Geology and Igneous Petrology of the Northern Elkhorn Mountains Jefferson and Broadwater Counties, Montana

GEOLOGICAL SURVEY PROFESSIONAL PAPER 510

Prepared partly on behalf of the U.S. Atomic Energy Commission

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By HARRY W. SMEDES

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GEOLOGY AND IGNEOUS PETROLOGY OF THE NORTHERN ELKHORN MOUNTAINS JEFFERSON AND BROADWATER COUNTIES, MONTANA

By Harry W. Smedes

ABSTRACT

The northern Elkhorn Mountains comprise an area of about 132 square miles in west-central Montana. The area includes parts of four major geologic units: (1) in the northern part, a narrow belt of folded and faulted upper Paleozoic and Mesozoic sedimentary rocks more than 5,700 feet thick; (2) in the eastern part, a folded and faulted sequence of Upper Cretaceous volcanic rocks more than 11,500 feet thick, and related intrusive rocks; (3) in the western part and near the northeastern corner, plutonic rocks of the Boulder batholith, with small bodies of Tertiary igneous rocks cutting and resting upon them; and (4) along the northern edge, poorly consolidated and unconsolidated deposits of ash, tuff, and gravel of Tertiary and Quaternary age.

The oldest rocks are limestone of the Lower and Upper Mississippian Madison Group, divided into a thin-bedded lower unit, the Lodgepole Limestone, and a thick-bedded to massive upper unit, the Mission Canyon Limestone. They probably are separated by an erosional unconformity from the overlying siltstone and dolomite of the Amsden Formation of Late Mississippian and Pennsylvanian age, which in turn is conformably overlain by vitreous quartzite and limestone of the Quadrant Formation of Pennsylvanian age. The Quadrant Formation is conformably overlain by quartzite, chert, limestone, and phosphatic quartzite of the Phosphoria Formation of Permian age.

The oldest Mesozoic unit is the Swift Formation of Late Jurassic age, which is a thin highly calcareous cherty marine sandstone resting with slight erosional unconformity on the Phosphoria Formation. The Swift is overlain by nonmarine siltstone and calcareous sandstone of the Morrison Formation of Late Jurassic age, followed by the Kootenai Formation of Early Cretaceous age, which consists of marine sandstone, siltstone, and shale and two beds of fresh-water limestone near the top. The Kootenai Formation is overlain by the Colorado Formation of Early and Late Cretaceous age—an assemblage of marine dark shale and siliceous mudstone and nonmarine quartz-chert sandstone and siltstone.

The Colorado Formation is overlain by the Slim Sam Formation, which comprises a lower unit of cherty and feldspathic sandstone, siltstone, and siliceous shale and an upper unit that contains a sandstone facies and a tuffaceous facies.

In places grading upward from, and in places resting with angular unconformity on, the Slim Sam Formation is a thick sequence of basaltic, andesitic, rhyodacitic, quartz latitic, and rhyolitic volcanic rocks called the Elkhorn Mountains Volcanics. These volcanic rocks probably all are of Late Cretaceous age and comprise three gross regional stratigraphic units, the aggregate thickness of which is more than 11,500 feet. The lower unit is predominantly fragmental volcanic rocks and autobrecciated lava flows and subordinate thin sheets of quartz latite ash-flow tuff. The middle unit is characterized by thick sheets of welded rhyolitic tuff having intercalated more-calcic fragmental volcanic rocks and autobrecciated lava flows. The upper unit contains well-bedded water-laid andesitic and basaltic sedimentary rocks and subordinate beds of pyroclastic rocks.

The Tertiary is recorded by a sequence of rhyolitic volcanic and related epiclastic rocks, thick remnants of which occur on Lava and Burnt Mountains, and by thick deposits of tuff, ash, gravel, sand, and mudflow breccia, which form a thick blanket along the northern part of the area and extend northward where they fill an intermontane basin.

The Pleistocene and Recent are represented by terrace gravel, glacial moraine and outwash debris, flood-plain deposits, alluvium, hillwash, landslide debris, and talus.

