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William G. Melson

Geology of the Lincoln Area, Lewis and Clark County, Montana

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ABSTRACT

Melson, William G. Geology of the Lincoln Area, Lewis and Clark County, Montana. *Smithsonian Contributions to the Earth Sciences,* number 7, 29 pages, 13 figures, 1971.— The Lincoln area (townships 13 and 14 N, ranges 7 and 8 W, about thirty miles northwest of Helena, Montana) is underlain by Pre-Cambrian Belt sedimentary rocks intruded by late Cretaceous (?) granitic stocks with concomitant widespread contact metamorphism and mineralization. The granitic stocks are probably related to the Boulder batholith. The pre-intrusion structure is characterized by high angle faults and broad open folds of Cretaceous age (Laramide). Oligocene (?) volcanic rocks were extruded on an eroded surface of the Belt rocks and granitic stocks. A second period of mineralization followed extrusion of the volcanic rocks.

Fracture cleavage which dips consistently to the southwest as well as the overall structure show that a southeast plunging syncline which marks the north end of the Boulder batholith continues into the Lincoln area. The syncline extends at least twenty miles north of the batholith and dominates the structure over an area of about 350 square miles.

About forty square miles of middle Tertiary volcanic rocks are composed of a lower series of andesitic to latitic flows and an upper series of rhyolitic welded ash flows. The features of the welded ash flows suggest that they were deposited in part by a vesiculating mass of rhyolitic magma (pumice froth flows). The volcanic rocks are presumably about the same age as the Lowland Creek volcanics of the Butte area.

The area and the region several miles to the north are about the northern limit of Boulder batholith activity, Tertiary volcanism, and associated mineral deposits. The superposition of these two periods of igneous activity and their gross similarities imply that they are genetically related.

Gold and silver have been produced from epithermal fissure veins. The scant available data suggests that the veins are vertically zoned. There were probably at least two periods of epithermal mineralization: one during the late stage cooling of the stocks, and a second after extrusion of the lower volcanic series.

Remnants of Tertiary surfaces preserved under the volcanic rocks imply that there have been topographic inversions since the middle Tertiary.

Glacial deposits suggest at least one early period of valley glaciation and later, perhaps recent, periods of restricted mountain glaciation. Rich gold placer deposits, such as in McClellan Gulch, accumulated after the earliest period of valley glaciation.

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William G. Melson

Geology of the Lincoln Area, Lewis and Clark County, Montana

Introduction

The Lincoln area, which is in the east-central part of the Rocky Mountains of Montana, contains features which are of interest to topical petrologic studies and to the regional geology of western Montana. The location of the Lincoln area and some of the major geologic features of western Montana are shown in Figure 1.

Of particular topical interest in volcanology is a series of welded ash flows which contain features suggesting deposition by the pumice froth flow mechanism (Smith 1960). Of these features, fluid inclusions with uncommonly large vapor-to-glass ratios are the most striking.

Contact aureoles around granitic stocks in the area are developed in a wide variety of sedimentary rocks. These aureoles have features which bear on problems in metamorphic petrology and are the subject of a separate study (Melson 1966).

On a regional geologic scale, the study of the Lincoln area establishes some lithologic correlations of the Pre-Cambrian Belt Series of western Montana, describes part of the northernmost extent of the Boulder intrusive activity and of middle Tertiary volcanism in the eastern Rocky Mountains, and points out the large size of a complexly faulted syncline which marks the north side of the Boulder batholith.

A collection of rocks in the National Museum of Natural History from the Marysville mining district (Barrell 1907) was of special interest to the following study. Other suites of rocks in the Museum collected during the early geologic surveys of the western United States and of particular interest to development of geologic knowledge of Montana are listed in Table 1.

The field work, which was carried out in 1962 and 1963, and much of the laboratory work involved in this study were done by the writer as part of a Ph.D. thesis submitted to Princeton University in 1964.

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Geography

The Lincoln area is used here to refer to townships 13 and 14 north, ranges 7 and 8 west, about thirty miles north of Helena, Montana (Figure 1). Figure 2 shows some of the major topographic features of the region. The Continental Divide, the most prominent feature, trends northeast, and is at elevations between 6,300 and 7,581 feet (Granite Butte). The local relief is mainly between 1,000 and 2,000 feet.

The area is mountainous except for the Lincoln Valley, which is a relatively flat, gravel-covered surface at about 4,600 feet. The mountains have forest-covered slopes, a few cliffs and rounded crests. Most geologic information was gained from traverse along ridge crests, where there are normally good outcrops. The intersections of major valleys with the divides generally are marked by steep slopes and, in places, cliffs which are the headwalls of former glaciers.

The topography bears little relation to the structure of the underlying Belt rocks. The resistant contact rocks around granitic stocks, however, commonly

TABLE 1.—*Rock collections from Montana in the collections of the National Museum of Natural History and published reports concerning some of them, or source of the collections*

BEARPAW MOUNTAINS. Geology. Weed and Pirsson (1896a).
BIG BELT MOUNTAINS. Geology. Weed, W.H.
BOULDER HOT SPRINGS. Mineral vein formation. Weed (1900).
BUTTE. Manganese deposits. Pardee (1919a).
BUTTE. Geology and ore deposits. Weed (1913).
BUTTE. Geology. Weed et al. (1897).
CASTLE MOUNTAIN DISTRICT. Geology. Weed and Pirsson (1896b).
CRAZY MOUNTAINS. Geology. Wolff, J.E.
DILLON. Geology and mineral deposits. Winchell (1914).
DUNKLEBERG DISTRICT. Geology and mineral deposits. Pardee (1918b).
ELKHORN DISTRICT. Geology and mineral deposits. Weed (1901).
ELLISTON. Phosphate deposits. Stone and Bonine (1915).
FLATHEAD INDIAN RESERVATION. Rocks and ores. Stone, R.W. U.S. Geological Survey.
FORT BENTON. Geology. Weed (1899).
GALLATIN COUNTY. Phosphates. U.S. Geological Survey of the Territories, 1871–1872.
GARNET RANGE. Mineral deposits. Pardee (1918a).
GARRISON AND PHILLIPSBURG. Phosphates. Pardee (1917).
HELENA MINING REGION. Mineral deposits. Pardee and Schrader (1933).
HELENA MINING REGION. Mineral deposits. Knopf (1913).
HIGHWOOD MOUNTAINS. Geology. Weed and Pirsson (1894).
JUDITH MOUNTAINS. Geology and mineral deposits. Weed and Pirsson (1897).
LITTLE BELT MOUNTAINS. Geology. Weed and Pirsson (1900).
LITTLE BELT MOUNTAINS. Geology. Weed (1899).
LITTLE ROCKY MOUNTAINS. Geology. Weed and Pirsson (1896c).
LIVINGSTON. Geology. Iddings, J.P. and Weed, W.H. (1894).
MADISON COUNTY. Manganese deposits. Pardee (1919b).
MADISON COUNTY. U. S. Geological Survey of Territories, 1871–1872.
NORTHERN PACIFIC LAND GRANT. Geology. Stone, R.W. U.S. Geological Survey.
PARK COUNTY. Geology. U.S. Geological Survey of Territories, 1871–1872.
PHILIPSBURG. Geology and mineral deposits. Emmons and Calkins (1913).
PHILIPSBURG. Geology and mineral deposits. Emmons and Calkins (1915).
THREE FORKS. Geology. Peale (1893).
THREE FORKS. Geology. Peale (1896).
TOWNSEND VALLEY. Geology. Pardee (1925).
VARIOUS LOCALITIES. Manganese deposits. Pardee (1922).

form natural amphitheaters around deeply eroded stock interiors.

Principal access to the area is by the Poorman-Virginia Creeks secondary dirt road. Montana Route 289 is near the northeastern part and Route 20 near the northern part of the area. These roads lead to and from the small town of Lincoln, which marks the area's northwestern corner.

The Lincoln area is principally in the Helena National Forest, and the Dalton Mountain, Continental Divide, and Humbug Creek foot-trails, which are maintained by the United States Forest Service, provide access to the remote parts of the area.

Geologic data were plotted on United States Forest Service 1:15840 aerial photographs (Project 102a, Helmville-Lincoln area). There are no accurate topographic maps available at a scale of 1:31680. Data were transferred to part of the United States Army Map Service 1:125,000 Butte, Montana, topographic sheet (1958) enlarged to 1:31680. There are, thus, some inaccuracies in the base map used in preparing the geologic map of the Lincoln area.

Most of the data on which the study of the Lincoln area is based are shown on the geologic map (Figure 3), reproduced here in reduced form. Approximately four months were spent in the field during the study.

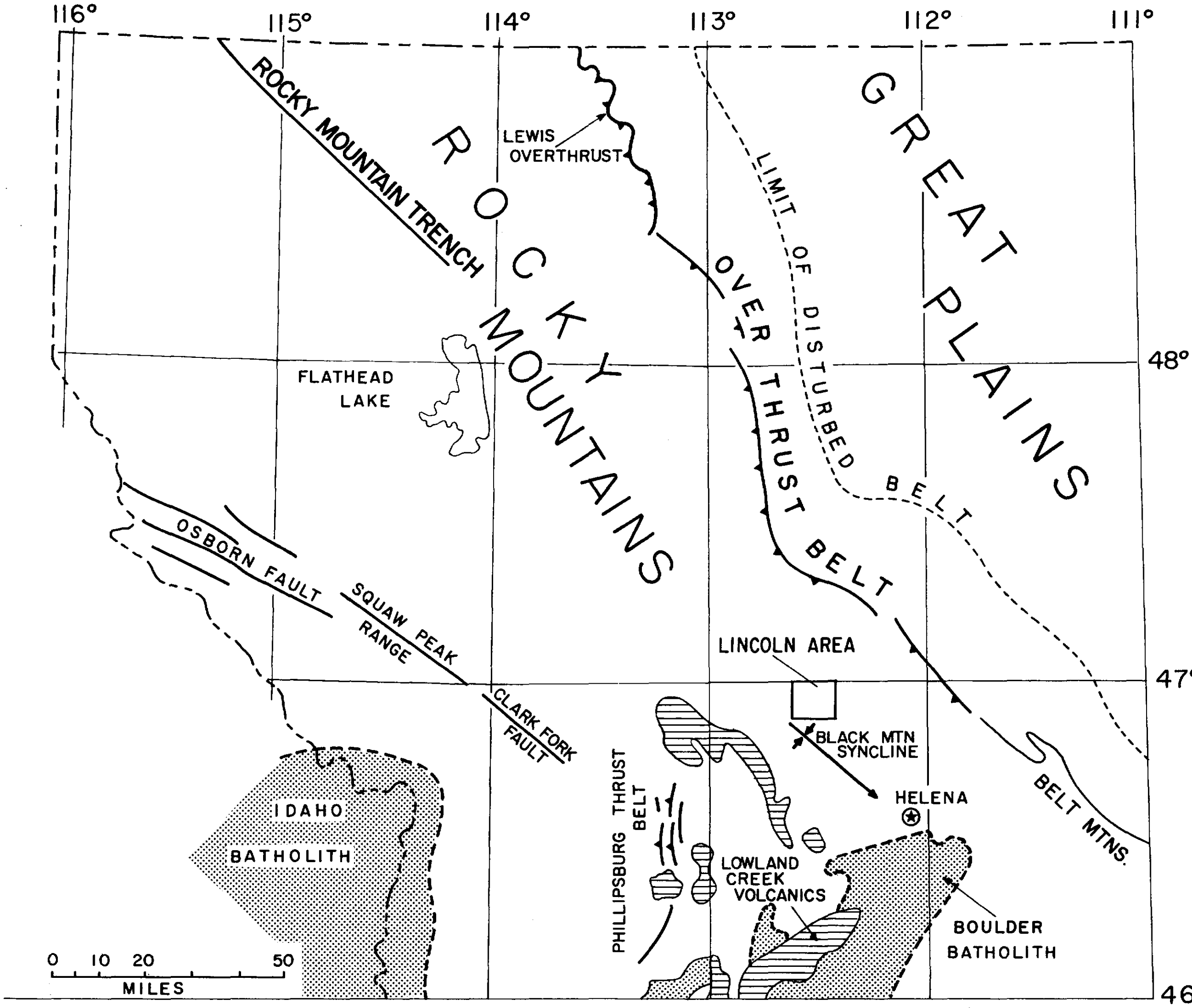


FIGURE 1.—Location of the Lincoln area with regard to some major regional geologic features. Regional geology from the Tectonic Map of the United States. (U.S. Geological Survey 1962), and Nelson and Dobell (1961, fig. 20).

Summary of Previous Work

Charles D. Walcott first described the Pre-Cambrian rocks in the area north of Helena in 1899. Most of the formation names proposed by him have been retained with only minor modification.

The important mineral deposits in the Helena area led to several early studies by the United States Geological Survey. Some of these which were useful in the present study are by Barrell (1907), Knopf (1913), and Pardee and Schrader (1933).

Barrell (1907), in his report on the Marysville mining district, several miles southeast of the Lincoln area, presented one of the earliest studies of magmatic stoping and of contact metamorphism.

Knopf's work on the Marysville mining district (1950), the Boulder batholith (1957), and the mineral deposits of the Helena area (1913) has proven helpful in relating the igneous rocks of the Lincoln area to areas nearer the batholith.

Pardee and Schrader (1933) discussed some of the mineral deposits of the Lincoln area and presented a reconnaissance map. Although they mapped some of the igneous rock contacts in the Lincoln area, their map does not show structure or differentiate between the formations of the Belt Series.

