	14.63	16.84	14.41	14.20
Fe ₂ O ₃	.16	.82	1.62	1.68	.87
FeO	1.93	.84	1.44	1.55	1.10
MgO	12.89	.37	.77	.63	.43
CaO	18.42	1.21	1.60	2.15	5.00
Na ₂ O	.73	4.02	4.58	3.65	2.60
K ₂ O	.60	4.81	6.07	4.50	.76
H ₂ O+	.72	.33	.20	.68	6.38
H ₂ O-	.09	.04	.03		2.36
TiO ₂	.14	.37	.57	.42	.47
P ₂ O ₅	.05	.05	.18	.12	.08
CO ₂	27.71	.24	.07		.05
MnO	.10	.08	.11	.06	.04
SrO		.02	.06		
BaO		.13	.15		.17
S			.03		
F					.05
	99.90	99.77	99.82	100.00	99.65
		Less O=S	.01	Less O=F	.02
			99.81		99.63
d	2.78	2.63	2.65		2.38

I Helena dolomite; west of B. M. 4450, Scratchgravel Hills. Analyst, E. H. Oslund.

II Dellenite; north of Moose Creek, Tenmile Creek. Analyst, J. J. Engel.

III Dellenite vitrophyre welded tuff; Continental Divide, north of MacDonald Pass. Analyst, Doris Thaemlitz.

IV Average dellenite; compiled by Nockolds (1954).

V Obsidian-like welded tuff; Great Northern Railway quarry, Wolf Creek. Analyst, E. H. Oslund.

15 feet thick and traceable for thousands of feet along the strike occur from the bottom to the top of the Helena dolomite. See plate 1. Algal growths of this kind were originally called cryptozoons by Walcott, but in 1914 he renamed the genus *Collenia*, after M. Collen, of White Sulphur Springs, Mon-

PLATE 1

Collenia, in the Helena dolomite.



A. Third biostrome from top in a succession of four biostromes occurring through a stratigraphic thickness of 75 feet. North side of Cherry Valley, northwest of Helena.



B. Largest *Collenia* so far found in the Helena dolomite. Bedding dips 15°E. West side of ridge on west side of Broadwater Gulch, 2 miles west of Helena.

tana, who had supplied him with much material. They were reported to be abundant in the Newland limestone (considered to be stratigraphically far below the Helena dolomite) from base to top, and to occur in the Spokane "shales", but were not mentioned as occurring in the Helena dolomite. The presence of *Collenia* reefs or biostromes throughout the entire 4000 feet of the Helena dolomite indicates that the beds accumulated in a shallow basin never deeper than the depth at which photosynthetic activity was possible.

Overlying the Helena dolomite is the Marsh formation, 3000 feet thick (Knopf, 1950, p. 838). It consists of deep-red argillites, mud-flake breccias, and quartzites. Casts of salt crystals occur locally, and this is probably the one distinctive feature of the Marsh formation. Above the Marsh, forming the topmost member of the Belt series in this region is a quartzite belt 1800 feet thick, which has been named the Greenhorn Mountain quartzite (Knopf, 1950, p. 839), from the great mountain forming the Continental Divide north of Mullan Pass.

The Belt series in this region aggregates 12,000 feet in thickness and is unmetamorphosed except near the Boulder batholith.

The Paleozoic begins with the Flathead quartzite of Middle Cambrian age. Between the Flathead and the Precambrian there is widespread disconformity. At the Continental Divide the Flathead quartzite rests on the Greenhorn Mountain quartzite; eastward at Helena it rests on Helena dolomite; still farther east, in the Belt Mountains, the Helena dolomite has been thinned to a feather edge. At least 5000 feet of strata were removed by erosion in the Helena region before the Flathead quartzite was laid down. Deiss (1940, p. 1092) thinks that 20,000 feet were removed, his argument being in part that mild orogenic activity and epeirogenic uplift took place in post-Beltian time, whereby mountains, which he called the Helena Mountains, were formed. These mountains according to Deiss were reduced to a peneplane before the deposition of the Flathead quartzite in Middle Cambrian time. The important evidence adduced by Deiss that extended erosion took place between the end of Beltian deposition and the beginning of Paleozoic sedimentation is one of several powerful reasons for not accepting the statement often made in regard to the Beltian geosyncline that a geosyncline can subside to a depth of 70,000 feet before it is subjected to orogenic appression.

The post-Beltian section, extending from Middle Cambrian to late Cretaceous, is 9000 feet thick. It is not the result of continuous sedimentation, however, for at least two long interruptions occurred. The first break lasted from the end of the Cambrian to late Devonian time. The second interruption lasted from late Permian to middle Jurassic time. During the second interval the region was reduced to a peneplane, according to Condit (1918) and Collier (1927).

Marine sedimentation began again late in Middle Jurassic time, signified by the deposition of the Ellis group. This event is held to mark the beginning of a new geosyncline, originally called Coloradoan by Schuchert (1939) and later renamed Rocky Mountain geosyncline by Dunbar (1949):

In Colorado time rhyolite tuff was erupted, which marked the beginning of volcanism in this part of the Rocky Mountain geosyncline (Lyons, p. 451).

Later in the Cretaceous a thick series of andesites and latites was poured out. Eruption took place under submarine conditions, as shown by marine fossils found in the associated tuffs on Indian Creek on the east flank of the Elkhorn Mountains. These fossils were kindly determined for me in 1947 by Dr. J. B. Reeside, who identified them as of Niobrara age.