Calcalkaline intrusive rocks occupy large areas in the mapped area. They fall into four principal groups: (1) intrusives partly contemporaneous with the Elkhorn Mountains Volcanics; (2) rocks of the composite Boulder batholith; (3) rocks correlated with the Lowland Creek Volcanics; and (4) rocks correlated with the extrusive rhyolite in the map area.

Intrusion of basaltic to rhyodacitic magma was partly contemporaneous with extrusion of the volcanics, and reservoirs of magma probably moved ever higher into the growing volcanic pile. The main episodes of intrusion of these shallow bodies appear to have followed, and perhaps partly overlapped, the period of deposition of the upper unit of the volcanics. Intrusion was accompanied by large-scale block faulting, and some of the blocks foundered in the magma chambers. Large compound and complex intrusive masses of basaltic and andesitic rocks lie along, and probably were partly controlled by, a broad syncline. Sills and dikes, locally in complex swarms, abound around margins of the larger intrusive masses; they also occur in the older sedimentary rocks. A possible composite cone sheet was emplaced around the present site of the Antelope Creek stock. The Elkhorn Mountains Volcanics were thoroughly altered by volcanic fluids and heat; many episodes of alteration commonly are recorded in a single rock.

The Boulder batholith was emplaced at the close of a main orogenic episode, in at least four major stages, probably during very Late Cretaceous and Paleocene time. The earliest stage involved intrusion of mafic rocks, mostly gabbro, syenogabbro, diorite, syenodiorite, monzonite, and related rocks. These are now preserved principally in the northern part of the area where they are a component of a large mass called the Koko-

ruda Ranch complex, which lies between layered host rocks to the north and northeast, and quartz monzonite of the main intrusive stage of the batholith to the south. A partial ring dike of these early mafic rocks borders the Antelope Creek stock in the northeastern part of the area, and plugs lie in volcanic rocks in the middle-eastern and southern parts of the area.

The second, or intermediate, intrusive stage of the batholith involved less-calcic magma that produced granodiorite and related rocks. These occur as a component of the Kokoruda Ranch complex, where they cut early mafic rocks, and as the Antelope Creek stock. Granodiorite in the Kokoruda Ranch complex is coextensive with the Unionville Granodiorite to the west.

The third, or main, intrusive stage produced hornblende and biotite quartz monzonite and granodiorite correlated with the Butte Quartz Monzonite and Clancy Granodiorite; it comprises the bulk of the Boulder batholith. The eastern margin of the main mass of the batholith was controlled by a major north-northeast-trending fault.

The final stage of emplacement is represented by alaskite, aplite, pegmatite, potassic granite, leucogranite, and leucogranodiorite, which generally form steep and flat dikes and small irregular masses mostly within the batholith.

Thermal metamorphism attendant on the emplacement of the batholith produced broad zones of hornfels and granulitic rocks.

Tertiary dikes and plugs occur in many parts of the batholith and locally in prebatholith rocks. The older of these are quartz latite, the younger are rhyolite. Large blocks of the batholith and the extrusive Tertiary volcanics foundered in a shallow chamber of rhyolite in the Lava Mountain area.

The structural history is complex. The earliest deformation recorded in the area was local folding along south-southwest-plunging axes after, and probably during, deposition of Slim Sam beds. The main episode of deformation occurred after deposition of the Elkhorn Mountains Volcanics when all the pre-Tertiary stratified rocks were folded and faulted. During this deformation steep faults in an east-west tear fault zone cut the northern part of the area. Rocks to the north in part lie in a southeast-plunging anticline, whereas to the south they lie in a broad south-southwest-plunging syncline which is cut by steep faults and large prebatholith intrusive bodies that were partly contemporaneous with the Elkhorn Mountains Volcanics.

Some of these faults guided emplacement of the batholith and older intrusive bodies. Recurrent movement along some faults resulted in offset of the batholith and older rocks and guided postbatholith intrusive bodies and veins. Young faults and intrusions have to some extent modified or obscured the relations of older structures and intrusions, and many of the faults are collapse structures related to the intrusions.