The Montana Geologic Map (1955) shows the rock types of the Lincoln area, but the writer's map-

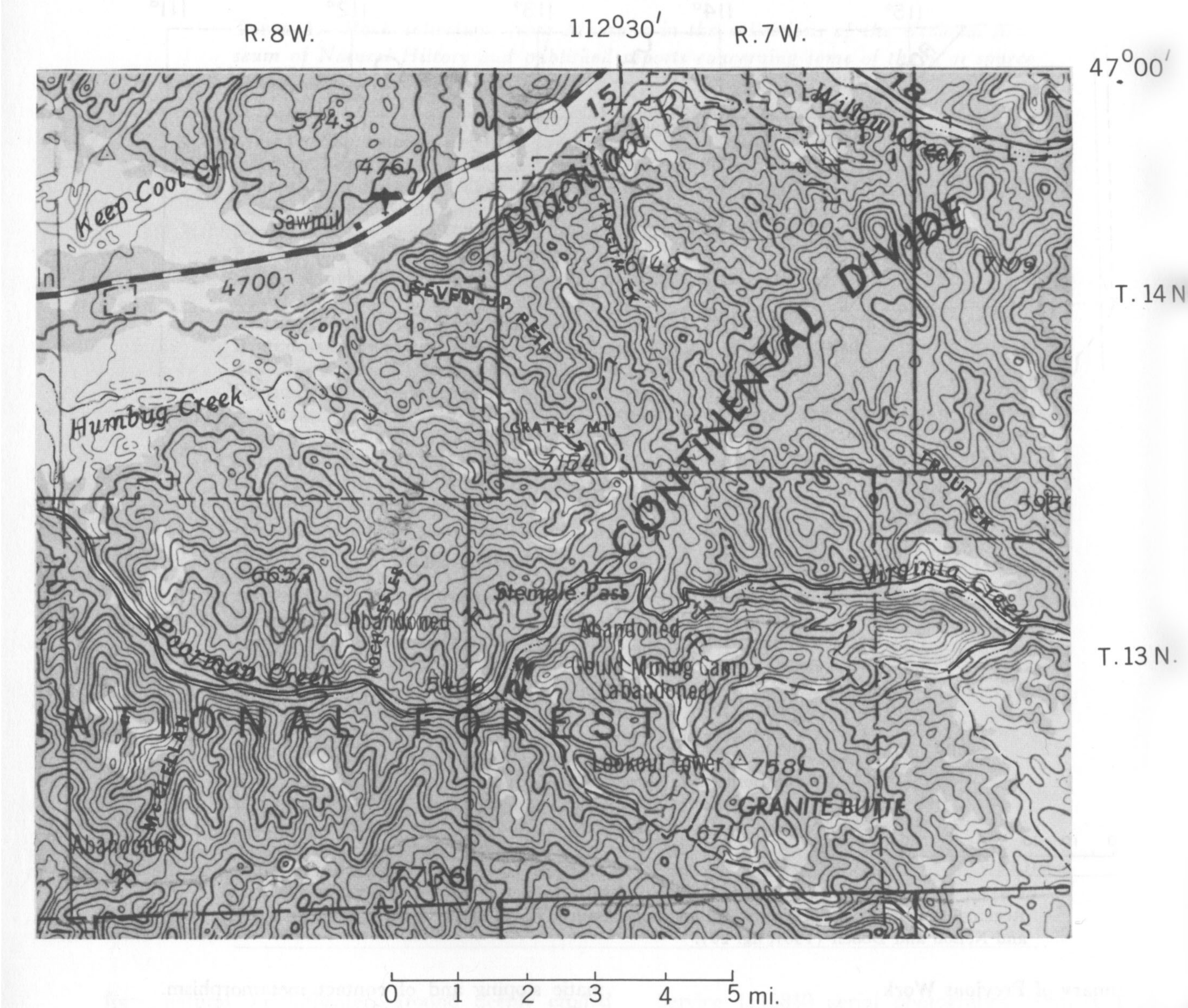
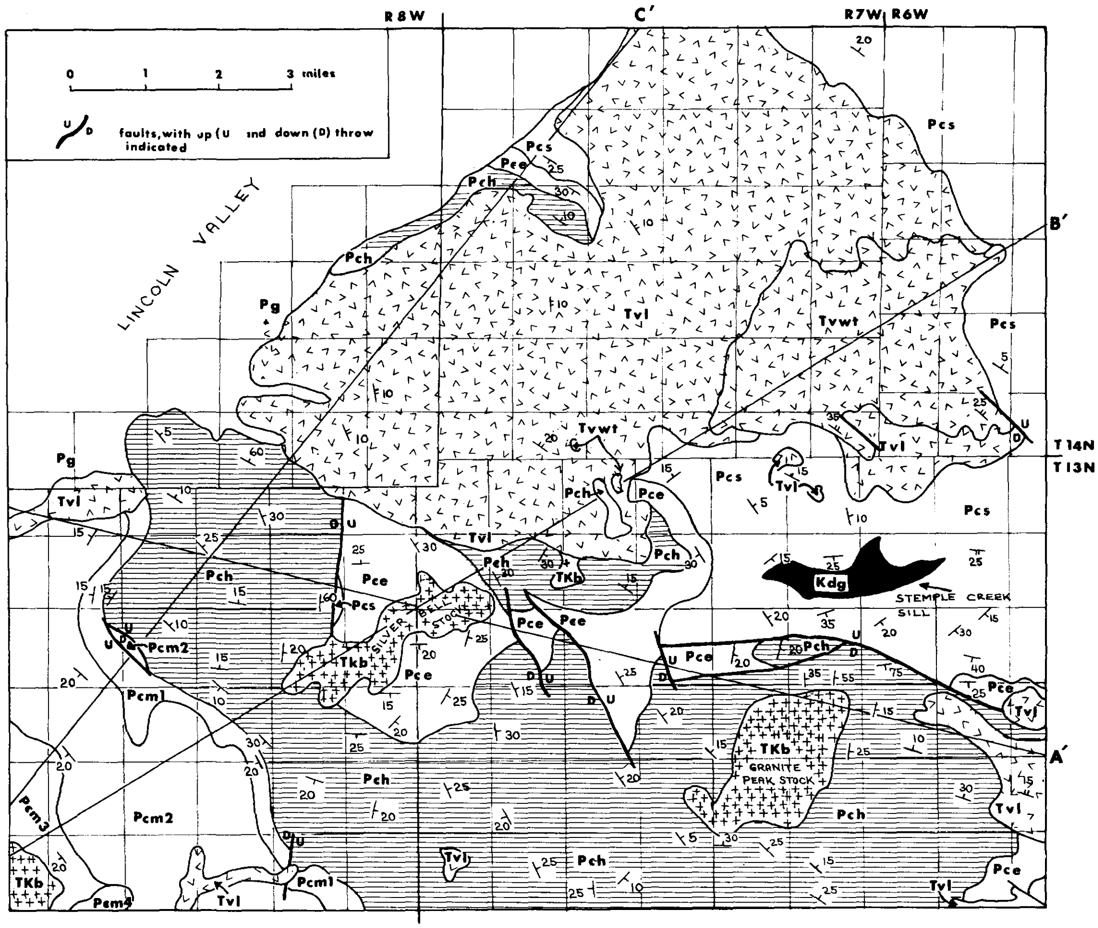


FIGURE 2.—Topographic features of the Lincoln area, reproduced from the Butte, Montana, 1:250,000 topographic map (U.S. Geological Survey 1962).

ping suggests that several important modifications are needed. Figure 4 permits direct comparison of the two maps. There is no Newland formation in the Lincoln area, as indicated on the state map. The area mapped as Newland formation is actually Helena formation. The designation and contacts of the igneous rocks of the Lincoln area should also be modified, particularly the large areas of "Cretaceous Diorite-gabbro" shown in the western and northern parts. Some of these correspond roughly to areas of middle Tertiary volcanic rocks.

FIGURE 3.—Summary geologic map of the Lincoln area. Reduced from a 1:31680 geologic map (Melson 1964). Formations, which are fully described in the text are as follows, from youngest to oldest: Pg=mainly Pleistocene gravels and recent alluvium; Tvwt=Tertiary, probably Oligocene, welded tuffs; Tvl=Tertiary volcanic rocks, probably mainly latitic, but ranging from basalt to rhyolite; Tkb=dioritic to granitic stocks of probable Boulder batholith age; Kdg=Cretaceous "diorite and gabbro," mainly quartz gabbro in the Lincoln area; Pcm=Pre-Cambrian Marsh formation, with each of four members indicated; Pch=Pre-Cambrian Helena formation; Pce=Pre-Cambrian Empire formation; Pcs=Pre-Cambrian Spokane formation.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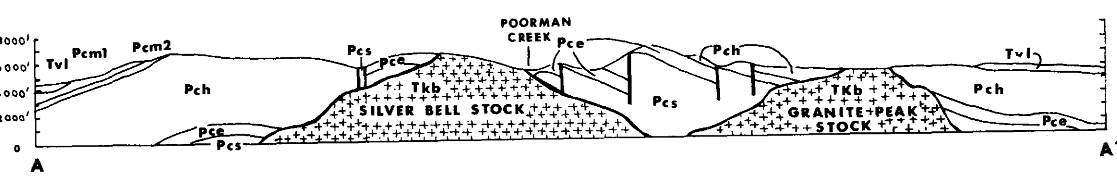
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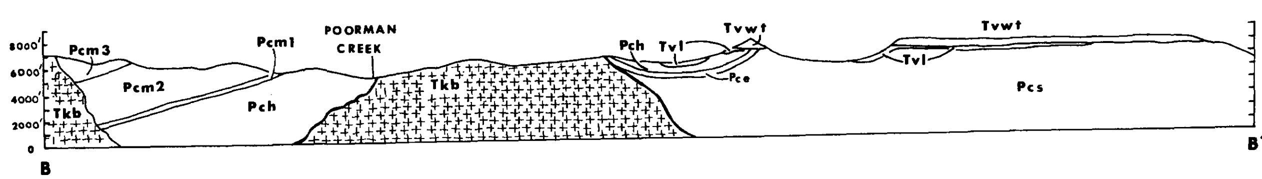
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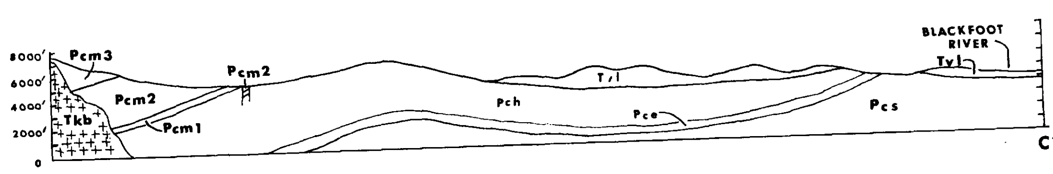
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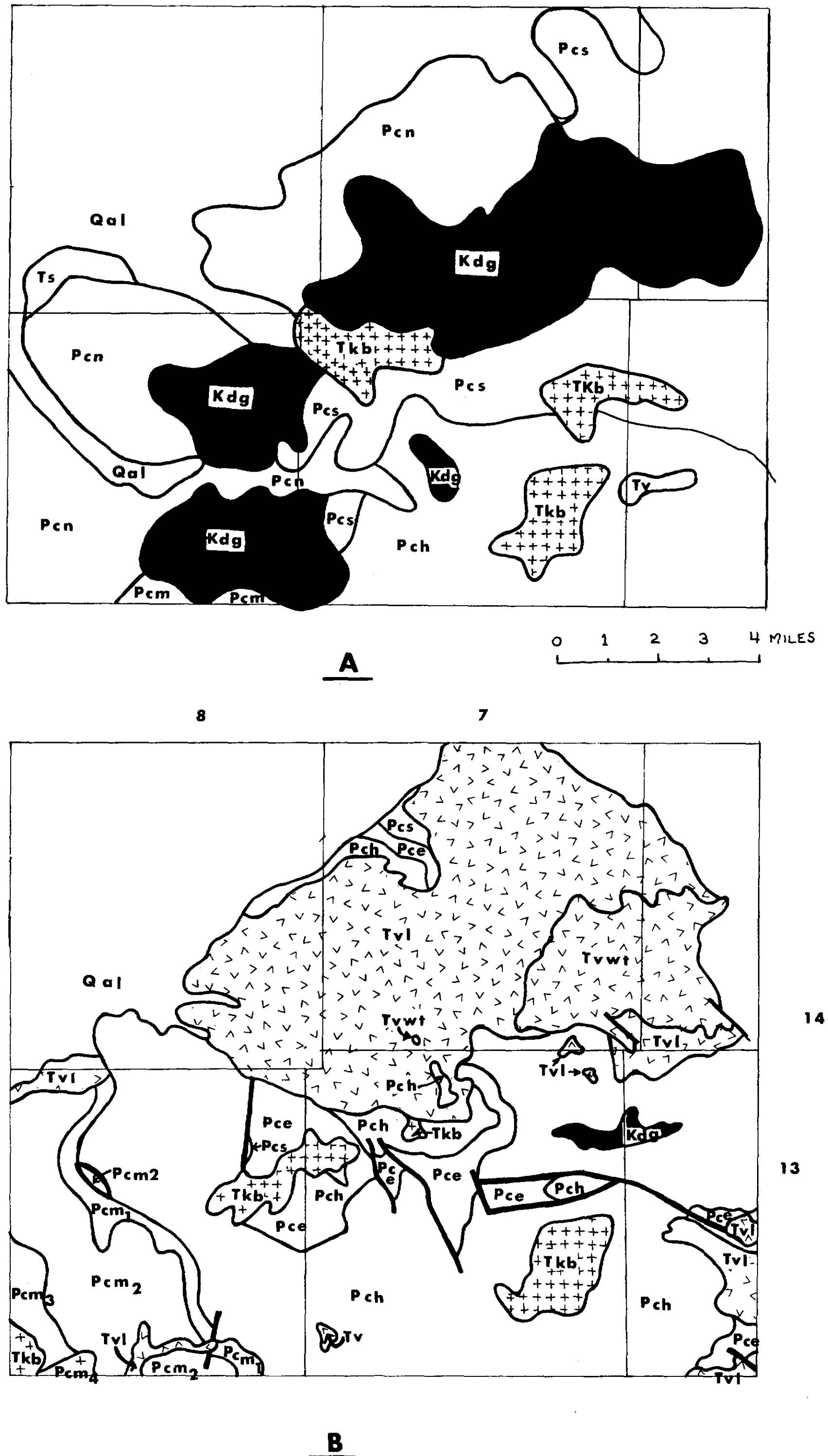

FIGURE 4.—Comparison of new and old geologic maps of the Lincoln area. A. Geologic map of Montana (1955). Symbols the same as in Figure 3, with the addition of Pcn, the Pre-Cambrian Newland formation, and Qal, Quaternary alluvium. B. New geologic map (this study), redrawn to the same scale as A. Symbols same as in FIGURE 3, except for Qual, Quaternary alluvium.

Stratigraphy of the Belt Series

Discussion

The Lincoln area is underlain by about 80 square miles of heretofore undescribed sedimentary rocks of the Pre-Cambrian Belt Series. The rocks of the Belt Series of western Montana form one of the largest areas of unmetamorphosed Pre-Cambrian rocks of the world, and thus are important to the interpretation of Pre-Cambrian sedimentary environments, and have provided evidence of Pre-Cambrian life. Regional studies of the Belt Series, however, have been impeded by the many unmapped areas in western Montana and consequent lack of satisfactory lithologic correlations.