Volcanism was later renewed subaerially. During this second episode andesites were erupted as well as abundant highly flow-banded rocks that resemble sparsely porphyritic biotite andesites, "pheno-andesites". They carry scattered phenocrysts of andesine (An_{40}) and a few of biotite. They correspond to dellinite, as shown in table 1. Many of them are welded tuffs. A chemical analysis of a black vitrophyric welded tuff of dull pitchy luster from the Continental Divide north of MacDonald Pass is given in table 1 (analysis III). It proves to be unusually high in K_2O —6.07 per cent. It corresponds closely in chemical composition to the silicic extrusive named toscanite by Washington (1897, p. 37), but called rhyodacite, quartz latite, dellinite, subaluminous rhyolite, as well as other names by other petrographers. Its chemical composition corresponds to that of an orthoclase-rich quartz latite but neither orthoclase nor quartz have developed modally.

That welded tuffs were formed during the second period of volcanic activity in late Cretaceous time proves that the eruptions of this period, in contrast to the earlier submarine outbreaks, took place under subaerial conditions. In the Adel Mountain volcanics, a series of potash-rich lavas occurring on the Missouri River north of the Boulder bathylith, I found brilliantly vitreous obsidian-like welded tuffs (Barksdale, 1951). An analysis is given in table 1 (analysis V); it shows that the analyzed rock is of unusual composition and indicates that further investigation of the Adel volcanics is necessary. The obsidian-like welded tuffs are associated with green and purple lithoid welded tuffs. These volcanics had earlier been mapped by Pardee and Schrader (1933) as part of the "andesite-latite" series that consists of the youngest rocks invaded by the Boulder bathylith. This correlation is probably strengthened by finding that welded tuffs occur both in the roof rocks of the bathylith and in the Adel Mountain volcanics. The correlation is of particular significance, as Lyons (1944, p. 460) found leaves in the Adel Mountain volcanics, from which their age is inferred to be very late Cretaceous, probably late Montanan. The major diastrophism, as emphasized by Lyons, took place after, presumably soon after, the eruption of the Adel Mountain volcanics.

ONSET OF THE LARAMIDE OROGENY

The main deformation that has affected the region now set in, presumably, as just mentioned, shortly after the final volcanism. It was the first severe Laramide orogenic crisis in Montana. The Beltian, Paleozoic, and Mesozoic rocks, including the youngest volcanics, were folded, involving a thickness of 20,000 feet or more. These rocks had accumulated in three geosynclines, currently named the Beltian, Cordilleran, and Rocky Mountain. The Beltian and Cordilleran geosynclines were of the kind called miogeosynclinal. The Rocky Mountain geosyncline, however, which began its life late in the Jurassic and ended late in the Cretaceous after the eruption of the two series of volcanic

rocks just mentioned, was manifestly pliomagmatic in this part of Montana and can probably qualify as a eugeosyncline.

The regional folding was of an open character, with the resultant folds trending northwest. The folding was followed or accompanied by the intrusion of the Boulder bathylith, which was emplaced in successive pulses or surges of magma of differing compositions.

Near the bathylith the invaded country rock has been more closely folded than at a distance from the contact. In places the strata adjacent to the bathylith stand vertically and have even been overturned. Locally a series of reverse faults has developed along the eastern border of the bathylith. The intrusive magma manifestly has made room for itself partly by crowding aside the enveloping rocks, by close appression of the beds, by overturning them, and by imbricate high-angle thrusting.

To Stille (1940, p. 264) the intrusion of the Boulder bathylith was the result of "allochthonous synorogenic plutonism fed by the lateral migration of sialic magma." The magma had migrated from the west in the direction of the eastward progression of folding. The feebler intensity of folding in the Rocky Mountains compared to the Nevadan folding farther west precluded the possibility of autochthonous synorogenic plutonism. So, says Stille, "I have come by way of magmatectonic considerations to a conclusion that Lindgren had formulated from a more mineralogic-petrographic viewpoint."

SATELLITIC STOCKS

Some 20 stocks occur in proximity to the northern end of the Boulder bathylith. They comprise a wide range of petrographic types: olivine-orthoclase gabbro, diorite, tonalite, adamellite, granodiorite, granite, alaskite, syenodiorite, and diorite porphyry. Every one of them presents this problem: (1) was it emplaced before the intrusion of the bathylith or (2) was it emplaced during the intrusion of the bathylith, and if so, with which surge of magma; or (3) was it emplaced long after the intrusion of the bathylith? Most of the stocks appear to be genetically related to the bathylith, but to have been emplaced at different stages in its history. The best known of the satellitic stocks is the Marysville granodiorite stock. In an earlier paper I have discussed in detail the problem of determining that the Marysville stock is genetically allied to the Boulder bathylith (Knopf, 1950). The largest stock is the Scratchgravel Hills stock, 8 square miles in area, which forms the group of hills northwest of Helena, rising out of the great circular intermontane depression known as the Helena Valley. It proves to be an anorthoclase syenodiorite of weakly alkalic character. Its chemical composition is shown by analysis VII in table 2.

Recently Rittman (1953) has shown that from the chemical analysis of a rock can be calculated an index "p", which gives a measure of the alkalicity¹ of the rock. The dividing point between lime-alkalic and alkalic rocks is at 55; values between 50 and 55 indicate a weakly alkalic character, and values between 55 and 60 indicate a weakly lime-alkalic character. The value of the ¹ "Alkalicity" is suggested as a more appropriate term than "alkalinity", which is a chemical term and is measured by pH.