Mineral deposits in the area comprise metalliferous quartz and chalcedony veins, largely confined to the area of the batholith; a small oxidized gold deposit along the gouge zone of a bedding-plane fault in the Quadrant Formation; small disseminated silver-lead-zinc deposits in the Tertiary rhyolite in Lava Mountain; small replacement magnetite deposits in a monzonite dike west of the Antelope Creek stock; and several gold placers, mainly along Prickly Pear Creek and in Mitchell Gulch. Quartz veins have been subdivided into four groups on the basis of proportions of contained base and precious metals, and type of gangue: (1) epithermal high-grade silver, (2) mesothermal lead-zinc-silver-gold, (3) mesothermal gold and silver, and (4) hypothermal gold. Veins of epithermal type may be contemporaneous with the chalcedony veins. The mesothermal veins probably are variants of a single type. The hypothermal veins probably are the oldest deposits and are thought to be closely associated with the late stage of consolidation of the batholith.

Chalcedony occurs as veins, stringers, and zones, mostly devoid of metallic minerals but locally containing sparse silver or uranium minerals, pyrite, galena, chalcopyrite, sphalerite, carbonate minerals, barite, and opal. Uranium ore has been mined from a zone of chalcedony veins of the W. Wilson mine in the westernmost part of the area.

INTRODUCTION

The area described in this report comprises the north half of the Clancy 15-minute quadrangle and about 28 square miles of the eastern part of the East Helena 15-minute quadrangle, Jefferson and Broadwater Counties, Mont. (fig. 1), a total of about 132 square miles. That part of the map in the East Helena quadrangle is bounded on the north by the Lewis and Clark County line and on the west by long. 111°52′30″.

The northern and western parts of the area are low rolling sparsely timbered to treeless grassy hills with altitudes of 4,100–4,500 feet and are readily accessible by county and forest roads. U.S. Highway 91 and the Great Northern Railway pass through the western part of the area. The southeastern part of the area is heavily wooded and mountainous with altitudes as high as 8,770 feet and is accessible only by foot or on horseback from the ends of gravel roads leading up Beaver Creek from Winston on the east, from Wilson Creek on the south, or from McClellan Creek within the map area. The central and eastern parts of the area are accessible by good gravel and dirt roads. A large part of the mapped area is shown in figure 2.

PREVIOUS WORK

Earlier geologic studies in the area included mine descriptions and reconnaissance mapping by Stone (1910) Knopf (1913), and Pardee and Schrader (1933). Adolph Knopf and Eleanora B. Knopf were completing detailed studies and mapping of a large area to the northwest while the present investigation was underway (Knopf, 1963). Detailed mapping in adjacent areas published by the U.S. Geological Survey is shown on figure 1.

The geology of about 2½ square miles west and southwest of Clancy was mapped and described by Roberts and Gude (1953). For uniformity, that area was remapped during the present study.

In addition to the above and to publications specifically cited in this report, the publications cited in figure 1 serve as general references to the geology of adjoining and nearby map areas.