The Belt Series of the Helena area were first described by Walcott (1898) as part of a survey of the "Algonkian" of Montana. Subsequent work has resulted in mapping of large parts of the Belt Series and elaborate regional correlations and interpretation of sedimentary environments. Most of this work has been reviewed recently by Ross (1963). Bierwagen (1964) and the writer have cooperated in mapping of the Belt Series of the Black Mountain and Lincoln areas. Suggested regional correlations and probable local environment of deposition were presented by Bierwagen and are not repeated in this study.

The principal features of the Belt formations and the features which mark their contacts in the Lincoln area are summarized in Tables 2 and 3, respectively. The formation names are essentially those proposed by Walcott (1898) with but one modification. The Marsh formation is thicker and more variegated in the Lincoln area than in the Marysville and Helena areas where it was first described. It was subdivided, therefore, into four easily mappable members.

Stratigraphic Repetition of Similar Rock Types

The Belt Series of the Lincoln area has a remarkable repetition of rock types. Note that in Table 1 the sequence of grayish-red siltstones grading upward to grayish-green siltstones is repeated twice: (1) Spokane to Empire formations, and (2) member B to member C of the Marsh formation.

Of these units, the Spokane formation and member B of the Marsh formation are particularly similar. Both consist mainly of thinly bedded grayish-red (5R4/2, Geologic Society of America Color Chart)

TABLE 2.—*Diagnostic features of the Pre-Cambrian Belt Series formations in the Lincoln area (from oldest to youngest, with thickness in feet)*

SPOKANE. Over 5000, bottom not exposed. Dominantly thin-bedded noncalcareous red siltstone with argillaceous mud-cracked partings.[1] Some thin white fine-grained quartzite layers. Lower portion composed of green massive noncalcareous mudstone commonly showing intense fracture cleavage.

EMPIRE. About 1000. Lithologically transitional to the Spokane and Helena formations. Dominantly grayish-green to dark grayish-red, commonly calcareous or dolomitic, mudstones. Distinguished from Spokane formation by finer grain size, predominant color (green) and common calcareous to dolomitic beds. Distinguished from Helena formation (gray) by green color and common grayish-red layers.

HELENA. 5000–7500. Calcareous to dolomitic gray siltstones and mudstones. Buffweathering dolomitic beds common. Several thin *Collenia* beds. "Molar tooth" beds abundant. Thickest carbonate-rich formation in area. Siliceous to locally cherty noncalcareous mudstone beds common near top.

MARSH.

Member A. 600–1000. Calcareous or dolomitic green to gray siltstones and sandstones. Commonly platy (thin-bedded) and buff weathering. Distinguished from Helena formation by platy beds (Helena more massive) and by speckled sandstone beds composed of green (chlorite after glauconite?), pink (microcline) and white-to-red quartz grains in a green calcareous matrix.

Member B. 2500. Reddish-gray siltstones with interbedded dark reddish-gray mudflakes in white fine-grained quartzites locally common. In isloated outcrops indistinguishable from the Spokane formation. Lower portion contains interbedded red and greenish-gray noncalcareous siltstones and fine-grained quartzites.

Member C. 2500. Calcareous and dolomitic siltstone and mudstone. Platy and dominantly greenish-gray beds which weather buff. Thin interbeds of grayish-red calcareous siltstone common. In isolated outcrops may be mistaken for Empire formation. One thin "molar tooth" and one *Collenia* bed (Continental Divide section) noted.

Member D. Highly viariable. Thick-bedded, light pinkish-gray, arkosic quartzites. Restricted to southwest corner of area. Wedge-shaped beds up to 300 feet thick intertongued with the upper part of member C.

[1] Siltstone and mudstone are used here in preference to the term "argillite" to specify more clearly the grain size. All the Belt rocks, as a whole, are intensely indurated.

TABLE 3.—*Definition of contacts of Belt formations in the Lincoln area (from oldest to youngest)*

Contact	*Character*
Spokane-Empire	First occurrence of grayish-green, calcareous to dolomitic (buff weathering) siltstones to fine-grained sandstones.
Empire-Helena	First occurrence of gray carbonate-rich siltstones and mudstones. "Molar tooth" beds are particularly distinctive.
Helena-Member A of the Marsh formation	Buff weathering grayish green to very light gray fine-grained dolomitic to calcareous sandstones, mudstones, or siltstones. Mottled pink and green sand-sized grains in a calcareous matrix are distinctive. Contact is apparently gradational over about 50 feet.
Member A-Member B	Occurrence of hard, grayish-green, fine-grained quartzites and siltstones which grade upward into grayish-red, fine-grained quartzites and siltstones.
Member B-Member C	Marked by occurrence of grayish-green, buff weathering siltstones and fine-grained, calcareous siltstones.
Member C-Member D	Occurrence of massive, commonly cross-bedded, arkosic sandstones. Contact varies greatly stratigraphically because of rapid facies changes common in the arkosic sand near the top of the Marsh formation.

siltstones and fine-grained quartzites with thin, mudcraked, shaly partings. White quartzites about 3 to 5 inches thick and with dark reddish-gray mudflake inclusions are more common in member B of the Marsh formation but have also been noted in the Spokane formation.

The repetition of these rock types may lead to confusion in correlations as well as in determining structure. In the Lincoln area, the Helena formation, which separates the repeated lithologies, and the arkosic quartzites of the upper part of the Marsh formation are distinctive and led to eventual recognition of the repeated sequence. In areas of isolated outcrops or of complicated structure, however, the distinction between repeated rock types may be impossible. This should be kept in mind during further work on the Belt rocks near the Lincoln area, particularly just to the north in the unmapped Belt rocks of the Bob Marshall Wilderness Area.

Belt Formation Contacts

An attempt was made to use the descriptions of Knopf (1950) for the Marysville area to identify the contacts of the Spokane, Empire, and Helena formations in the Lincoln area. The contacts as listed by him, however, were not distinctive in the Lincoln area and thus were redefined (Table 2). Although the formations are grossly similar in the two areas, facies changes are sufficient to make precise definitions of the contacts of only local applicability.

Structural Geology

Discussion

The Lincoln area is characterized by broad areas of Belt sedimentary rocks which rarely dip more than 30 degrees. They show evidence of at least four periods of deformation: (1) gentle regional Pre-Cambrian tilting, (2) "Laramide" (Cretaceous) folding and faulting, (3) late Cretaceous (?) faulting associated with intrusion of granitic stocks related to the Boulder batholith, and (4) faulting related to Oligocene (?) volcanism. Table 4 summarizes the structures produced during each of these periods of deformation. Although extremely complicated on a small scale because of these superimposed structures, the main structural features are simple and dominated by northwest to north trending high-angle faults, open folds and fracture cleavage developed during the "Laramide orogeny."

The Lincoln area and Black Mountain area (Bierwagen 1964) are dominated structurally by a broad southeast plunging syncline, referred to hereafter as the Black Mountain syncline. The gross structure of the Lincoln area shows that it lies entirely on the northeast limb of this syncline. Although there are many subordinate folds, successively younger rocks from Spokane to Marsh occur toward the axis of the Black Mountain syncline (Figure 3).

TABLE 4.—*Periods of deformation (from oldest to youngest)*

Age	*Structures*
Late Pre-Cambrian	Gentle tilting and erosion of the Pre-Cambrian Belt Series, as seen in the Black Mountain area. (Bierwagen 1964).
Cretaceous (Laramide)	North to northwest trending folds, faults, and fracture cleavage.
Late Cretaceous (?)	Faults in contact zones of stocks.
Middle to late Tertiary	"Collapse" faults along eastern margin of welded ash flow sheet and small faults in lower volcanic series. High angle, small displacement faults which cut epithermal fissure veins.

Relation Between Folding and Fracture Cleavage

Fracture cleavage is developed in argillaceous beds throughout the area. Although the Pre-Cambrian section is about 15,000 feet thick, fracture cleavage shows no stratigraphic restrictions. It has proven useful in defining the regional trend of fold axes from bedding-cleavage intersections and in showing that the Black Mountain syncline is the dominant structure.

DESCRIPTION OF FRACTURE CLEAVAGE.—Cleavage is excellently developed in some outcrops but absent in others. Commonly it is inclined at between 5 and 40 degrees to bedding and may be strongly refracted in a sequence of interbedded argillaceous and quartzite beds. The spacing between cleavage fractures varies from microscopic in argillaceous beds to more than an inch in quartzites.

RELATION TO THE BLACK MOUNTAIN SYNCLINE.—Throughout the southern two townships (Poorman and Virginia Creek drainage basins) the fracture cleavage strikes mainly northwest and dips southwest regardless of the attitude of bedding.

Figure 5 shows the idealized relationship of bedding and fracture cleavage in folds. If the cleavage is formed by stresses generated within a given fold, it will dip toward the axial plane of the fold. The fracture cleavage in the area as a whole, however, dips west regardless of its position in the limbs of more local folds. Thus, as shown in Figure 5*b*, the dominant stress within the beds during folding was probably due to the development of the regional

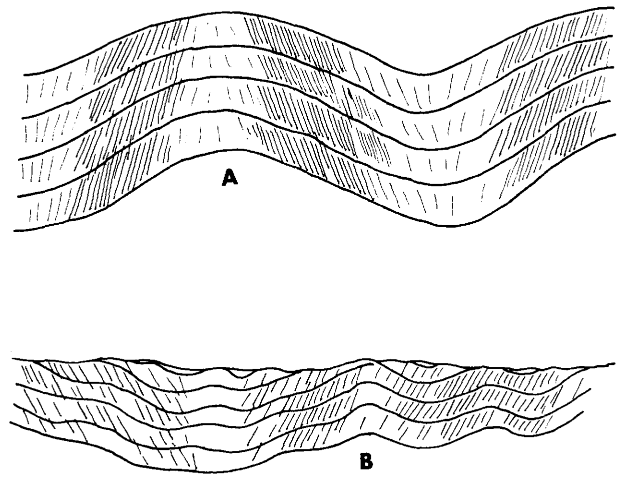

FIGURE 5.—Idealized relation between fracture cleavage and folds (A), and relationship in the Lincoln and Black Mountain areas (B), showing control of fracture cleavage by the Black Mountain syncline.

syncline and not to stresses generated by smaller folds.

Figures 6 and 7*a* show that on a still larger scale fracture cleavage fans about the axis of the Black Mountain syncline. The cleavage dips consistently east in the Washington Creek area, west of the syncline axis.

Some fifteen to twenty miles northeast of the syncline axis (near Flesher Pass), fracture cleavage fans on minor folds and thus in places dips east. Here there is little indication of the regional Black Mountain syncline.

Cleavage-bedding intersections dip mainly to the south throughout the southern half of the area. Figure 7*b* shows that they dip most consistently southeast in the McClellan Creek area, just east of the axis of the Black Mountain syncline. The intersections thus reliably reflect the larger scale structures in the area.

Farther northeast of the axis of the Black Mountain syncline, cleavage-bedding intersections dip more irregularly and commonly dip and strike north (Figure 7*b*). They, thus, suggest another regional syncline beginning immediately north or northwest of Lincoln in the Bob Marshall Wilderness.

Laramide Faults

The two major faults noted in the area, the Fool Hen Ridge and Rochester Gulch faults, are probably

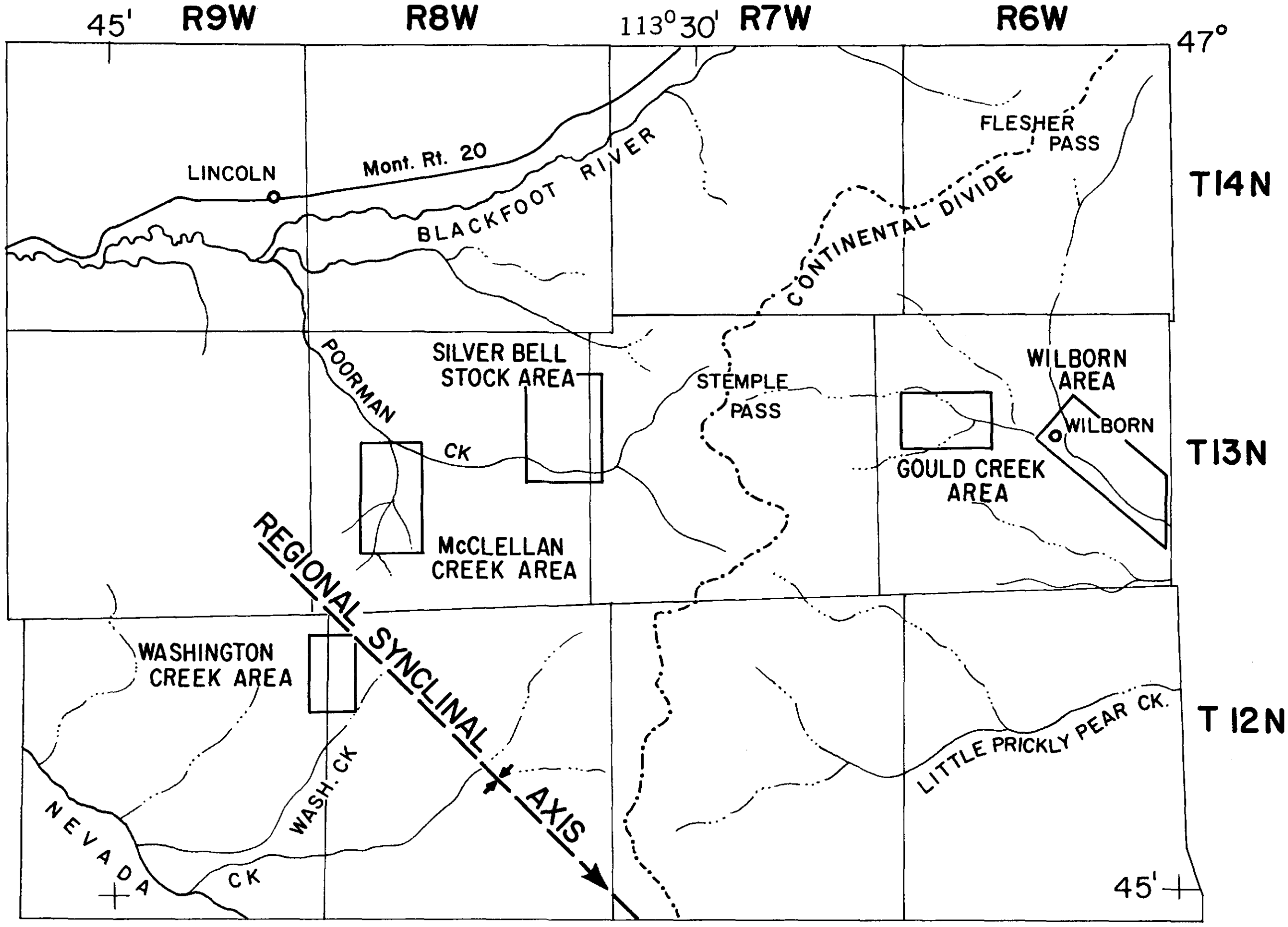

FIGURE 6.—Index map to areas of cleavage and bedding measurements used in Figure 7.

high-angle faults. Their actual orientation is uncertain because of poor exposures. They appear, however, to be relatively straight regardless of topography.