TABLE 2
Analyses of Plutonic Rocks of the Boulder Bathylith and Two Related Stocks

	I	II	III	IV	V	VI	VII	VIII	IX	X
SiO ₂	61.14	61.40	54.63	65.49	66.14	71.28	68.48	56.01	64.13	51.95
Al ₂ O ₃	15.28	15.41	16.60	14.49	15.69	14.50	14.93	17.84	16.77	12.58
Fe ₂ O ₃	1.90	2.26	3.32	2.11	1.93	1.04	1.32	3.56	1.96	3.12
FeO	4.52	3.76	5.62	2.90	2.06	1.19	2.07	3.05	1.69	3.91
MgO	3.41	2.99	4.65	2.45	1.60	.98	1.37	2.57	1.29	5.61
CaO	5.51	4.86	7.93	4.29	3.71	2.45	2.61	7.39	2.72	13.00
Na ₂ O	2.78	2.69	2.48	2.80	3.50	3.16	3.01	4.01	3.92	2.85
K ₂ O	3.34	4.12	2.10	3.66	3.54	4.29	4.59	3.33	5.77	4.61
H ₂ O+	.65	.55	.85	.56	.47	.43	.60	.61	.39	.76
H ₂ O-	.09	.18	.14	.05	.05	.13	.12	.24	.19	.03
TiO ₂	.82	.80	.89	.65	.43	.26	.39	.65	.52	.55
P ₂ O ₅	.26	.25	.42	.21	.24	.09	.17	.42	.23	.46
CO ₂	.08	.07	.02	.05	.08	.10	.31		.02	
MnO	.12	.09	.16	.10	.10	.06	.07	.19	.05	.14
SrO	.04	.07	.04	.04	.08	.02	.02	.10	.02	.06
BaO	.08	.12	.05	.05	.13	.11	.11	.12	.10	.05
S	.01	.02	.04	.01	.03	.01			.01	.01
		99.65	99.94		99.74					
Less O = S		.02	.02		.01					
Total	100.03	99.64	99.94	99.91	99.73	100.10	100.17	100.09	99.78	99.88
d	2.78	2.76	2.84	2.71	2.70	2.65	2.67	2.76	2.66	2.93

I Unionville granodiorite; type locality, old quarry 0.9 mi. NW of BM4589, Clark Gulch. Analyst, J. J. Engel.

II Unionville granodiorite; near Benson xenolith. Analyst, Doris Thaemlitz.

III Granogabbro; at contact NW of Park City. Analyst, Doris Thaemlitz.

IV Clancy granodiorite; Kain quarry, Clancy Creek. Analyst, J. J. Engel.

V Porphyritic granodiorite; Schimpf quarry, 7 mi. W of Helena. Analyst, Doris Thaemlitz.

VI Biotite adamellite; ridge between Jackson Creek and Lump Gulch. Analyst, J. J. Engel.

VII Biotite adamellite; Broadwater stock, Helena. Analysts, B. Smith and R. B. Ellestad.

VIII Syenodiorite; old quarry near Great Northern Railway, Scratchgravel Hills, Analyst, L. C. Peck. SrO determined by S. S. Goldich.

IX Priests Pass leucomonzonite; road cut just west of Priests Pass. Analyst, H. Baadsgaard.

X Nepheline shonkinite; 3/4 mi. southeast of Montana City. Analyst, H. Baadsgaard.

alkalicity index for the syenodiorite is 53.8. For the prevailing rocks of the Boulder bathylith the value averages around 62.

This stock of syenodiorite is the first recorded occurrence of alkalic rocks in association with a large mass of ordinary lime-alkali rocks within the Rocky Mountains of Montana. East of the Rockies is the remarkable alkalic province of the Highwood Mountains made famous by Pirsson (1905) and by Larsen (1940).

AGE OF INTRUSION OF THE BOULDER BATHYLITH

The time of intrusion of the Boulder bathylith has been narrowed down somewhat in recent years. In the marine volcanic tuffs on Indian Creek fossils

were found, which as already mentioned, are of Niobrara age, i.e., of late Colorado age. By correlation of the welded tuffs in the roof of the bathylith with the welded tuffs in the Adel volcanics, a very late Montanan or possibly post-Montanian age is indicated for the youngest rocks invaded by the bathylith.

In the southwestern Montana, according to Eardley (1951), the first main phase of the Laramide orogeny took place in latest Cretaceous or early Paleocene time. As a result of this orogeny the very coarse and thick Beaverhead conglomerate was laid down. The Beaverhead conglomerate makes up the greater portion of the Beaverhead formation, of exposed thickness of 9700 feet, and according to Lowell and Klepper (1953) the middle portion of the formation is tentatively indicated on the basis of fossil fresh-water gastropods to be of early Paleocene age.

By the beginning of the Oligocene the bathylith had been deeply uncovered by erosion, for at Pipestone Springs, east of Butte, beds carrying a well-defined vertebrate fauna of earliest Oligocene—Chadronian—age (Wood et al., 1941) rest on the surface of the granodiorite. So far as the geologic evidence goes, the bathylith was emplaced sometime between late Cretaceous and the beginning of the Oligocene.

Five determinations of the absolute age of the Boulder bathylith have recently been reported by Chapman, Gottfried, and Waring (1955). They are based on alpha-counting and measurement of the lead content of zircon and monazite obtained from rocks of the Boulder bathylith. The reported ages range from 62 to 72 million years. Dr. J. H. Reynolds, of the Physics Department of the University of California at Berkeley and Dr. R. E. Folinsbee, of the University of Alberta, have kindly determined for me, by the potassium-argon method, the age of the granodiorite that makes up the larger part of the Boulder bathylith (Knopf, 1956). Dr. Reynolds reports "that the most probable age is 87 million years". This potassium-argon age determination suggests that the Boulder bathylith was emplaced late in the Cretaceous; consequently during the first main phase of the Laramide orogeny. The time of intrusion cannot be placed closer in the absolute geologic time scale however, until agreement is reached on what strata mark the end of the Cretaceous and until we have a definitive determination of the absolute age of those strata, be they topmost Maestrichtian or topmost Danian.