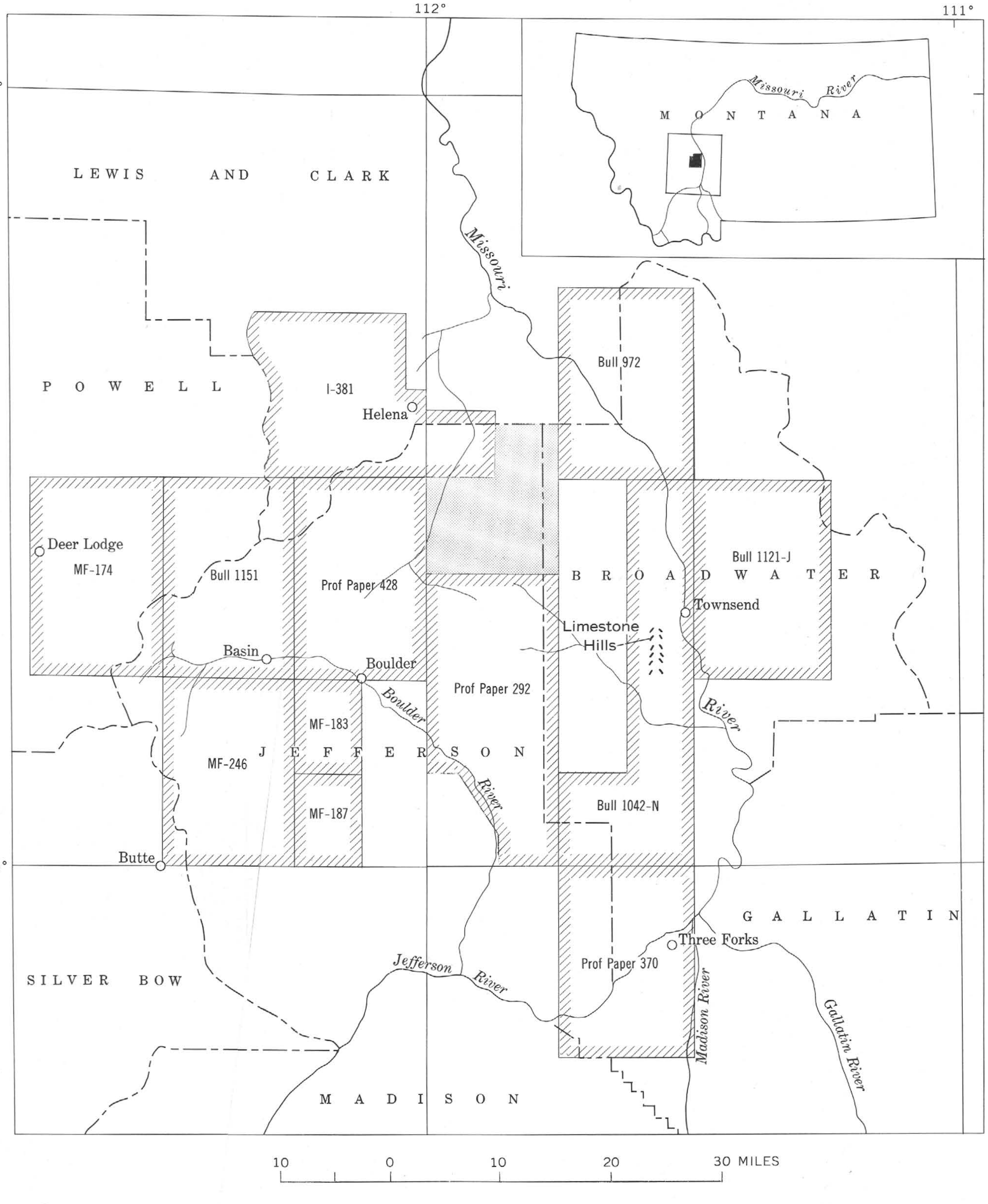


FIGURE 1.—Index map to area described in this report (shaded) and nearby map areas. Letters and numbers refer to publications of the U.S. Geological Survey:

Bull. 972, Mertie and others, 1951
Bull. 1042–N, Freeman and others, 1958
Bull. 1121–J, Nelson, 1963
Bull. 1151, Ruppel, 1963
Prof. Paper 292, Klepper and others, 1957
Prof. Paper 370, Robinson, 1963
Prof. Paper 428, Becraft and others, 1963
MF–174, Ruppel, 1961
MF–183, Becraft and Pinckney, 1961
MF–187, Pinckney and Becraft, 1961
MF–246, Smedes and others, 1962
I–381, Knopf, 1963

PRESENT STUDY

This study is part of a comprehensive investigation of the Boulder batholith and surrounding rocks, under the direction of M. R. Klepper. The greater part of the map area is underlain by igneous rocks. The determination of their composition, mode of formation, age, stratigraphic and structural relations, and relations to ore deposits was the prime objective of this study.