The Fool Hen Ridge fault separates the Spokane and Helena formations in the southeastern part of the area. Because of lack of distinctive units in these formations, and their great thickness, only very rough limits may be placed on the amount of stratigraphic displacement. Where the fault parallels Gould Creek, estimated stratigraphic displacement is between 1,000 feet (thickness of Empire formation) and 10,000 feet. A rather peculiar, and as yet unexplained, observation is that the beds dip toward the fault on both sides of the Fool Hen Ridge fault.

The Rochester Gulch fault is one of the major north-south structures in the area. Because of the difficulties in determining the magnitude of displacements in Belt rocks, precise throw is again uncertain. There probably is, however, a minimum of 1,000 feet of stratigraphic displacement.

The Rochester Gulch fault parallels cleavage and minor fold axes on the west side of the fault and, thus, probably was connected with strain developed during Laramide folding. Contact metamorphism extends across the fault, clearly showing that it formed before intrusion of the Silver Bell stock.

The relative age of the Fool Hen fault is more difficult to determine. On the basis of the inferred large displacement, it is assumed that the fault developed during Laramide folding and faulting, the major period of deformation.

The Empire-Helena contact is repeated by faulting three times between the Silver Bell stock and Fool Hen Ridge. The faults are assumed to be of Laramide age because they parallel fracture cleavage. They occur between broad areas of contact-

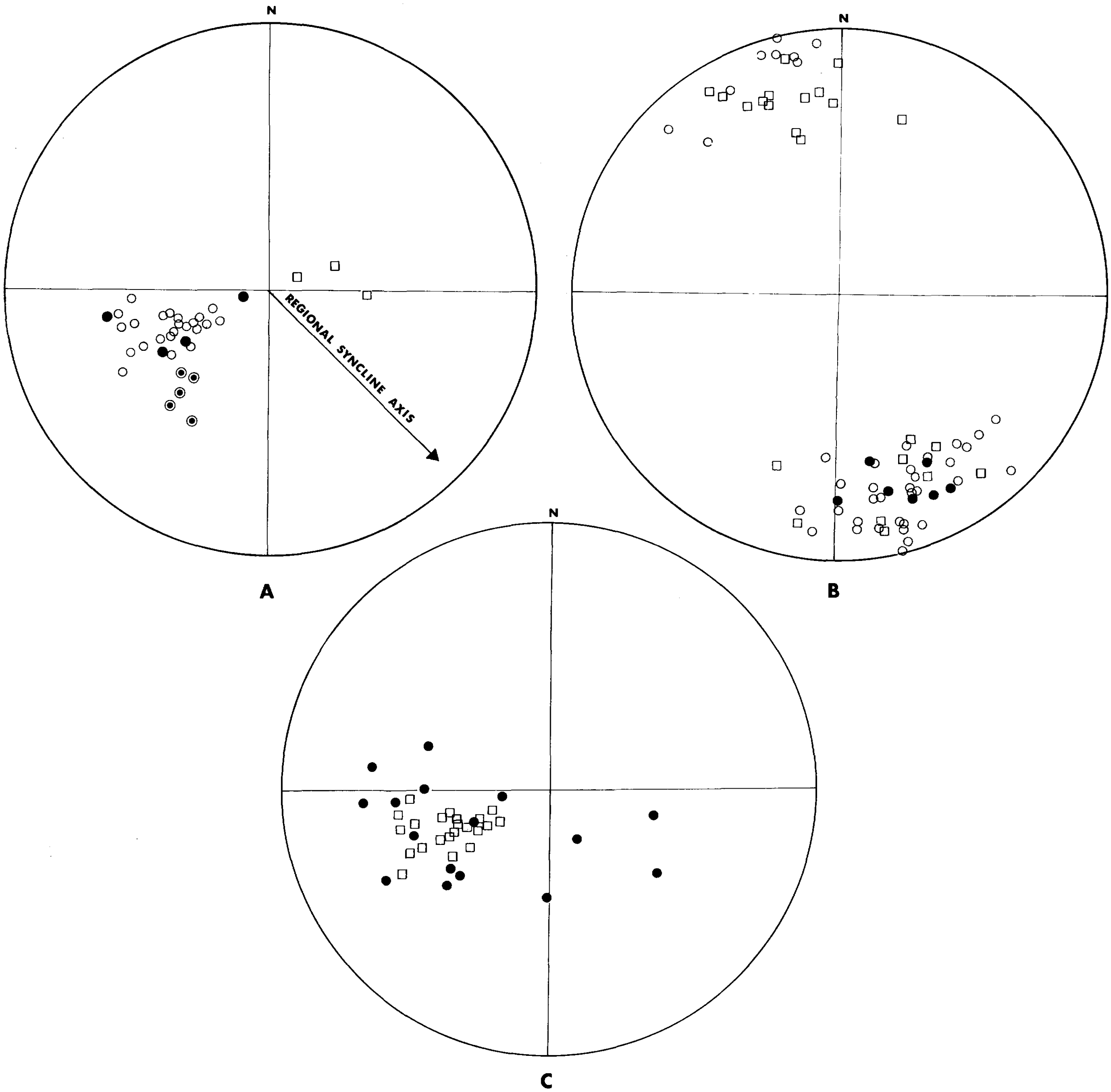

FIGURE 7.—A. Fracture cleavage fans about the axis of the Black Mountain syncline. Squares: Washington Creek area. Solid circles: Wilborn area. Open circles: McClellan Creek area. Open circles with solid centers: Gould Creek area. Dip "vectors" plotted on lower half of equal area stereographic projections. B. Most cleavage-bedding intersections dip southeast in the southern part of the area, which is parallel the Black Mountain synclinal axis. Cleavage-bedding intersections dip more divergently in the northern part of the area. Open circles: southeastern part of the area, mainly T7W, R13N. Squares: northern part of area. Solid circles: McClellan and Washington Creek areas. C. Intrusion of the Silver Bell stock resulted in random rotations of the contact rocks. Solid circles: fracture cleavage orientation in the contact aureole of the Silver Bell stock. Open circles: fracture cleavage in the McClellan Creek area for comparison.

metamorphosed rocks, however, and are perhaps related to faulting during the intrusion of the Silver Bell and Granite Peak stocks. These stocks may well be connected at a shallow depth under the faults. The faults are not exposed and, therefore, their orientation is uncertain. Stratigraphic displacement is probably between 500 and 1,000 feet and the west sides are consistently down, relative to the east sides. The consistent downward movement of the west sides of faults relative to the east sides contributed substantially to the occurrence of the youngest rocks in the western part of the area.

Igneous Rocks

Discussion

At least four periods of igneous activity are evident in the Lincoln area (Table 5). Two pre-Laramide periods of intrusion gave rise to an early series of dioritic sills and a later series of thick quartz gabbro sills. The most pronounced periods of igneous activity in the area were (1) post-folding, late Cretaceous (?) intrusion of three large granitic stocks and concomitant mineralization and widespread contact metamorphism, and (2) middle Tertiary volcanism and mineralization.

TABLE 5.—*Principal igneous rock types (from oldest to youngest)*

Name	*Comments*
1. Dioritic sills	Very common in the Helena and Empire formations. Commonly altered mainly to chlorite and calcite. Mainly less than ten feet thick.
2. Quartz gabbro sills	Noted only in the Spokane formation. Mainly unaltered plagioclase and clinopyroxene with minor quartz. Up to several hundred feet thick.
3. Granite stocks and associated dikes and sills	Granite Peak, Silver Bell, and Dalton Mountain granodioritic stocks. Probably of same age as Boulder batholith.
4. Tertiary extrusives and intrusives	Rhyolitic (mainly welded tuffs) to andesitic flows. Clearly post-folding. Lie unconformably on Belt Series as well as granite stocks.

Pre-Cambrian (?) Dioritic Sills

Sills less than ten feet thick but laterally extensive occur throughout the Empire and Helena formations. They are rare in the Spokane and Marsh formations. In most outcrops, the sills are clearly cut by fracture cleavage and, thus, were intruded before Laramide folding.

Chlorite and calcite locally have replaced the original hornblende and plagioclase of the sills. This replacement of the dioritic sills by chlorite and calcite is probably a result of very low-grade, regional metamorphism. These rocks are typically grayish green because of the abundance of chlorite and lesser amounts of amphibole.

The diorite sills, in the few places where they are unaltered, are petrographically similar to the "microdiorites" exposed near Bald Butte in the Marysville district (Barrell 1907:12) and to the numerous sills in the Helena formation several miles west of Lincoln along Montana Route 20.

Cretaceous (?) Pre-Laramide Quartz Gabbro Sills

Younger sills, also pre-Laramide folding, occur in the Spokane formation. In contrast to the Pre-Cambrian (?) sills, they are much thicker (up to 300 feet thick), unaltered, and contain clinopyroxene as the principal mafic mineral. Intermediate weakly zoned plagioclase (about An_{50-60}) composes about 40 to 60 percent of the rock. Small amounts of interstitial quartz and myrmekite usually are present. The sills characteristically contain late-magmatic granophyric seams and dikelets composed mainly of quartz and plagioclase. Locally, specimens of the sills show malachite stains, suggesting that they contain small amounts of disseminated copper sulfides.

The Stemple Creek sill ("Kdg." Figure 3) is the only large quartz gabbro intrusion in the area, although several large bodies occur east of the map area and one is particularly well exposed near Flesher Pass on Route 285. These sills show a remarkable stratigraphic restriction. They were noted only in the Spokane formation.

The age of the sills is uncertain, and a Cretaceous age is assumed from their designation on the Montana geologic map. The reason for this designation as of Cretaceous age is not clear. They are, however, probably younger than the altered dioritic sills.

Petrographically, the quartz gabbro sills are identical to gabbro sills described from the northeastern part of the Marysville mining district (Barrell 1907: 13) and to quartz gabbro sills described by Knopf (1963:6) from the immediate Helena area. Knopf (op. cit.) concludes that they are Pre-Cambrian because they occur only in Belt rocks. This is not conclusive proof of their age, however, because sills commonly show stratigraphic restriction. The western end of the Stemple Creek sill is cut by post-Laramide porphyritic dikes.

Granitic Stocks

Three granitic stocks and their contact aureoles are prominent features of the geology of the Lincoln area. The Granite Peak and Silver Bell stocks are about two square miles in surface area. The Dalton Mountain stock, which continues southwest of the Lincoln area and was not mapped entirely, is probably about three square miles in surface area. Several areas of hornfelsed Helena formation, such as between Mead Gulch and Prickly Gulch, occur without central exposures of granitic rocks, suggesting that an intrusive underlies them at shallow depth.

Although the Granite Peak stock is a single continuous exposure, the Silver Bell stock is but the largest exposure of many granitic exposures within a continuous contact aureole. Thus, the present level of exposure appears to be the roof zone of a single pluton.

The stocks in the Lincoln area have many features in common: (1) strongly discordant contacts, intensely and brittlely deformed without plastic should-

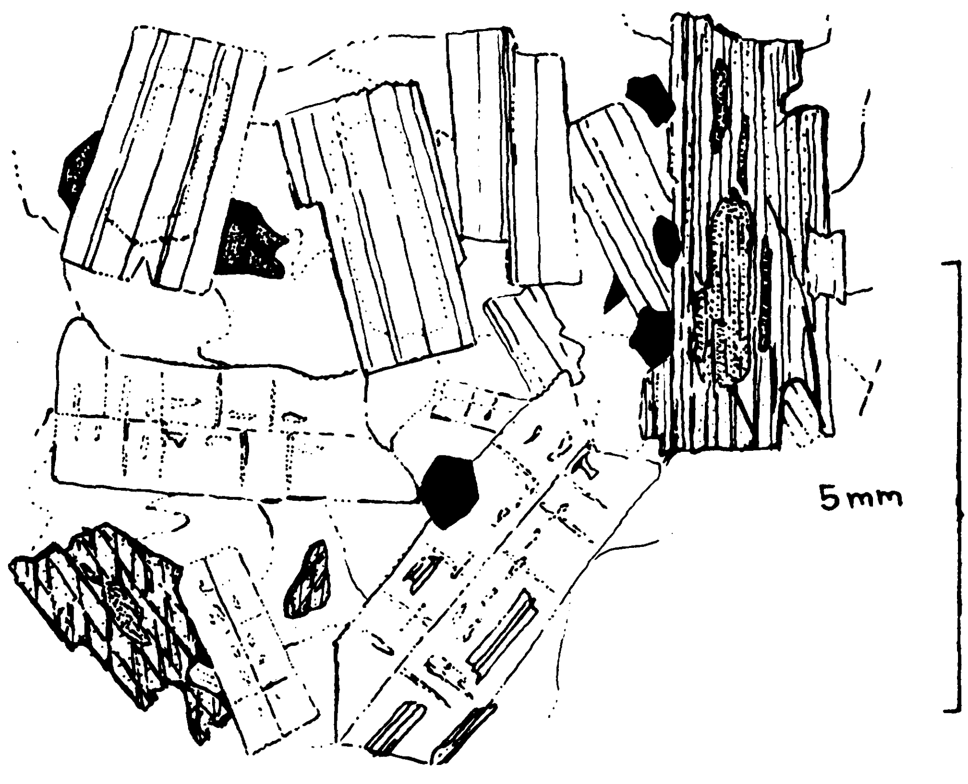

FIGURE 8.—Petrographic sketch of hornblende pyroxene granodiorite from the inner portion of the Granite Peak Stock. Hornblende (lightly stippled, high relief) has clinopyroxene cores (heavily stippled). Orthoclase shows carlsbad twins and commonly vein and patch perthite. Plagioclase (about Ar_{30}) is weakly zoned. Plagioclase and orthoclase in parallel intergrowth in lower central crystal. Quartz in anhedral interstitial grains. Sphene is most common accessory (upper left, heavily stippled).

ering aside; (2) large contact aureoles, in general exceeding the area of exposed granitic rock; (3) lack of chilled contacts; (4) mainly massive, unfoliated, and unlineated granodiorite to quartz monzonite, although small amounts of more mafic contaminated rocks may occur along contacts with calc-silicate rocks; (5) mainly composite (Table 6) without chilled contacts between separate phases; and (6) associated with mineral deposits.