COMPOSITE NATURE OF THE BATHYLITH

The Boulder bathylith has heretofore been considered to be a one-magma bathylith. As the present mapping proceeded it became clear, however, that the bathylith was built up by successive intrusions, which arrived in place according to the well-known order of increasing silica content. In short, the bathylith proves to be a composite mass that has been built up by five or more magmas arriving one after the other in what the evidence suggests was a geologically short time.

Unionville granodiorite.—The earliest intrusion is a basic granodiorite. It is dark, heavy, and resembles a diorite. Neither quartz nor potassium feldspar are visible to the unaided eye, but as seen under the microscope enough po-

tassium feldspar and quartz (15 percent) are present to allow the rock to qualify as a granodiorite. It is a hypersthene-bearing augite-biotite-hornblende granodiorite. A chemical analysis of the type rock is given in table 2.

There are at least seven definitions of granodiorite: by Lindgren (1900), Iddings (1913), Niggli (1931), Johannsen (1932), Tröger (1935), Hatch, Wells, and Wells (1949), and Nockolds (1954), but none agrees fully with any other. Niggli and Johannsen agree in drawing the line between granite and granodiorite so that granites are distinguished by having potassium feldspar predominate over plagioclase and granodiorite by having sodic plagioclase predominate over potassium feldspar. This usage has the advantage of simplicity, and as pointed out by Johannsen (1932) makes the Brögger term quartz monzonite [= adamellite] superfluous.

Nockolds (1954) in a notable paper giving newly computed average chemical compositions of igneous rocks presents a tabular classification of igneous rocks. He distinguishes adamellite from granodiorite as follows: adamellite has a potassium feldspar content between 60 percent and 40 percent of the total feldspar content, whereas granodiorite has a potassium feldspar content between 40 percent and 10 percent of the total feldspar. In accordance with Tröger and Shand, 10 percent is taken as the lower limit for the quartz content of granite, adamellite, granodiorite, and tonalite.

These definitions appear to be logical; furthermore they embody the greatest measure of agreement so far reached and will therefore be used in describing the granodiorite and allied rocks of the Boulder bathylith.

The basic granodiorite is well exposed south and southeast of Helena. Hence it is proposed to call it the Unionville granodiorite, from a small village south of Helena. Near the contact it develops a basic facies having the high density of 2.85 or more. Its chemical analysis is given in table 2 (no. III). Petrographically the facies proves to be a hypersthene granogabbro, granogabbro being the name given by Johannsen (1932, p. 367) to the orthoclase-bearing variety of quartz gabbro. At many places the granogabbro and granodiorite contain numerous large plates of poikilitic biotite 1 to 3 cm. in diameter, the result of biotitization. That is, the biotite continued to grow after the other constituents had ceased growing, and has spread out at the expense of the plagioclase. This continued growth of the biotite is interpreted as a magmatic end-stage reaction or deuteritic effect. It has produced very striking-looking rocks of coarsely poikilitic habit, much more "basic" in appearance than they really are.

Clancy granodiorite.—The second intrusion is the Clancy granodiorite, so named from the Kain quarry on Clancy Creek. It is a coarse-grained rock in which quartz is conspicuous. Its chemical analysis is given in Table 2 (no. IV). The earlier, Unionville granodiorite had already solidified and was cut by dikes of the younger invading magma, as is well shown on the summit of Colorado Mountain (plate 2). The Clancy granodiorite is not perceptibly chilled against the earlier granodiorite. However, the light-gray color of the younger, Clancy granodiorite contrasts strongly with the dark gray of the earlier, more basic, granodiorite. The Clancy granodiorite is in appearance, density, and chemical composition like the bathylithic rock at Butte, the so-



Clancy granodiorite (light gray) cutting the Unionville granodiorite, which is the earliest intrusive of the Boulder batholith. Summit of Colorado Mountain.

called Butte quartz monzonite. The naming of the Butte rock has had a remarkable history. Originally named the Butte granite by S. F. Emmons (1888), it continued to be called so by Weed in the Butte Special Folio (1897), for the reason that "thin sections of the rock studied under the microscope show that orthoclase is the most abundant mineral, and that the rock is therefore a granite." At the same time however, Weed recognized that the chemical analyses, of which four were available, "closely resemble those of the granodiorites of the Gold Belt of California". Later, Weed (1899) renamed the "granite" of Butte "quartz monzonite," without much explanation.

Subsequently detailed work was done by Cross, Iddings, Pirsson, and Washington (1903) on the microscopical petrography of the Butte "granite". Two thin sections of the granite, one from rock near the Parrott vein and the

other of unknown provenance, were measured according to the Rosiwal method, with closely agreeing results. They found that the zoned plagioclase, considered to average An_{40} in composition, amounted to 41.98 percent by weight and the orthoclase to 18.7 percent. Consequently, if they had followed the proposal of Lindgren (1900) to redefine granodiorite as having sodic plagioclase characteristically "at least double the amount of the alkali feldspar," they would have called it granodiorite; however, they remained content to refer to it as "granite". They computed also the mineral composition of the "granite" at Walkerville, on the north edge of Butte, which as well as its hornblende and biotite had been chemically analyzed. This computation also showed that the amount of plagioclase (An_{40}) is more than double the orthoclase.