FIELDWORK

Fieldwork was done during 10 months in the summers of 1953, 1954, and 1955. I was assisted by Paul E. Myers for 2 months in 1953. All mapping was done by Brunton compass, altimeter, and graphic locator (Varnes and others, 1959) on a topographic base map at a scale of 1:24,000. The results of this mapping are depicted on a geologic map (pl. 1) and on a fence diagram (pl. 2).

Color names were determined by comparison with the Rock-Color Chart (Goddard and others, 1948).

IGNEOUS ROCK NOMENCLATURE

Rocks with less than 95 percent dark minerals are divided into families based on the relative modal proportions of K-feldspar, plagioclase, and quartz (fig. 3). Feldspathoidal rock names are omitted because such rocks occur only locally as narrow syntectic border zones around some xenoliths. If phenocrysts are abundant or conspicuous, the adjective "porphyritic" is used for medium- and coarse-grained rocks and the word "porphyry" for fine-grained and aphanitic rocks, as in porphyritic monzonite, monzonite porphyry, and latite porphyry. Mineral names are used as modifiers in accordance with standard usage, as in olivine monzonite. When two mineral modifiers are used, the first is the less abundant of the two; an olivine-augite monzonite has more augite than olivine.

The Butte Quartz Monzonite and related rocks were mapped according to texture and color, as was done by Becraft (1955). On the basis of grain size, the rocks were divided into three groups—coarse, medium, and fine—and were further subdivided into light and dark groups. Some of the rocks were further subdivided on the basis of the presence of conspicuous phenocrysts or of an aplitic groundmass.

The term "alaskite" is used in this report to refer to leucocratic quartz-feldspar rocks whose textures are heterogeneous and complex, as described by Roberts (1953). These rocks commonly exhibit textures ranging in a single hand specimen from aplitic, through granophyric, granitic, and porphyritic, to pegmatitic and graphic.

The term "lamprophyre" is used in the descriptive sense as advocated by Knopf (1936, p. 1748–1749).