TABLE 6.—*Modes of specimens from the Granite Peak stock*

Mineral	*Abundance in volume percent*						
	a	*b*	*c*	*d*	*e*	*f*[1]	*g*[2]
Plagioclase	52.3	51.4	44.4	39.6	34.6	16.8	1.9
Orthoclase	2.3	17.1	24.0	26.8	25.9	50.7	53.5
Quartz	6.4	15.4	2.6	6.0	8.4	27.6	44.0
Hornblende	7.0	11.5	19.5	9.3	18.0	1.1	0.0
Biotite	17.3	1.0	1.0	15.8	4.8	0.0	0.2
Clinopyroxene	12.9	1.2	1.7	1.4	7.3	3.6	0.0
Accessories[3]	1.8	2.4	6.8	1.1	1.0	0.2	0.4

[1] Sketch in Figure 8.

[2] Aplite dike.

[3] Accessory minerals: Fe-Ti oxide, sphene, pyrite, apatite, epidote.

Stratigraphic reconstruction suggests that the stocks were emplaced at a maximum depth of about three to four miles. The stocks are thus, in view of the above features and shallow depth of intrusion, typical epizonal plutons as described by Buddington (1959:676).

COMPARISON OF STOCKS IN THE LINCOLN AREA.—The mineralogy of the Silver Bell and Granite Peak stocks suggests that they are compositionally similar and are mainly granodiorite and quartz monzonite. The Silver Bell stock, however, in contrast to the Granite Peak stock, shows considerable evidence of late magmatic alteration and mineralization by hydrothermal solutions.

Specimens from the Silver Bell stock characteristically contain considerable quantities of epidote dispersed as a deuteric alteration of plagioclase. Epidote also occurs along joints, commonly with hematite, within the stock and in the contact rocks nearest the granite. Prospect pits show that much of the Silver Bell stock contains considerable disseminated pyrite and in places contains seams and disseminated grains of chalcopyrite. One prospect pit reveals a small irregular body containing libethenite, a copper hydroxy phosphate, and fluorite.

These features suggest that late magmatic solutions were largely retained during cooling. Alternatively, the present level of exposure of the Silver Bell stock is at the roof of a much larger body, and was permeated by solutions derived during cooling of the underlying magma. This latter idea is supported by the broad contact aureole and common shallow dips of the contact. If these features are restricted largely to the roof zones of the stocks, erosion has tripped much of the roof zone of the Granite Peak stock.

The Silver Bell stock also differs texturally from the Granite Peak stock. Most of the Granite Peak stock shows a well-developed, even-granular texture, although it locally contains large crystals of orthoclase near its northern margin (see mode *f*, Table 6). In contrast, the Silver Bell stock characteristically is porphyritic and contains large crystals of strongly zoned plagioclase and, more rarely, orthoclase.

Only a small portion of the Dalton Mountain stock was mapped and thus it cannot be compared satisfactorily with the Silver Bell and Granite Peak stocks. The few specimens collected, however, suggest that the stock is slightly more mafic than the Silver Bell stock and Granite Peak stock, contains about 20 to 40 percent hornblende, and is probably mainly quartz diorite with, perhaps, some granodiorite. Where mapped, it has an even-granular texture, and no porphyritic phases were noted.

The most mafic stock, hornblende gabbro, is near the head of Washington Creek south of the Lincoln area (R. 8 W, T. 12 N, Figure 3). It contains oval, corroded clinopyroxene crystals which are up to one-half inch in diameter and are surrounded by a thin rim of uralitic hornblende. The matrix consists of plagioclase which is deuterically altered to calcite, epidote, and micaceous minerals.

RELATION TO THE BOULDER BATHOLITH.—Barrell (1907:81) suggested that the "great Boulder Batholith" is but the largest exposure of a widespread intrusive mass which underlies a considerable region in western Montana, and that stocks such as at Marysville and Granite Peak are upward prolongations or cupolas in its roof.

Although radiometric dates have not been made on the stocks in the Lincoln area, their age is clearly bracketed between formation of fracture cleavage (presumably middle-to-late Cretaceous), and extrusion of volcanic rocks (probably Oligocene, page 38). The fracture cleavage is randomly rotated in the inner contact zones (Figure 7*c*) and must have formed before the differing competency of beds was destroyed by hornfelsing. The stocks, thus, are presumably the same age as the Boulder batholith, which gives radiometric ages on five samples of 61 to 72 million years by the lead-alpha method (Chapman, et al. 1955) and of 87 million years by the potassium-argon method (Knopf 1956). Numerous new, more reliable K-Ar ages on biotite and hornblende indicate that the emplacement occurred over a long time span, between 78 to 68 million years ago (Tilling, et al. 1968).

Other evidences of genetic relationship to the Boulder batholith are proximity of stocks to the batholith and similar modes of emplacement.

Two field trips permitted brief comparison of the stocks of the Lincoln area with parts of the Boulder batholith near Butte, Montana. Although the batholith is slightly coarser grained than the stocks, they are essentially similar. Hornblende and biotite are the principal mafics in the batholith, although small amounts of clinopyroxene may occur within the hornblende. The stocks in the Lincoln area, neglecting the small mafic intrusion near the Dalton Mountain stock, similarly show clinopyroxene only as relics in the core of hornblende crystals (Figure 9).

Both the batholith and the stocks are composite. As pointed out by Knopf (1957), the batholith contains a wide variety of rock types. The variations in composition, however, are probably no greater than variations within and between the stocks in the Lincoln area.

Aplite dikes in the batholith and stocks are common. Simple pegmatites occur in both and are composed mainly of orthoclase and quartz. Such pegmatites are common in the Granite Peak and Dalton Mountain stocks, but are rare in the Silver Bell stock.

The stocks and associated mineral deposits apparently end at, or just north of, the northern limit of the Lincoln area. The area, thus, is perhaps near the northernmost limit of batholith activity.

Mode of emplacement.—Barrell (1907) in his study of the Marysville stock, located several miles southeast of Granite Peak, presented one of the first completely documented arguments for granite emplacement by magmatic stoping. Although the details of the granite-hornfels contacts at depth are not known in the Lincoln area, the surface exposures of the contact are very similar to those about the Marysville stock.

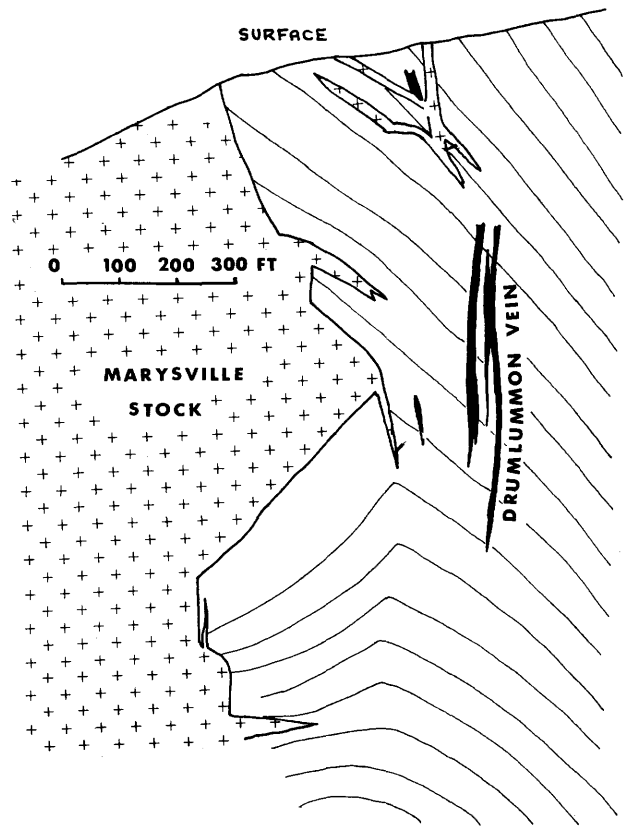

Figure 9.—"Frozen-in" stoping of the Marysville stock. Cross-section of the Drumlummon mine, simplified from Barrell (1907).

For example, detailed mapping about the Granite Peak stock shows that within the inner contact zone intricate brittle deformation has occurred. Structural trends are not deflected by the stock except in the inner contact zone. Thus, because of the lack of doming or other evidence of shouldering aside of the country rock, and abundant faulting and random rotations in the inner contact zone, the Granite Peak stock is inferred to have been emplaced by magmatic stoping. Barrell's evidence (1907, such as plate X, summarized in Figure 9), however, is a much better case for emplacement by magmatic stoping than can be given by surface mapping. The extensive mining of epithermal veins which parallel the contact of Marysville stock at the Drumlummon mine (Figure 9) clearly provides evidence of magmatic stoping which has been "frozen" in process.

The general lack of extensive contamination of the granites, even where they intrude carbonate rocks, as well as the lack of abundant inclusions, shows that the stoped blocks were removed without assimilation at the present level of exposure. The Silver Bell stock is free of inclusions and uncontaminated. If it is the roof zone of a large stock as the field evidence indicates, the fragments of the roof presumably were removed downward.

Diopside-rich rocks which characterize the contact hornfels of the Silver Bell and Granite Peak stock have densities between about 2.9 and 3.1, and thus would readily sink in granitic magma. The Dalton Mountain stock, however, which also shows evidence of emplacement by magmatic stoping, is largely in quartzites of the Marsh formation, which were perhaps slightly less dense than dioritic-to-granodioritic magma. Thus, the subsidence of stoped blocks regardless of density implies that there were downward movements of magma in the stocks. The evidence of emplacement by stoping, the lack of chilled contacts, and the large contact aureoles suggest that the stocks were not emplaced by a single injection of granitic magma but rather were intruded over a long period of time. Perhaps large-scale convection occurred during emplacement and during the initial stages of cooling of these stocks.

Lack of extrusive equivalents.—It is difficult to reconcile the shallow depths of intrusion of the stocks in the Lincoln area with the lack of extrusive equivalents. Barrell (1907:172–173) shows that this problem exists for the Marysville stock and for the Boulder batholith as a whole. He points out that the Boulder batholith, which also lacks extrusive equivalents, may have maintained a thin cover, perhaps a half mile to a mile thick, over some thousands of square miles although it too was emplaced by sinking of blocks from its roof:

> The greatest theoretical difficulty in the way of accepting magmatic stoping as one method of batholithic invasion, a perhaps dominant method in the zone of fracture, is the fact that it apparently ceases without breaking through to the surface with crustal foundering over the limits of the batholithic invasion. Such a caving in of the surface would presumably lead to enormous outpourings which find no suggestion in nature.

The middle Tertiary volcanic rocks, on the other hand, as discussed in the following section, reached the surface from probably numerous vents and are associated with some small intrusive bodies. These contrasting observations, although clearly presented by Barrell in 1907 for the Boulder batholith region as a whole, still lack adequate explanation.

Recent radiometric ages on the Elkhorn Mountain volcanics show that they are but slightly younger than the Boulder batholith. Thus, it appears that during an early stage the Boulder batholith did break through to the surface, only to later intrude its early eruptives.

Middle Tertiary Volcanic Rocks

The area contains about forty square miles of middle Tertiary volcanic rocks which occur mainly in the northern two townships. The volcanic rocks are particularly well exposed at and to the west of Crater Mountain.

The volcanic rocks are mainly acid-to-intermediate flows, flow breccias, and welded ash flows. They reach a maximum of about 1,000 to 1,500 feet thick in the north-central part of the area. Here they consist of a thick series of latitic-to-andesitic rocks and an upper rhyolitic series. The rhyolitic rocks are between 50 and 500 feet thick and are composed mainly of welded ash flows. The welded ash flows show several features which suggest they were deposited as pumice froth flows (Smith 1960:809). Rhyolite domes occur along a minor unconformity which separates the two series.

As noted by Knopf (1963:8–9), the immediate Helena area contains flows which range from rhyolite to olivine basalt. Thus, regionally, as well as in the Lincoln area, the volcanic rocks show a wide variation in composition and fit well into the postorogenic basalt-andesite-rhyolite association of Turner and Verhoogen (1960:282):

> Surface eruption of basalts, andesite, and rhyolite during and following elevation of the folded (land) mass. This phase is typically separated by a lengthy period of time from the main phase of folding and plutonic activity.

The precise age of the volcanic rocks is uncertain. They clearly followed unroofing of the major stocks. Near the Dalton Mountain and Silver Bell stocks they rest unconformably on the contact aureoles. Volcanic rocks lie directly on the eroded surface of the Blackfoot City stock in the Black Mountain area (Bierwagen 1964:pl. 1). Except along later mineralized zones, the flows have remained essentially unaltered since their final cooling. Fresh glass is particularly common at the bottom of welded tuff sheets in the vicinity of Crater Mountain.

Unidentifiable plant fragments were collected near Crater Mountain in thin tuff beds. A few plants, however, of probable Oligocene age (Erling Dorf, oral communication) were collected by the writer in siltstone beds in lavas near Little Prickly Pear Creek, which is on the north side of the Marysville district. These volcanic rocks are lithologically similar to the lower latitic series in the Lincoln area and are perhaps about the same age. The Lincoln area volcanic rocks, thus, are referred to as of Oligocene age, but confirmation by additional fossil finds or radiometric dates is needed. The unconformity within the volcanic rocks, as well as evidence of considerable erosion between periods of volcanism, suggest that eruptions occurred intermittently over a long period of time.

The lower volcanic series are cut by gold- and silver-bearing fissure veins. Such veins were not noted in the overlying welded ash flows.

Lower Volcanic Series

The lower volcanic series is characterized by dark gray to dark reddish-gray massive flows. In general, they are aphanitic and thus their composition is uncertain. Where finely porphyritic, however, the dominant phenocrysts are plagioclase and hornblende or biotite.

The flows characteristically show considerable deuteric alteration and are locally vesiculated. Vesicles near the Seven-Up Mine and in volcanic rock fragments in the Crater Mountain landslide are filled by euhedral calcite crystals. The vesiculation as well as the abundance of deutric alterations suggest that the lavas were, as a whole, water-rich on eruption.