Despite this demonstration, Weed (1912, p. 32) in his final memoir on the Butte district reaffirmed that the rock at Butte is a quartz monzonite, because "thin sections of the rock studied under the microscope show that the orthoclase and plagioclase feldspars are present in nearly equal amounts, so that the rock according to precise petrographic nomenclature should be called a quartz monzonite".

An attack from another angle on the use of the term quartz monzonite comes from a detailed restudy of the rocks of the type area Predazzo-Monzoni, in the Tyrol (Leitmeier, 1940). He affirms that Brögger ought not to have proposed to use "quartz monzonite" for rocks other than those called quartz monzonite by Romberg and by Rosenbusch, which are rocks that contain not over 5 percent of quartz. All the quartz monzonites in Predazzo-Monzoni according to Leitmeier (1940, p. 180; 1948, 79-81) "are true monzonites and have no kinship with the quartz-rich alkalicalcic granitic rocks of Walkerville, Butte, Montana, erroneously called quartz monzonite".

Porphyritic granodiorite.—The third intrusion is here called the porphyritic granodiorite. It is characterized by its content of orthoclase phenocrysts an inch in length and 1/2 inch across. It is more constant in composition (table 2, no. V) than any of the other intrusive masses that make up the batholith. Its average density is 2.68, the range being only from 2.71 to 2.65. The plagioclase is zoned from An_{35} in the core to An_{20} in the peripheral zone. Granodiorite of this kind extends to Mullan Pass, the northernmost limit of the batholith.

The position of the porphyritic granodiorite as the third member in the intrusive sequence remains so far inferential, as critical contacts have not been found.

Biotite adamellite.—The fourth intrusion is a "white granite", as it was called in the field; petrographically, however, it is a biotite adamellite. It is definitely intrusive into the Clancy granodiorite, and a dike 5 feet thick was found to cut the Clancy granodiorite. The dike has unchilled borders, so manifestly no great interval of time separated the successive intrusions.

In chemical composition the adamellite (table 2, no. VI) is almost identical with that of the average biotite adamellite as recently computed by Nockolds (1954). The adamellite is higher in silica (71.3 percent), much higher in quartz, and is lower in density (2.65) than the earlier intrusives.

The plagioclase is An_{40} however, like that in the porphyritic granodiorite. Therefore the evolution of the bathylith as measured by the anorthite content of the plagioclase did not advance during the interval between the third and fourth intrusives. In terms of the ferromagnesian minerals, however, the evolution had advanced so far that only biotite was crystallizing from the magma. The type locality is on the ridge between Jackson Creek and Lump Gulch. Large masses occur on Clancy Creek; on U. S. Highway 91 south of the Helena-Boulder divide; and along U. S. 10S from one mile east of Pipestone Pass to the water fountain on the west side of the Continental Divide.

Biotite granite.—The fifth intrusive is a medium-grained biotite granite low in plagioclase (An_{30}). Muscovite is generally present, but it is all of replacement origin and is probably deuteric. This granite ($d = 2.61$) forms relatively small masses and clearly intrudes the Clancy granodiorite, into which it sends dikes. It is in places remarkably and conspicuously tourmaliniferous, being crowded with tourmaline nodules, each nodule being surrounded by a white border 1 cm. wide. These features are spectacularly developed near Montana City southeast of Helena. Younger than the muscovite-biotite granite are aplite dikes up to 40 feet thick, cutting both the granite and the country rock. The aplites are highly tourmaliniferous, the tourmaline occurring both in disseminated form and localized along fractures.

The muscovite-biotite granite was mapped by previous investigators as aplite. The discovery that it is itself cut by dikes of genuine aplite ($d = 2.59$) is therefore significant and proves that these aplites represent a still more advanced stage in the evolution of the bathylith.

Alaskite and aplite (aplite might well be called microalaskite) are common throughout the area of the Boulder bathylith. In fact, aplite has been estimated by one investigator (Knopf, 1913b, p. 34) to make up 5 percent of the exposed area of the bathylith and 10 percent by another investigator (Billingsley, 1915); but these estimates were not supported by areal mapping or by precise petrographic knowledge. Alaskite and aplite have doubtless been formed during each of the five recognized stages of the development of the bathylith, but they appear to have been more abundantly developed in connection with the later, more silicic intrusives. Inasmuch as an aplite, regardless of which of the five intrusive masses to which it is genetically linked, represents an ultimate stage in differentiation, it was of interest to compute the new alkalinity index for the granodiorite at Walkerville, Butte, containing 63.88 percent of SiO_2 , and for the aplite (76.87 percent of silica) cutting it. For both these rocks excellent chemical analyses are available. The indices prove to be almost identical (61.1 for the granodiorite and 60.4 for the aplite), and indicate therefore that the extreme differentiation necessary to produce the aplite has not changed the value of the alkalinity index.

ABERRANT INTRUSIONS

The five intrusions, ranging from Unionville granodiorite to muscovite granite, constitute the normal stages of the evolving bathylith. Some other masses represent unsolved problems.

One such mass occurs at Priests Pass just south of Mullan Pass, and is unlike the rocks already described. It is of monzonitic composition nearly

devoid of quartz and has but a very moderate content of biotite and hornblende. It is here called "Priests Pass leucomonzonite." Its chemical composition is given in table 2 (no. IX). The contact between the leucomonzonite and the porphyritic granodiorite is cleanly and perfectly exposed southwest of Austin, and gives convincing evidence that the leucomonzonite is not a facies of the granodiorite. Inasmuch as neither rock is chilled or otherwise modified against the other, the time sequence remains unknown.