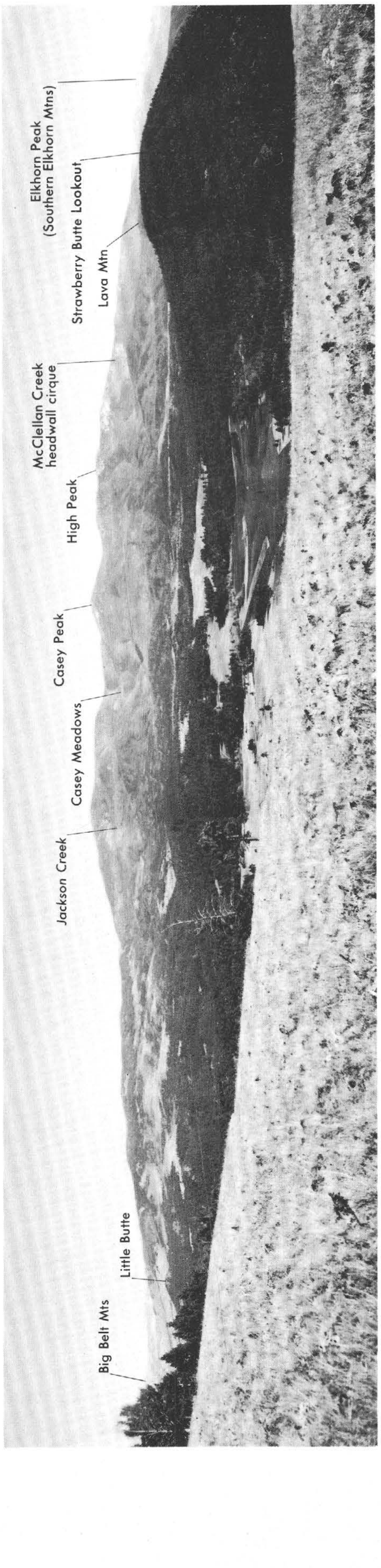
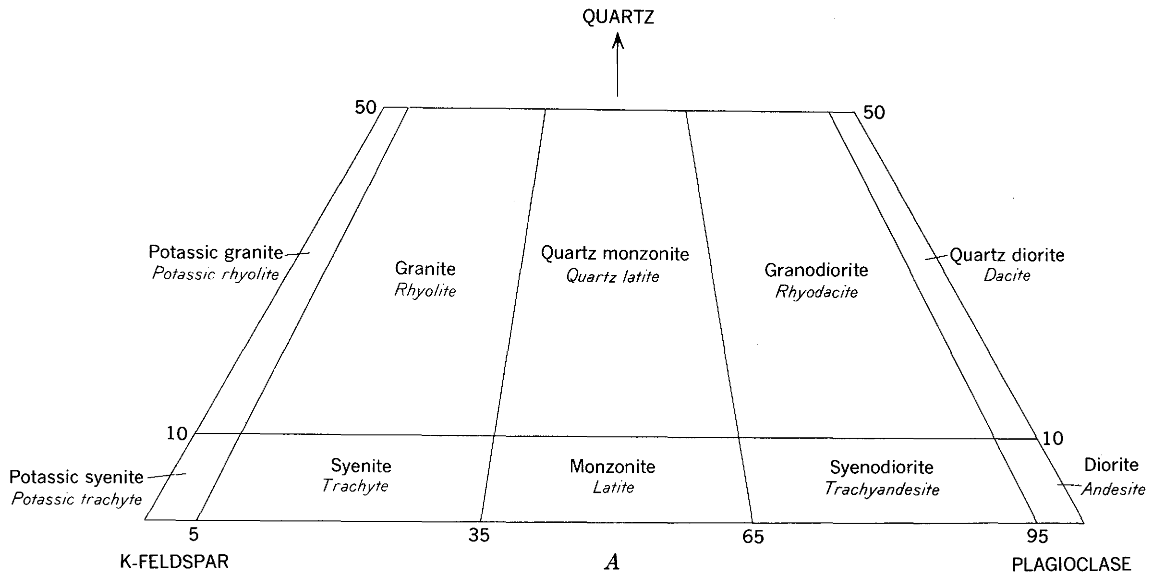


FIGURE 2.—Panorama of the northern Elkhorn Mountains illustrating relief and vegetation and identifying some geographic features. View is east and south from near the summit of Shingle Butte, sec. 36, T. 9 N., R. 3 W.