A well-developed platy structure is commonly present. Generally, the platy structure is nearly perpendicular or at high angles to the flow contacts.

Isolated areas of volcanic rocks similar to the lower volcanic series to the north occur along the Dalton Mountain-Continental Divide trail which marks the southern limit to the area.

Flows also similar to the lower volcanic series are exposed on the north side of the Lincoln Valley and along the dirt road leading south from the valley to the Dalton Mountain lookout. The full extent of rocks similar to the lower series remains uncertain, although reconnaissance mapping suggests that they probably do not extend more than several miles north of the Lincoln Valley.

VENTS.—The many isolated patches of volcanic rocks of varying composition suggest that there were numerous local centers of eruption. Dikes and irregular intrusive breccias composed largely of volcanic rock fragments occur in several places in the lower volcanic series. These are particularly well exposed along the Blackfoot River and Willow Creek in and just outside the northeastern part of the area, and along the Poorman Creek road just before it emerges into Lincoln Valley. The intrusive breccias perhaps are associated with vents in the lower volcanic series.

The volcanics along the Dalton Mountain Trail are associated with latitic (?) dikes and fine-grained porphyritic pluglike intrusives commonly containing plagioclase and hornblende phenocrysts. Both dikes and plugs may have served as vents. These are well exposed at the head of Mead Gulch and in a cirque at the head of Prickly Gulch.

Upper Rhyolitic Series

Welded ash flows form a topographically prominent high, flat, steep-sided area which is at an elevation of about 7,000 feet along the northeastern part of the Continental Divide. The ash flows are well exposed along escarpments which everywhere mark the edge of the flat area. As evidenced by isolated erosional remnants on Crater Mountain and on an unnamed mountain about one-half mile due east of it, the ash flows initially covered a much larger area.

Typically, the contact of the ash flows with the underlying Spokane formation in the eastern and northeastern part of the sheet, and with the lower volcanic series, is irregular. The lower contact ranges from an elevation of about 6,300 to 6,700 feet, suggesting a minimum relief of about 400 feet on the surface on which the ash flows were deposited.

A poorly consolidated conglomerate is commonly exposed at the base of the ash flows. The conglomerate on the south and northwest side of the sheet is composed largely of pebbles and cobbles of the older volcanic rocks; and on the east and northeast side, of the Spokane formation. Locally on the northwest side blocky pyroclastic beds as much as 10 feet thick occur at the base of the sheet. No interbedded sedimentary rocks or soil zones were noted within the main ash flows, suggesting that they were deposited over a relatively short period of time.

The ash flows are remarkably similar to one another in hand specimens. They are light gray, and contain about 10 to 30 percent crystals (sanidine and dark gray quartz in varying ratios) and less than 5 percent accidental lithic fragments. The lithic fragments are mainly silstones derived mostly from the Spokane formation. The ash flows contain no mafic minerals except for rare flakes of biotite.

The ash flows lack well-developed contacts where examined carefully at two places along the escarpment. The presence, however, of several ash flows which individually may be up to 50 to 100 feet thick is suggested by varying degrees of welding. Some specimens presumably from the upper parts of ash flows are not welded and are more properly termed crystal tuffs.

Characteristically, the more intensely welded ash flows contain beautifully opalescent ("moonstone") sanidine crystals. Opalescent (or chatoyant) sanidine crystals are due to cryptoperthitic exsolution and are most common in the slowly cooled parts of ash flows (Smith 1960:829; Boyd 1961:399). Thus, their occurrence at specific horizons in vertical sections of the main sheet also suggests the presence of a number of individual ash flows.

Two quantitatively minor but perhaps significant variations occur in the ash flows. Along the Continental Divide at the head of Specimen Creek, unusually large sanidine crystals up to an inch and a half long occur. The significance of this coarser grain size is uncertain, but it is clear that such large crystals crystallized before eruption.

The second textural variation occurs in thin, welded ash flows near Crater Mountain. Although only about 10 feet thick, the ash flows are commonly welded to a black glass at the bottom. The black glass portion of the flows grades rapidly upward into a partially welded top. The index of refraction of the glass is about 1.50 ($\pm$.01) suggesting a silica content of around 73 percent. The glass is rhyolitic and has the following composition based on electron probe analysis: $SiO_2 = 75.9$, $Al_2O_3 = 12.4$, total Fe as $FeO = 0.93$, $MgO = <0.01$, $MnO = 0.08$, $CaO = 0.21$, $Na_2O = 2.9$, $K_2O = 3.9$, $TiO_2 = 0.06$, total $= 96.4$.

Such intense welding of thin ash flows implies high temperatures of emplacement, because there is little load pressure to aid welding and compaction (Smith 1960:830). Rapid cooling of the thin ash flows is suggested by the lack of opalescent sanidine crystals, which are common in the thicker flows.

VENTS.—Several rhyolitic "domes" are associated with the main welded ash-flow sheet. One such body is excellently exposed at the upper part of a landslide scar at Crater Mountain (Figure 10), and consists of strongly flow-banded spherulitic rhyolite. A thin hydrothermally altered zone and a coarse, perhaps intrusive, pyroclastic body occur between the dome and the nearest welded ash flow. The contact between the pyroclastics and the welded ash flows and "dome" are, however, gradational. Thus, the plug which gave rise to the rhyolite dome perhaps earlier served as a vent for the welded ash flows.

At least two other rhyolitic "domes" are exposed near the welded ash flows. The largest of these bodies occurs about one mile west of Crater Mountain and at about the same altitude. Here the flow-banded rhyolite contains spherulites up to four inches in diameter. The "dome" here, however, is separated from the nearest welded tuff by about one mile of exposures of the lower volcanic series (Figure 2). Although plugs were perhaps the source of welded ash flows, fissure eruptions may well have been involved. Domes or intrusives were not noted in the northern portion of the ash flows.

MECHANISM OF ASH FLOW DEPOSITION.—Welded ash flows have not been noted in recent "nuee ardente" deposits (Smith 1960:802), and thus their origin has been controversial. For several reasons it is clear that welded ash flows do not represent normal volcanic flows or more typical tuffs. Although of rhyolitic composition, which implies high viscosity, the ash flows were apparently very fluid and flowed considerable distances. In spite of these distances, sufficient heat was conserved to give intense welding after cessation of flow. Smith (1960) has shown that ash flows must be at a minimum temperature of 600° C to weld and for thin flows perhaps at 800° C at the time of deposition. The occurrence of pheno-

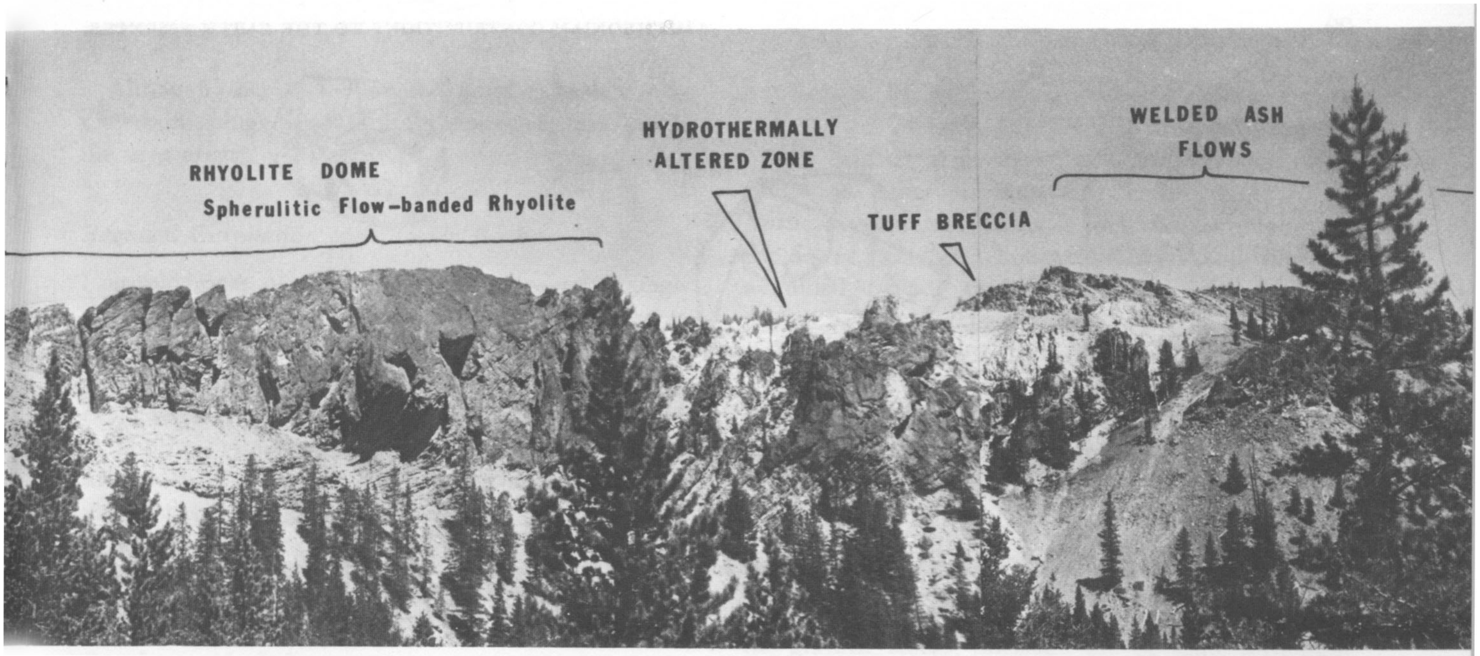

FIGURE 10.—Rhyolite dome and environs exposed in the landslide scar on the southwest side of Crater Mountain.

crysts of quartz and sanidine at the time of eruption suggests that the temperature could not have been much above 900° C at eruption and certainly was less than 1000° C (Smith 1960). Thus, the temperature decrease between eruption and deposition could not have been greater than about 300° C.

A principal problem then lies in proposing a mechanism for rapid emplacement of the flows with sufficient conservation of heat to cause welding. Smith (1960:802–809) has summarized the possible modes of eruptions of ash flows and favors emplacement by "avalanche or flowage of fragmental material and hot gas." He considers "particulate or foam (froth) flows" as a less likely mode of emplacement and summarizes some problems presented by the "froth flow mechanism":

> The supporters of the particulate flow mechanism generally agreed that the driving force of the ash flow or avalanche is gravity aided by expanding gases. Herein lies a problem that needs solution, namely, what is the true nature of the gas emission process, and how does it vary in different ash flows? Is total vesiculation confined to the vent, conduit, or chamber, or does some of it take place in the flow, and if so, how much?

The welded ash flows in the Lincoln area show several features which support the "froth flow mechanism" and suggest that although much vesiculation occurred in the vent, small amounts of gases were emitted even during final welding.

Figure 11 shows fluid inclusions which commonly occur in quartz phenocrysts in the ash flows. Only two or three inclusions occur in thin sections of each phenocryst, and are widely separated. The walls of the inclusions commonly "mimic" the beta quartz form (dipyramids) of the quartz crystals at the time of initial crystallization.

The inclusions are commonly filled by brown glass, with the volatile phase confined to a bubble which segregated before solidification of the glass. Several inclusions show what may be a liquid phase within the gas phase. The size of the bubble suggests that the magmas trapped by growth of the crystals were rich in volatiles, which, along with fragmentation, would greatly lower the viscosity of the ash flow. With release of pressure during eruption, an immense quantity of volatiles probably were evolved from the magma.

Figure 12 suggests that the lavas were supersaturated with volatiles even during final welding and compaction. Thus, continuous emission of volatiles may have occurred after, as well as during, flow. Smith (1960:810) suggests that only small amounts of gases liberated by diffusion would be sufficient to "lubricate" ash flows:

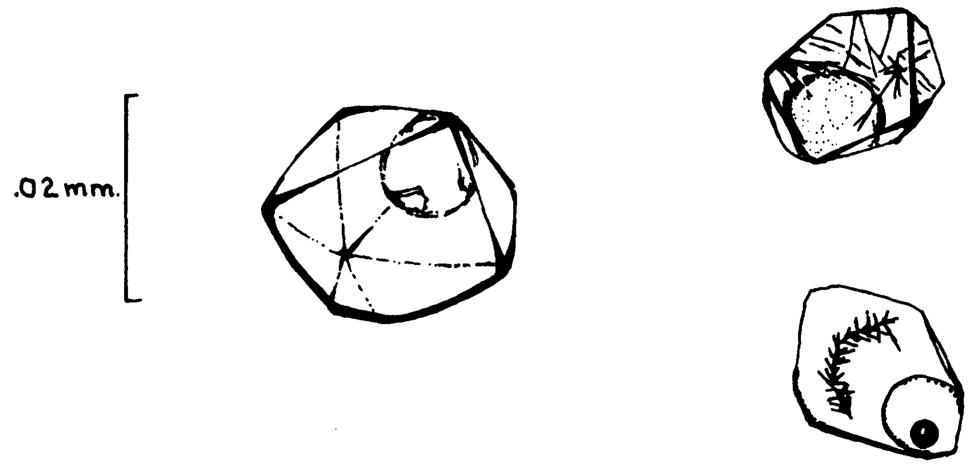

FIGURE 11.—Petrographic sketch of glass inclusions in quartz phenocrysts from the welded ash flows. Dipyramidal shape of the inclusions reflect beta quartz habit during crystallization. Glass normally contains a large gas bubble, trichites, and is light brown and in places fractured.