Another mass but different from the Priests Pass leucomonzonite, constitutes the high mountainous portion of the bathylith south and east of Helena. It consists of a darkish granitic rock resembling to the eye the Unionville granodiorite. Unexpectedly it proved to be, as seen under the microscope, a graphophyre, or "granophyre", with phenocrysts of labradorite and pyroxene in a superbly developed groundmass of micropegmatite. In reference to "granophyre", Michel-Levy (1889, p. 19) said that the name "me paraît aussi mal choisi que possible pour représenter des roches dont le magma présente les formes de la pegmatite graphique." No other rock mass of this kind has previously been reported from the Boulder bathylith.

The position of the graphophyre in the intrusive sequence is only partly known: it cuts the earliest intrusive, the Unionville granodiorite, in dikes and is itself cut by tourmaliniferous aplite. Mapping the graphophyre has proved to be an exacting and nearly impossible task.

CONTACT METAMORPHISM

The metamorphism exerted by the Boulder bathylith on its enveloping rocks is a notable feature. According to Billingsley however, (1915, p. 47), "the intrusion produced only slight metamorphic effects", and Grout and Balk (1934) wrote "For a coarse-textured intrusive with an area of about 1200 square miles, the zone of prominent contact metamorphism is remarkably narrow—at some places it is hardly recognizable". To which the answer can be made "Never underestimate the power of a bathylith".

The voluminous development of calc-hornfels in the contact zones is impressive. The calc-hornfels occur in nine formations at least, ranging from the Precambrian Empire formation to the Cretaceous. They are white, light-gray, or creamy-colored aphanitic rocks of chert-like aspect. They consist of diopside and tremolite, and subordinate scapolite. The Helena dolomite has furnished the largest amount of calc-hornfels, extending as far as 10,000 feet from the visible contact. Despite the drastic metamorphism, the weathered outcrops of hornfelsed Helena dolomite retain completely the innocent appearance of normal sedimentary rocks (plate 3).

An intensive study was made of the contact zone that surrounds the Broadwater stock in the western outskirts of Helena. Here the Helena dolomite has been transformed into an aureole of aphanitic calc-hornfels (or better calc-magnesian hornfels) that encircles the stock and ranges from 300 to 2500 feet in width. The chief minerals are diopside and tremolite, with wollastonite occurring only at the immediate igneous contact. In the outer fringe of the aureole sodic scapolite and the white chlorite, leuchtenbergite, have developed. A bed of wholly unmetamorphosed blue oölitic limestone occurs well



Calc hornfels (hornfelsed Helena dolomite) in the contact-metamorphic aureole of the Broadwater stock, showing retention of bedding and sedimentary appearance. Four miles west of Helena, on U. S. Highway 10N. Photograph by Geo. Switzer.

within the contact zone, where it is intercalated between rocks completely altered to calc-hornfels; this intimate association of unaltered and completely altered rocks emphasizes vividly that dolomite is enormously more susceptible to thermal metamorphism than limestone.

The widespread development of these calc-hornfels by the Boulder batholith and its satellitic stocks strikingly illustrates the principle of dedolomitization announced by Teall (1903)—namely that during metamorphism of dolomite the magnesium is liberated as periclase (MgO), or if silica is available the magnesium is preferentially silicated, resulting in the liberation of calcium carbonate.

Cordierite hornfels is another notable feature of the contact metamorphism. No less than seven formations have developed cordierite hornfels. The most striking development is shown by the Park argillite, 200 feet thick, which mile after mile has been converted solidly into cordierite hornfels. A show-place is east of Austin on the Mullan Pass highway. Large blocky outcrops of massive black rock resembling a basic igneous rock occur here. On lightly weathered surfaces of the hornfels the cordierite resembles wheat grains or fusulines, but on strongly weathered surfaces the cordierites have been etched out and the hornfels closely simulates a vesicular basalt. Among the many geologists to whom I have shown this cordierite hornfels was Prof. Goodspeed, of the University of Washington, who took back to the University a cubic foot or so. On the field trip during the Butte meeting of the Rocky Mountain section of the Geological Society of America in 1953 this show place was one of the stops. The geologists present were much impressed by the cordierite hornfels, but a group of graduate students from the University of Washington were particularly interested: they saw at last what the rock they had been calling vesicular basalt in their PhD orals really was and where it came from!

The highest rank of metamorphism attained by any of the rocks in the contact zone is represented by sillimanite-micropertthite-cordierite hornfels. These are notable rocks in which the sillimanite occurs in minute gleaming prisms in random arrangement, and the micropertthite is distinguished for its regular, evenly distributed, delicate exsolved discs of albite. Probably on further study this micropertthite will serve as a better geologic thermometer than the sillimanite. These rocks occur only in roof pendants or in immediate contact with the bathylith, and although they have been found at widely separated localities they occur only near the contacts with the Unionville granodiorite, the earliest and presumably the hottest intrusion.

REACTION OF THE BATHYLITH WITH THE COUNTRY ROCKS

On my preliminary examination of the bathylith I found a large perfect exposure of a portion of its extreme northern contact. A broad apophysis of the porphyritic granodiorite extends conveniently across the Mullan Pass Road into the Madison limestone. The granodiorite in this apophysis, even at the borders and tip of the apophysis, is completely normal, its density is unchanged, its orthoclase phenocrysts are present in normal fashion—manifestly, the magma absorbed no limestone, nor has it been basified or otherwise changed. The Madison limestone has been transformed to a diopside-bearing marble, which also is the normal behavior: diopside at the immediate contact with the bathylith, tremolite at a greater distance. Only later did it become plain that the magma has in other places reacted with limestone, with results of a remarkable character and of great diversity. “Never underestimate the power of a bathylith”—this was learned the hard way.