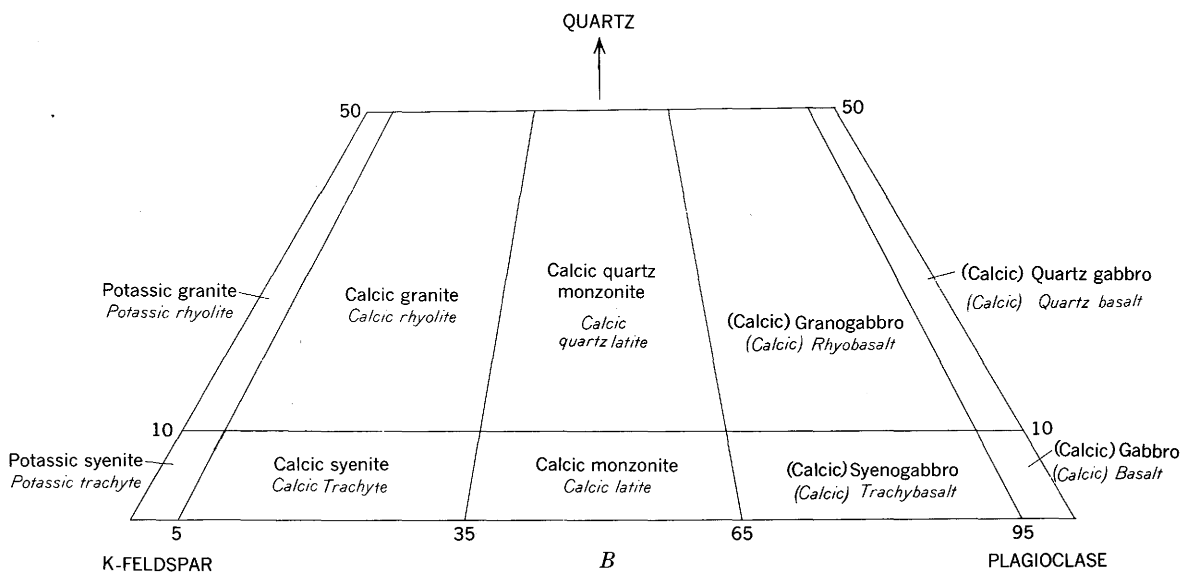


FIGURE 3.—Igneous rock nomenclature used in this report. Names of aphanitic varieties are in italics. *A*, Rocks with plagioclase of composition An_{0-50}. Rocks with plagioclase of composition An_{0-10}, except syenite and potassic granite, are prefixed by the adjective "sodic." *B*, Rocks with plagioclase of composition An_{50-100}. Where the adjective "calcic" is set in parentheses, it is used for that rock only when the plagioclase is of composition An_{90-100}.

Chemically analyzed volcanic and aphanitic intrusive rocks are named according to the classification of Rittman (1952).

The classification of pyroclastic rocks used in this report is mainly that of Wentworth and Williams (1932), in which the major groups of pyroclastic rocks are based on grain size. These include volcanic breccia, tuff breccia, lapilli tuff, coarse tuff, and fine tuff. In addition to these major rock names, special prefixes are employed to indicate composition or mode of formation, such as crystal tuff, lithic tuff, mudflow breccia, water-laid tuff, and andesitic breccia.

Terms describing water-laid pyroclastic materials are here used in a little different sense than that of Wentworth and Williams. In this report, volcanic sediments and volcanic sedimentary rocks (for example, volcanic sand, andesitic sand, andesitic sandstone) refer to materials entirely or dominantly of volcanic derivation that have either fallen into water or have been transported by water. These correspond to the detrital tuffs of Green (1919, p. 165) and to the epiclastic volcanic rocks of Fisher (1960, 1961) that were all washed into place, as contrasted to those explosion tuffs or pyroclastic rocks that were dropped into place.

The terms "tuffaceous sediment" and "tuffaceous sedimentary rocks" (for example, tuffaceous sand, tuffaceous sandstone) are used to refer to material dominantly nonvolcanic but having some admixture from volcanic sources.

The terms "ash-flow tuff" and "welded ash-flow tuff," and the shortened term "welded tuff," are used in this report as defined by Smith (1960a).

ACKNOWLEDGMENTS

Fieldwork was done partly on behalf of the Division of Raw Materials of the U.S. Atomic Commission. Miller Cowling made many of the photographs, and the late Roland W. Brown aided in collecting and identifying fossil plant remains. Innumerable courtesies of the local ranchers, miners, and townspeople greatly facilitated the field studies. Special thanks are extended to John Stackhouse, Jack E. Smith, and Dr. D. C. Betzner and family, of Helena. Information on many mines was freely given by officers and personnel of the Anaconda Co., Butte, Mont. I am especially grateful to Adolph Knopf and Eleanora B. Knopf for many courtesies and for stimulating and constructive discussions.

GEOLOGIC SETTING

The map area (pl. 1) includes parts of four major geologic units: (1) in the northern part, a narrow belt of folded and faulted late Paleozoic and Mesozoic sedimentary rocks, more than 5,700 feet thick; (2) in the eastern part, a folded and faulted sequence of Upper Cretaceous volcanic rocks, more than 11,500 feet thick, and related intrusive rocks; (3) in the western part and near the northeastern corner, plutonic rocks of the Boulder batholith (with small bodies of Tertiary volcanic rocks); and (4) near the northern edge, poorly consolidated and unconsolidated deposits of ash, tuff, sand, gravel, silt, and clay of Tertiary and Quaternary age.