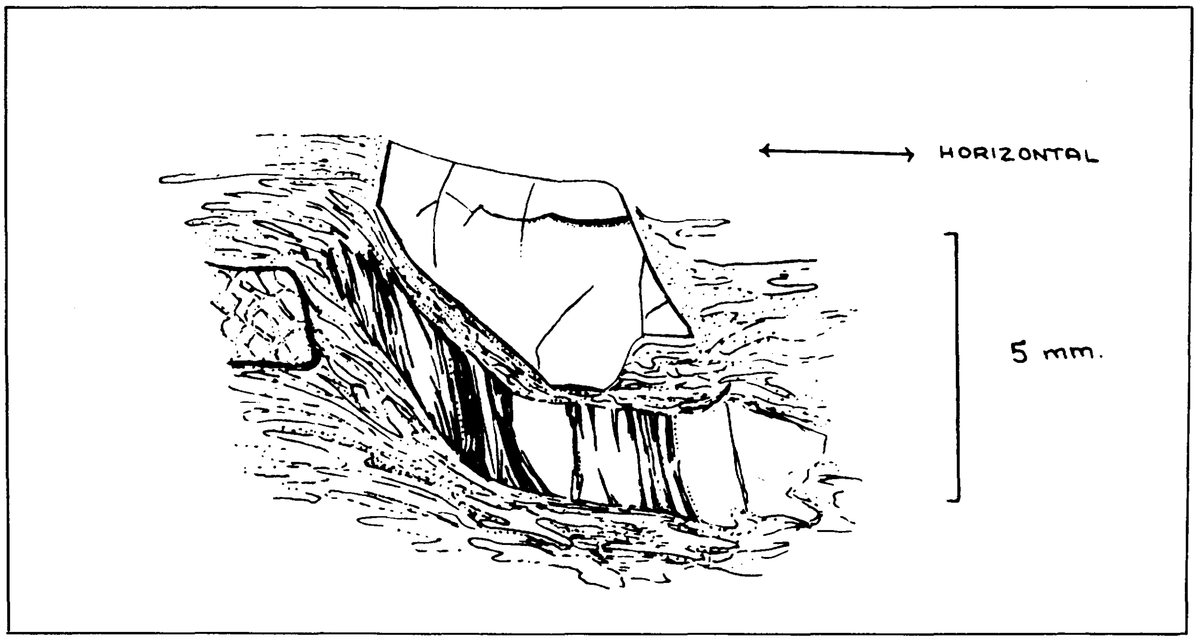

FIGURE 12.—Petrographic sketch of completely welded bottom of thin ash flow near Crater Mountain. Note "draping" of collapsed vesicular glass about quartz phenocryst. Tension zones in the collapsed and stretched glass are defined by numerous minute bubbles, presumably mainly of exsolved water vapor.

Vesiculation, especially in the vent, probably does not reduce the glass to a state of saturation or undersaturation and the glass may continue to lose gas even after some cooling. If the amount given off by diffusion were only a few hundredths of a per cent by weight, the volume at eruption would be impressive and would provide an adequate lubricant.

In summary, it is likely that the welded ash flows in the Lincoln area, particularly the thin but intensely welded flows in the vicinity of Crater Mountain, were deposited as a rapidly moving vesiculating mass of rhyolitic lava (froth flow).

Although the source for the flows as a whole is uncertain, plugs near Crater Mountain may mark the vent areas.

Regional Correlation of Volcanic Rocks

Volcanic rocks of the Lincoln area are mineralogically similar to some of the small areas of volcanic rocks in the Black Mountain locality described by Bierwagen (1964:89–102). Welded ash flows, however, were not noted in the Black Mountain area.

The Lowland Creek volcanic rocks (Smedes 1962) are probably about the same age as the volcanic rocks in the Lincoln area. They cover a much larger area, however, and their welded ash flows apparently are less indurated.

Post-Laramide Dikes

Porphyritic latitic dikes occur throughout the Lincoln area, but are particularly abundant between the Silver Bell and Granite Peak stocks and at the head of Mead Gulch in the southern part of the area. The dikes are clearly later than the formation of fracture cleavage.

In general, the dike rocks consist of about 10 to 30 percent plagioclase phenocrysts which rarely are rimmed by potassium feldspar. The plagioclase phenocrysts were not noted in the chilled contacts, and commonly are largest in the center of the dikes, suggesting formation of the phenocrysts after intrusion. Small phenocrysts of hornblende and biotite compose about 10 percent of most dikes.

Characteristically the phenocrysts and aphanitic matrix are altered deuterically to epidote, calcite, and mica minerals. Deuteric alteration is usually most intense at the center of the dikes. This abundance of deuteric alterations suggests that water was abundant in the intruded magmas and only partially escaped during cooling.

The dikes generally fill high-angle, en echelon tension fractures which individually are rarely more than 200 feet long and 10 feet wide. This arrangement is particularly well shown along ridge crests just south of Poorman Creek and the Silver Bell stock. No consistent regional orientation of the dikes was noted.

The relative age of the dikes to the stocks and Tertiary volcanic rocks is uncertain where the dikes are isolated in Belt rocks. Porphyritic dikes are common in the Stemple Pass mining area, and are cut by the epithermal fissure veins. They may be related, therefore, either to intrusion of the stocks or to Tertiary volcanism. Dikes in the contact aureole of the Silver Bell stock, however, characteristically lack a chilled contact, showing that they were intruded during or immediately after emplacement of the stock, at a time when the contact rocks were still hot.

Dikes and epithermal fissure veins are commonly associated, and may be parallel in the Silver Bell stock area. The dikes in general are earlier than the associated epithermal veins.

Contact Metamorphosed Belt Rocks

Most of the contact metamorphic rocks occur around the granitic stocks, although the Spokane formation is metamorphosed as much as fifty feet from the contact of the Stemple Creek quartz gabbro sill. Table 7 summarizes some of the principal changes produced by contact metamorphism of the Belt formations.

In general, formations may be identified even where they are contact metamorphosed. Around the Silver Bell stock, however, hornfelsed Helena and Empire formations apparently are intricately faulted and, with only isolated exposures, it is difficult to distinguish between the two. Both contain dolomitic siltstone beds which react to form tremolitic and/or diopsidic hornfels. Areas where the hornfels are predominately dark gray are mapped as Empire formation. Hornfels derived from the Helena formation are mainly lighter colored and as a whole contain considerably more diopside. Hornfelsed "molar tooth" beds are most useful in recognition of metamorphosed Helena formation.

In the few places, it has been seen, the transition from unmetamorphosed Helena or Empire formation to hornfels of the aureole occurs over a distance of several feet. Within the aureole itself, few megascopic changes occur in the hornfels on approach to the Granite except within 100 to 200 feet of the contact, where skarns and other metasomatic assemblages are common.

Broad contact aureoles are developed only in "reactive rocks," such as the impure carbonate rocks of member C of the Marsh formation and of the Helena and Empire formations. The quartzites of

TABLE 7.—*Hornfelsed Belt formations*

Formation	*Intrusive*	*Hornfels description*
Spokane	Quartz gabbro (Stemple Creek sill)	Dark gray due to recrystallization of red iron oxides to specular hematite. Detrital muscovite recrystallized and coarser grained.
Empire	Silver Bell stock	Dark brown and gray to light green to gray layered to massive hornfels. Dark colored varieties contain some recrystallized iron oxides (specular hematite) and/or biotite. Light green layers contain tremolite and/or epidote; light gray layers contain considerable diopside.
Helena	Granite Peak and Silver Bell stocks	Mainly light-colored, layered hornfels; diopside and/or tremolite main minerals. Hornfelsed "molar tooth" beds and massive white diopside, quartz, and calcite beds distinctive. Minor brown, biotitic layers.
Marsh		
Member A	Nowhere metamorphosed	
Member B	Dalton Mountain stock	Dark gray; colored largely by specular hematite.
Member C	Dalton Mountain stock	Mainly green layered hornfels composed largely of quartz, micas, and actinolitic amphibole. Some dark gray massive beds. Locally "spotted hornfels" occur showing spots of unreacted rock surrounded mainly by actinolitic amphibole, muscovite, and quartz.
Member D	Dalton Mountain stock	Massive quartzites, metamorphism suggested only by intense induration (conchoidal fracture) and some metamorphic minerals in rare impure beds.

the upper Marsh formation show little field evidence of contact metamorphism around the Dalton Mountain stock, presumably because they are composed mainly of quartz and feldspar, an assemblage stable at high temperatures.

Mineral Deposits

Introduction

The mineral deposits in the Lincoln area were formed after Laramide folding, and are probably genetically related to the late Cretaceous (?) granitic stocks and middle Tertiary volcanism. The deposits may be divided into (1) high-temperature veins and replacement deposits within the stocks and their inner contact zones, (2) epithermal gold- and silver-bearing fissure veins, and (3) gold placer deposits.

High-Temperature Veins and Replacement Deposits

Milky quartz veins, such as the Prize and Hubbard veins (Pardee and Schrader 1933), occur very near and within the Granite Peak stock and locally contain minable gold. The mineralogic details of the veins are uncertain, although the dumps show mainly milky quartz with considerable pyrite. These differ from the epithermal veins in their low calcite content, massive milky quartz, and lack of epithermal textures. Small milky quartz veins contain sulfides, mainly pyrite, chalcopyrite, and galena. Chalcopyrite and andraditic garnet-bearing skarns occur locally at the contact of the Granite Peak stock and more rarely at the contact of the Silver Bell stock. The skarn deposits are not large, and have not proven of economic value.

Pyrite and chalcopyrite locally occur in disseminated grains and in small veins in many prospect pits within the Silver Bell stock. The full extent of such areas and their copper content are unknown.

Scheelite has been found in the inner contact zone of the Marysville stock (Knopf 1950), but it was not noted in the few specimens of skarns and hornfels collected around the Granite Peak and Silver Bell stocks and examined in ultraviolet light.

Andraditic garnet fissure veins occur locally in the inner contact zone of the Granite Peak stock. The veins commonly contain small amounts of chalcopyrite, calcite, and epidote. In one well-exposed garnet vein in a prospect pit about a quarter of a mile east of the Granite Peak lookout, a thin but distinct seam of chalcedonic quartz occurs at the center. Thus, the last filling occurred at a much lower temperature than the initial deposition of andraditic garnet.

Epithermal Gold-Silver Fissure Veins

Most of the gold and silver deposits of the Lincoln area are discussed briefly by Pardee and Schrader (1933:77–87; 117–19) as part of the greater Helena mining region. Their descriptions are of particular value because many of the mines are now caved.

Gold and silver valued at a minimum of $10 million were produced in the area mainly between 1870 and 1930 (Pardee and Schrader 1933). Most of the gold was from placer deposits in McClellan Gulch (about $7 million) and from the Jay Gould mine (about $2.5 million).

STRUCTURE.—The fissure veins are in tension fractures which dip between 60 and 90 degrees and may be traced without interruption for distances up to a thousand feet although they are generally much shorter. The width varies, but rarely exceeds twenty feet, and in most places is less than five feet. The veins contain breccia which is mainly an open aggregate of fragments of their wallrocks. The breccias were probably formed by local collapse of parts of the vein walls during opening of the tension fractures. Fault gouge occurs locally along post-mineralization faults. Gold noted in a prospect pit in the Silver Bell area is deep yellow and occurs as films which coat amethystine quartz crystals. The only gold assays available to the writer for mines in the Lincoln area are those listed by Pardee and Schrader (1933:77–87).

As shown by stope maps of mines in the Lincoln area (such as for the Gould Mine, plate 10, Pardee and Schrader 1933), the ore distribution is restricted both vertically and horizontally. Intervening areas, though essentially barren of silver and gold, show gangue minerals and textures identical to those in ore. Figure 13 shows the location and orientation of some productive and nonproductive fissure veins.

The scant available data show that most gold and silver was produced less than five hundred feet below the ore-bearing outcrop. This restricted vertical extent of ore in the fissure veins is the only available evidence of vertical zoning in the area. As indicated by Pardee and Schrader (1933:79), however, the Marysville Drumlummon Mine, which shows well-developed vertical zoning, is similar to the Gould Mine. Thus, the zoning in the Drumlummon Mine, which corresponds to zoning in most of the epithermal veins in the Marysville area (William R. Wade, oral communication), is of interest as a guide to possible zoning in the Lincoln area. The zoning as summarized by Wade (Table 8) is of value to future studies of the epithermal veins, as well as an important aid to exploration and development of fissure veins in the Lincoln area.

TABLE 8.—*Zoning of minerals in the Marysville epithermal gold deposits (from the top down)*

1. TOP OF VEIN. Vein begins as narrow fissure which may be only a few inches wide. May contain calcite but no quartz. Vertical range about 500 feet and may begin about 1500 feet below surface at time of formation.
2. UPPER CALCITE ZONE. Zone most often exposed at surface in Marysville district. Vertical extent about 100 to 200 feet. No gold but maybe a trace of silver. Calcite and siderite or ankeritic calcite are most abundant gangue minerals. No quartz. Some breccia and perhaps fault gouge. Vein wider than at top.
3. MAIN CALCITE ZONE. Mainly ankeritic calcite with little or no quartz. Traces of manganese oxides. Traces of gold and about 0.1 to 0.2 ounces of silver per ton. Vertical range about 200 to 300 feet.
4. TOP OF ORE ZONE. Gold and silver content increases abruptly. Gold commonly about 2 to 3 ounces per ton and silver about 10 to 20 ounces per ton. Quartz more abundant and commonly chalcedonic. Manganese, iron oxides, and adularia commonly present. Sulfides become abundant and are dominantly pyrite and tetrahedrite. Vein generally about 8 to 12 feet wide. Vertical range 100 to 200 feet.
5. MAIN ORE ZONE. Gold about 0.5 ounces and silver about 6 ounces per ton. Vein commonly about 25 to 35 feet wide. Quartz often replaces platy calcite crystals giving "lamellar" quartz. Very little calcite present. Sulfides about 1 weight percent of ore and are mainly pyrite, tetrahedrite, chalcopyrite, galena, and sphalerite. Sulfides are mainly concentrated about fragments of hornfels breccia ("wedding ring" ore). Vertical range 500 to 800 feet.
6. NEAR BOTTOM OF ORE ZONE. Ore may stop abruptly along a horizontal plane or may decrease abruptly to 0.1 to 0.2 ounce gold per ton and less than 1.0 ounce per ton of silver. Vein may commonly divide into two veins. Sulfides continue as in main ore zone and may even increase to 2 or 3 weight percent. Chalcopyrite and galena are dominant sulfides. Vertical range about 100 to 200 feet.
7. BARREN ZONE. No gold or silver. Minerals and textures, however, similar to zones 4 and 5. "Milky" quartz common. Vein may grade downward into uncemented hornfels breccia.