At five widely separated localities magma and limestone have reacted with striking results.

The first example is at the Benson ranch, southeast of Helena. At this locality a xenolith, 40 feet long and 20 feet wide at most, is enclosed in the Unionville hornblende-biotite granodiorite. As shown by its chemical analysis

in table 2 (no. II), the granodiorite has closely the composition of the Unionville granodiorite at the type locality; its density is 2.76 and its plagioclase has the composition An_{41} . The xenolith is made up mainly of andradite, pyroxene, epidote, and minor highly calcic plagioclase (An_{80-90}). The granodiorite that surrounds the xenolith is lighter-colored than the normal granodiorite to a distance of 40 feet from the xenolith and is characterized by numerous patches of poikilitic orthoclase. Unexpectedly, this lighter-colored granodiorite has the high density of 2.90 next to the xenolith and shades off farther away to 2.80. The increased density is due to a high content of augite in place of hornblende and biotite. These relations are interpreted thus: the xenolith originally consisted of limestone or dolomite; part of it was dissolved by the magma; and the resulting increase of CaO and MgO in the magma suppressed the formation of hornblende and biotite and caused augite to form in their stead, and the potash that would have gone to make biotite was used to form the poikilitic orthoclase. In short, an augite granodiorite was formed instead of a hornblende-biotite granodiorite. Remarkably, the augite granodiorite in immediate contact with the tactite has a plagioclase of composition only as calcic as An_{50} , whereas the plagioclase in the tactite has the composition An_{80} . Finally, after the augite granodiorite had consolidated, pyrometasomatic activity ensued and converted the residual portion of the xenolith into a tactite composed of clinopyroxene (aegirine-augite), andradite, bytownite, and epidote. Minor actinolite, quartz, calcite, magnetite, and analcite and traces of pyrite also occur. The andradite has replaced clinopyroxene, and epidote has replaced both clinopyroxene and andradite, and has spread in very minor amount into the adjacent augite granodiorite.

Apparently the effect of the assimilation of limestone by the granodiorite magma at the Benson xenolith is somewhat analogous to phenomena at Tennberg, Sweden, described by von Eckermann (1923). There the granite adjacent to a limestone xenolith was rendered non-biotitic for a distance of 200 feet from the xenolith. But instead of augite having formed as the result of the addition of lime to the magma as in Montana, the hastingsite variety of hornblende was formed. Tilley (1949) also has found that at dolomite skarns the hornblende and biotite of the adjacent granite have given place to clinopyroxene. The suppression of biotite is probably the result of the strong affinity of lime for alumina to form the anorthite molecule; as long as any free lime was present in the magma biotite could not form.

More spectacular effects than at the Benson xenolith were produced at a xenolith or roof pendant east of Montana City. This xenolith consists of limestone and is 150 feet long by 30 feet wide at its widest portion. Attention was directed to this xenolith by the wollastonite and coarse yellow vesuvianite that form large masses gorgeously colored in the brilliant light of a Montana summer. Less conspicuous associates are grossularite and diopside. One end of the xenolith, the south end, has been converted solidly into pyrometasomatic rock, whereas the north end still consists of bedded limestone. The pyrometasomatic rock is traversed by dikes of nepheline shonkinite, plagioclase shonkinite, and allied rocks.

Chemical analysis of the nepheline shonkinite (table 2, no. X) shows that it is like that of the type shonkinite from Square Butte in the Highwood Mountains and that at Shonkin Sag, Montana. The alkalinity index of the nepheline shonkinite is 42, confirming, if that were necessary, its highly alkalic character. Here then is powerful support for Daly's theory that alkalic rocks are generated from lime-alkalic magmas by the absorption of limestone. You will recall that Dr. Tilley (1931) found at Scawt Hill, Ireland, that nepheline-bearing rock had been formed in a contact zone by reaction of a dolerite dike cutting chalk, the first field demonstration of the probability of Daly's theory of the origin of alkalic rocks by absorption of limestone. When I showed Dr. Tilley the Montana occurrence he exclaimed "you have found the underground equivalent of Scawt Hill". It must be admitted, however, that the place where the nepheline shonkinite magma was formed is still deeper underground.

This formation of shonkinite east of Montana City as a reaction product between granodiorite magma and carbonate rock is not a unique example. On the border of a small granodiorite stock on Grizzly Gulch just southwest of Helena there are shonkinite dikes up to 2 feet thick that cut a mass of vesuvianite-diopside tactite 100 feet thick and several hundred feet long.

The most voluminous production of shonkinite took place near Austin, at the northern border of the Boulder bathylith. The Madison limestone here has been converted into diopsidic tactite through a thickness of several hundred feet. Intrusive into this tactite are bodies of shonkinite as much as three hundred feet thick. The shonkinite in turn is cut by thin dikes composed wholly of coarse-grained alkali-feldspar rock—leucosyenite, or perthosite (Pheister, 1926).

In all the places where shonkinite has so far been found near the Boulder bathylith this triple association occurs: limestone, tactite, and granodiorite.