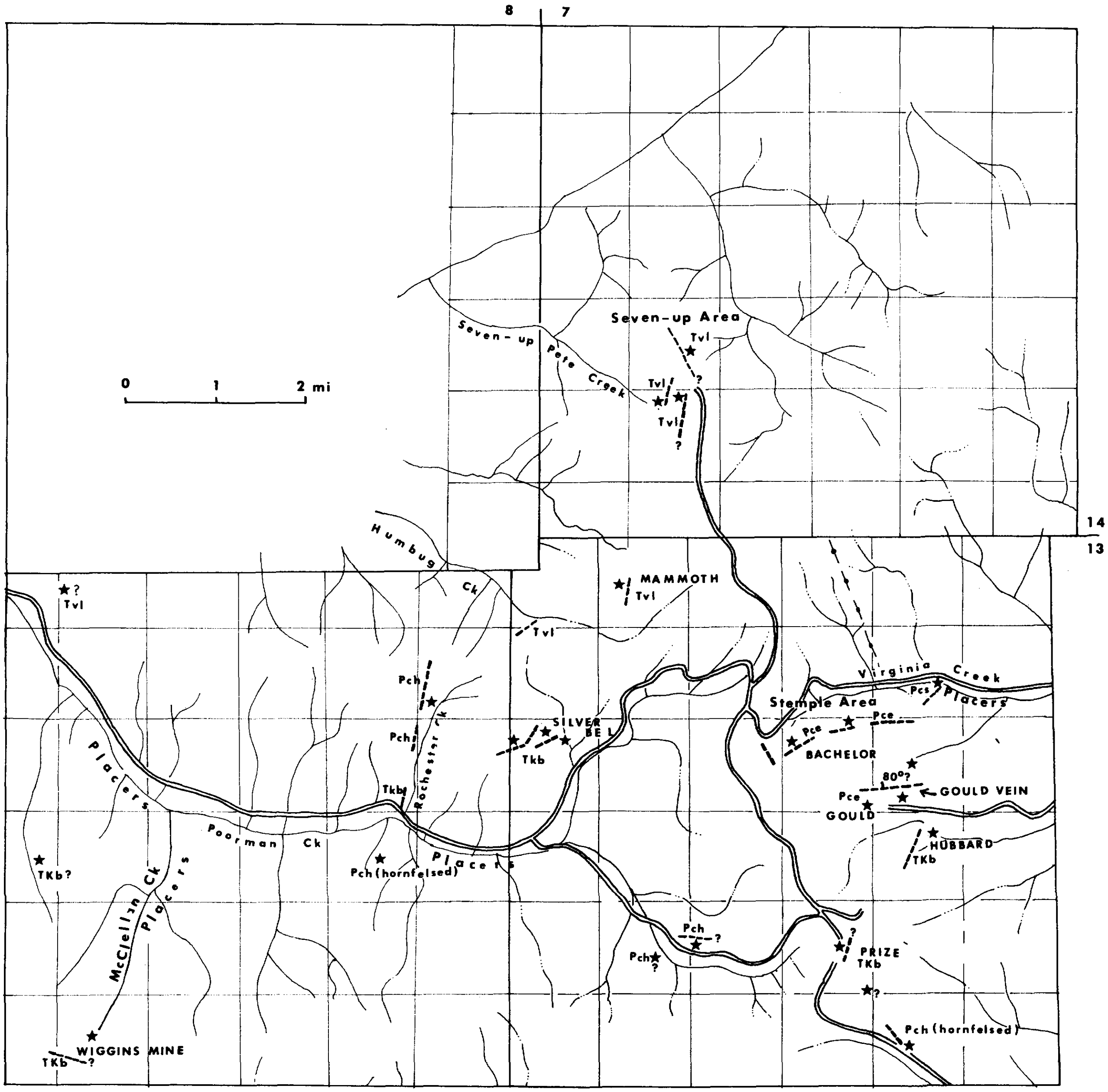

FIGURE 13.—Location and orientation of some fissure veins in the Lincoln area. Stars indicate mine locations. Most of these were abandoned prior to the period 1962–1963, and none were in major production. Heavy dashed lines indicate orientation of veins; both the length and width of the veins are exaggerated. Question mark indicates that the orientation of the vein was not obtained. Country rock is indicated as follows: Tvl = Tertiary volcanic rocks; Tkb = granitic stocks; Pch = Helena formation, Pce = Empire formation, and Pcs = Spokane formation.

MINERALOGY AND TEXTURE.—Quartz and calcite, the main gangue minerals, characteristically occur as plates of calcite in a matrix locally composed of anhedral quartz. In some specimens, quartz has replaced calcite plates. This platy calcite-quartz intergrowth is characteristic of epithermal deposits and has been discussed by Lindgren (1933:449) and Pardee and Schrader (1933:82–83). Calcite and quartz commonly fill interstitial areas in vein breccias, and quartz has in places completely replaced breccia fragments. Calcite, as shown by its common yellowish-to-dark-brown color where weathered, normally contains some iron (ankeritic).

Amethystine quartz, although common in epithermal veins (Lindgren 1933:446), was noted only in the veins in the vicinity of the Silver Bell stock. Here, quartz crystals show delicate "phantoms" of amethystine quartz. Colorless chalcedonic quartz also occurs in most veins.

Pyrite is the principal sulfide mineral, although small amounts of chalcopyrite were noted in the fissure veins in the Silver Bell and Seven-Up areas.

Gold occurs mainly as the native metal alloyed with some silver. Native gold from the Gould Mine is very light yellow, suggesting a high silver content, and commonly occurs as thin films and fillings around granular, clear quartz. Assays from the Jay Gould Mine suggest that such gold may contain about 5 percent silver (Pardee and Schrader 1933: 81). Robert Clearman of Helena provided the writer with a sample of such silver-rich gold from the Gould Mine. Joseph Nelen of the Smithsonian Institution analyzed this gold on the electron microprobe and found that it contains about 40 percent silver, and a minor amount (less than 1 percent) of copper. This gold alloy is thus electrum, a silver-rich alloy containing 20 or more percent silver.

Evidence of two periods of epithermal mineralization.—The age of the gold-silver deposits and their possible genetic relation to the granitic stocks and middle Tertiary volcanism in the greater Helena mining district have been discussed by several authors. Barrell (1907) suggested that there were at least two periods of mineralization: one following but genetically related to the intrusion of the Marysville stock, and a second later period after extrusion of middle or late Tertiary volcanic rocks. Knopf (1950:843) suggested that there was a single period of mineralization and that it occurred after extrusion of the middle Tertiary volcanic rocks. The study of the mineral deposits in the Lincoln area supports Barrell's conclusion that there were at least two periods of epithermal mineralization.

The gold and silver veins in the Seven-Up area formed after extrusion of the lower volcanic series and are probably the youngest mineral deposits in the area. Epithermal veins were not noted in the welded ash flows and perhaps formed before their extrusion.

The principal problem lies in establishing that there was an earlier period of mineralization associated with the granitic stocks. The evidence of low-temperature deposition of the gold-silver veins, such as their common content of chalcedonic-to-opaline quartz, suggests that they did not form immediately after intrusion of the stocks. Tremolite and diopside hornfels probably formed at least at 300° to 400° C, considerably higher than temperatures estimated for the formation of epithermal veins (100° to 200° C, Lindgren 1933:454). Thus, the epithermal veins in the contact aureoles of the Granite Peak and Silver Bell stocks undoubtedly formed after considerable cooling of the stocks and their contact aureoles. This, however, does not prove that the veins are unrelated to the stocks, as has been suggested for the veins about the Marysville stock (Knopf 1950: 843). They may well have been deposited from solutions from deeper parts of the cooling stocks or batholith, which were injected into the already cooled upper parts of the stocks and contact aureoles.

Such a genetic relationship between the epithermal veins and associated stocks is indicated by (1) the proximity of most epithermal veins to the stocks, and (2) the possible cooling sequence of the stocks shown by chalcedonic quartz fillings in the center of andraditic garnet veins. The presence of epithermal veins which parallel porphyritic dikes in the aureole of the Silver Bell stock (section 13, T. 12 N., R. 8 W.) is an additional line of evidence suggesting that the deposits are genetically related to the stocks. As shown by the lack of chilled contacts on such dikes, they formed during or immediately after intrusion of the stocks. It is likely that tension fractures which formed due to the same stress conditions during the cooling of the stocks were filled by magma and later, after considerable cooling, by hydrothermal solutions.

Origin of tension fractures.—Barrell (1907: 105) suggested that the tensile stress which resulted in formation of the Marysville fissure veins was developed during cooling and contraction of the stock and contact aureole.

Barrell's explanation cannot apply to veins in the unmetamorphosed Belt formations such as in the Stemple area. Similarly, fissure veins in the volcanic rocks are very linear, although they may cut many different flows. These areas suggest that the tension fractures may have developed in response to more regional, horizontally directed tensile stress—perhaps in connection with the fissuring which allowed lavas to reach the surface.

UNDISCOVERED ORE BODIES.—Exploration for gold and silver fissure veins was carried out mainly by shallow prospect pits. If these produced no workable ore, the site was abandoned. The restriction of ore bodies only to certain portions of the veins, both laterally and vertically (Table 8), makes this a most unsatisfactory method of prospecting. Once a sizable quartz-calcite vein has been discovered at the surface, only lateral tracing and drilling allow a realistic appraisal of the vein's value. Table 8, if correct, provides a valuable guide to the location of a prospect in regard to ore bodies. The scheme, however, is in need of additional verification.

Numerous unprospected and prospected fissure veins were noted during the mapping. These have not been adequately explored, and it is reasonable to expect that some of these contain sizable ore bodies.

Placer Deposits

Gravels, which locally contain gold, veneer the valley floors. According to Pardee and Schrader (1933), most placer deposits were largely exhausted before 1900. Placer deposits are along streams which drain mining areas, but the gold production of the placers bears no relation to production in known fissure veins. For example, the richest placer deposits occurred in McClellan Gulch, although fissure veins at the head of the Gulch have not been highly productive.

RELATION BETWEEN PLACER DEPOSITS AND GLACIATION.—As discussed under glaciation, many valleys were probably at times filled by glaciers. Such glaciation results in the scouring of the bed rock along valley bottoms and, thus, in the removal of placer deposits.

Small cliffs and abrupt steep slopes mark the head of McClellan Gulch as well as the adjacent head of Washington Gulch, and suggest perhaps an early period of valley glaciation in these gulches. Thus, the rich placer deposits of these creeks have probably accumulated since the earliest Pleistocene, or during a maximum period of about three million years. More likely, they have accumulated within the last several thousand years.

Summary of Post-Laramide Igneous Activity and Mineralization

The evidence presented here suggests that there were two major post-Laramide periods of igneous activity in the Lincoln area. Both were probably accompanied by approximately contemporaneous periods of mineralization and both were characterized by intrusion or extrusion of magmas of diverse composition, although granitic rocks predominated. The principal difference between the two periods is that the earlier or Boulder batholith period was mainly intrusive, whereas the magma involved in the Tertiary intrusions made their way to the surface.

Also, Tertiary volcanism, Boulder batholith activity, and mineralization all appear to end at, or just north of, the Lincoln area. Thus, there are not only gross similarities between the periods of igneous activity, but also spatial superposition.

Geomorphology

Middle Tertiary Surfaces

The area contains remnants of middle Tertiary surfaces under the volcanic rocks. Probably the earliest surface is that preserved under the lower volcanic series in the northwest part of the area. Beginning along the Continental Divide near Crater Mountain this contact is at about 6500 feet. West, toward the Lincoln Valley, the contact is exposed at about 4500 feet. The volcanic rocks show little evidence of extensive faulting and, thus, it is likely that the surface had a relief of about 2000 feet at the time of earliest eruptions. This surface, therefore, was probably similar in relief and slope direction to the present surface.

Several features, however, suggest some differences between the Tertiary and recent drainage patterns. Silicified conglomerates interbedded with flows cap several ridges south of Poorman Creek. The conglomerates are composed mainly of rounded, arkosic quartzite boulders and gravels derived mainly from the Marsh formation far to the south. Thus they probably came from south of the Dalton Mountain-Granite Peak Divide during a period when the drainage system was different from that at present. The boulders, which show no evidence of glacial origin, are up to a few feet in diameter and suggest very steep stream gradients and high relief at the time of deposition.

After eruption of the lower volcanic series a period of erosion and alluviation occurred, as shown by the soil zone and conglomerates between the welded ash flows and the lower volcanic series.

The ash flows presumably flowed into the lower areas. Thus, the present area below the ash flows of the Continental Divide may have been a flat or perhaps gently rolling valley bottom at the time of eruption. This shows that the volcanic field to the west must have been quite thick, perhaps with volcanoes towering to over 8,000 feet, and reaching more than 3,500 feet thick. Since their deposition, the compact, durable welded ash flows have resisted erosion, resulting in a reversal of topography. The steep canyons which begin near the unconformity under the ash flow have probably been eroded a minimum of 3,000 feet since the ash flow eruptions.

Pleistocene Glaciation

There were at least two periods of glaciation in the area. The earliest was marked by large-scale valley glaciation evidenced by the widespread glacial features of the Lincoln Valley. Later periods are indicated by local moraines near the heads of most valleys.

The western half of the Lincoln Valley is marked by numerous small lakes and glacially derived deposits. Near the eastern end of the glacial deposits, large boulders—many with glacial striae—occur up to about 500 feet above the valley floor. The boulders which veneer the northern part of the valley between Landers Fork and Keep Cool Creek (Figure 2) are mainly fragments of welded ash flows, and thus were derived near the Continental Divide about seven miles to the west. The glacial debris also contains abundant fragments of brightly colored chalcedony. The source of these is uncertain.

The abundant and, in general, high-level glacial deposits in and around the Lincoln Valley are perhaps a result of the narrow Blackfoot River canyon on the west side of the valley. Because of this constriction, valley glaciers at times may have accumulated rapidly, becoming over 500 feet thick around the valley margins. Flat, flood-plainlike areas with small abrupt gravel-covered hills mark the entrance of Humbug Creek into the Lincoln Valley. This surface perhaps formed during late periods of glaciation, when rapid additions of sediments from the head of Humbug Creek were deposited on the valley floor. These deposits partially bury older valley moraines.

The very steep slopes and cliffs which commonly mark the intersection of principal valleys and the Continental Divide and Poorman-Nevada Creek Divide are the headwalls of former valley glaciers. Additional evidence of extensive valley glaciation is shown by moraines and boulder trains composed mainly of welded ash flow fragments near the ridge crests about the intersection of Trout and Virginia creeks.

In spite of evidence of glaciation, the valleys are characteristically V-shaped. This is perhaps a result of post-glaciation erosion or very short periods of valley glaciation, or both.

Recent Surface Changes

A large landslide formed by the collapse of the west side of Crater Mountain into the upper valley of Humbug Creek. The slide stretches over a mile down the Creek and is composed mainly of blocks of the lower volcanic series as much as thirty feet in diameter. A small lake has formed in a side canyon dammed by the slide.

The sparse growth of pines on the slide and the lack of weathering of the blocks suggest that the landslide took place recently.

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