TABULAR SUMMARY OF BOULDER BATHYLITH PHANERITES AND ASSOCIATED ALKALIC ROCKS

Table 3 gives a summary view of the evolution of the plutonic rocks of the Boulder bathylith. It begins with the Unionville granodiorite and its basic border facies the granogabbro from the contact at Park City southwest of Helena, and ends with the muscovitic biotite granite at Montana City. The table brings out clearly the strong contrast between the normal rocks of the bathylith and the alkalic rocks: the syenodiorite of the Scratchgravel Hills stock, the Priests Pass leucomonzonite, and the nepheline shonkinite, which are regarded as having been formed by limestone syntexis.

LOCALIZATION OF ORES IN THE BOULDER BATHYLITH

A major problem that the Boulder bathylith presents is what are the factors that have determined the remarkable localization of the ore deposits. The supreme outstanding feature of the ore deposits that are genetically related to the Boulder bathylith is the enormous concentration of copper and zinc at Butte. Another facet of this problem is what factor or factors have determined the localized or restricted distribution of certain metals to certain

TABLE 3

Parameters of the Boulder Bathylith Phanerites and Associated Alkalic Rocks

	SiO ₂ content	Density	Alkalicity index	An in plag.	Normative plag.	qtz.	Color index
1 Unionville Granodiorite	61.14	2.78	60.7	47	44	15	21.6
1A Granogabbro	54.63	2.84	62.2	55	56	8.6	28.9
2 Clancy Granodiorite	65.49	2.71	62.1	44	39	22	15.0
3 Porphyritic Granodiorite	66.14	2.70	61.6	40-20	34	22	10.4
4 Adamellite	71.28	2.65	62.8	40	29	33	5.8
5 Granite		2.61		30			
Syenodiorite	56.01	2.76	53.8	35	31	3.0	21.8
Priests Pass Leucomonzonite	64.13	2.66	53.2	37	24	11.8	8.7
Nepheline Shonkinite	51.95	2.93	42.3				48.1

areas in the bathylith. Outside of Butte the ore deposits have been mainly silver bearing lead, in many places associated with abundant tourmaline, comprising the tourmalinic silver-lead type of ore deposit (Knopf, 1913a). Yet in other places in the bathylith extraordinary deposits of tourmaline occur, but no ore deposits were formed. On the other hand tourmaline is practically unknown at Butte. The problem thereby presented has never yet been clearly formulated, let alone any progress made toward solving it.

Butte has long called itself the richest hill on Earth and this claim is regarded by the geologists of the Anaconda Company as more than ever justified (Lindforth, 1952). Three attempts have been made to account for the extreme localization of copper and zinc in that part of the bathylith in which Butte is situated. One explanation, by Weed, was that the granitic rock at Butte is richer in ferromagnesian minerals, a feature that favored precipitation of the copper. But granodiorite of the composition of the rock at Butte is common throughout the bathylith as a whole. Probably for this reason Weed omitted this explanation in his final report on the Butte district (1912). Another explanation, much favored at Butte, is that the granodiorite at Butte was invaded by a porphyry, variously called quartz porphyry (Weed, 1897), Modoc porphyry, rhyolite porphyry (Weed, 1912, p. 40), or granite porphyry, which was directly responsible for the deposition of the ores. However, increasing knowledge of the areal geology and petrology of the bathylith shows that similar porphyry dikes occur in many places, but none of these places have copper deposits. A third explanation is that Butte is on an upward protuberance on the back of the Boulder bathylith, in short, a cupola, and this explanation would indeed be attractive if there were any field facts to support it. These attempts to explain the most remarkable economic feature of the bathylith emphasize the need of completing the areal mapping and petrologic study of the bathylith.

In conclusion, the present investigation, concerning itself mainly with the northern portion of the bathylith, has shown that the bathylith is not the result of the intrusion of a single magma in one pulse but was built up by the successive intrusion of at least five, probably six, bodies of magma. The problem of the emplacement of the bathylith is therefore not as Grout and Balk envisaged it in 1934 as the mechanics of intrusion of a single body of magma, but is the problem of how five different magmas in turn made room for themselves in the higher levels of the crust and built up a composite bathylith.

These magmas after arriving in place were capable of developing facies, such as the granogabbro facies of the Unionville granodiorite. Furthermore, they have been altered by biotitization, whereby strikingly poikilitic dioritoid and gabbroid rocks were formed. In places also changes were induced by dissolving limestone.

The successive major intrusive masses that make up the Boulder bathylith were emplaced in the normal order of increasing silica content. Whatever the process was that developed the successive magmas, it produced no change in the value of the alkalicity indices of the resultant rocks. All the rocks are normal lime-alkalic rocks.

In those masses that do not fit into the normal scheme, such as the Scratchgravel Hills syenodiorite, the Priests Pass leucomonzonite, and the nepheline shonkinite, the alkalicity index falls below 55 and attains a low of 42 for the nepheline shonkinite.

The field evidence in regard to the nepheline shonkinite as well as the chemical evidence (the shonkinite contains 13 percent of lime) strongly suggests that the alkalic nature of the shonkinite was determined by the assimilation of limestone. Consequently, in the absence of field evidence for the origin of the syenodiorite and the leucomonzonite we must conclude that their alkalic character like that of the nepheline shonkinite is the result of the assimilation of limestone, but that the assimilation took place at greater depth, below the present level of exposure.

As I mentioned in the beginning, it was the problem of the mode of emplacement of the Boulder bathylith that caused me to return to Montana. The bathylith and its enveloping rocks proved to be much more complex than was anticipated and detailed mapping therefore became necessary, and this mapping led to the demonstration of the composite nature of the bathylith and unexpectedly to the discovery of striking field evidence in support of Daly's theory of the origin of alkalic rocks. Many other interesting features were found such as the notable contact metamorphism, but these will require description at a future time.

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