The sedimentary rocks lie at or just beyond the eastern end of an eastward-trending belt of echelon folds, 80 miles long, whose axes plunge southeastward. Rocks in this folded belt are separated from Cretaceous sedimentary and volcanic strata to the south by an east-trending tear zone, marked in places by reverse and thrust faults.

The Upper Cretaceous volcanic rocks continue to the south and are part of the Elkhorn Mountains volcanic field which probably originally covered as much as 10,000 square miles.

The Boulder batholith is a composite intrusive body comprising plutons of gabbroic to granitic composition. The batholith is elongated north-northeast and has maximum dimensions of about 70 by 35 miles. The northeasternmost part of the batholith lies in the map area.

Thick sections of rocks of the Belt Series of Precambrian age and of rocks of Paleozoic and Mesozoic age crop out northwest, east, southeast, and south of the map area.

For information on the origin and evaluation of the formation names and data concerning correlations and faunal assemblages in nearby areas, see Ruppel (1950), Klepper and others (1957), and Freeman and others (1958).

CARBONIFEROUS SYSTEMS

The Carboniferous Systems are represented by the Madison Group of Mississippian age, the Amsden Formation of Late Mississippian and Pennsylvanian age, and the Quadrant Formation of Pennsylvanian age, totaling about 2,170 feet.

MADISON GROUP

In the Elkhorn Mountains the Madison Group is divided into the Lodgepole Limestone of Early Mississippian age and the overlying Mission Canyon Limestone of Early and Late Mississippian age. Their aggregate thickness is about 1,600 feet. This thickness is almost as great as the 1,750 feet found in the Limestone Hills to the southeast (Ruppel, 1950, p. 6, 45, 51), but it is appreciably greater than the 1,000 feet in the Canyon Ferry quadrangle directly to the east (Mertie and others, 1951, p. 27).

LODGEPOLE LIMESTONE

The Lodgepole Limestone is about 800 feet thick. The lower three-fourths is thin-bedded gray limestone, containing some darker dolomite beds in the lower half. The upper one-fourth is transitional into the Mission Canyon Limestone; it generally is of slightly lighter gray color and is characterized by the presence of medium- and thick-bedded limestone similar to that of the Mission Canyon.

The Lodgepole Limestone is exposed only near the center of sec. 12, T. 9 N., R. 2 W. The base is not exposed there, but it is well exposed just west of the area in the SE cor. sec. 7, the N½ sec. 18, T. 9 N., R. 2 W., and the NE¼ sec. 13, T. 9 N., R. 3 W. In those places the Lodgepole Limestone rests with apparent conformity on the Devonian and Mississippian Three Forks Shale.

MISSION CANYON LIMESTONE

The Lodgepole Limestone grades upward into the Mission Canyon Limestone, which is about 800 feet thick, and consists of white to pale-grayish-yellow medium-crystalline to coarsely crystalline thick-bedded limestone. Breccias, probably of solution-collapse origin, occur locally in the upper part. Siltstone and shale commonly form the matrix of these breccias: their presence suggests an erosional unconformity at the top of the formation.

Parts of the Mission Canyon Limestone are well exposed on a pediment surface and in gulleys incised into that pediment in sec. 12, T. 9 N., R. 2 W., and sec. 7, T.9 N., R.1 W. Three smaller outcrops in the northern part of the area are surrounded by poorly consolidated sedimentary and volcanic deposits of Tertiary age. Just west of the area the Mission Canyon Limestone is well exposed along steep slopes and ledges that rise above the gentle slopes underlain by the Lodgepole Limestone.

AMSDEN FORMATION

The Amsden Formation consists mainly of thin-bedded grayish-red to pale-grayish-red siltstone. Thin beds of pale-red-purple and pale-yellowish-gray dolomite occur near the middle of the formation. Rocks of Late Mississippian and Pennsylvanian age are included in the formation, which lies with apparent conformity on the Mission Canyon.

The Amsden Formation characteristically is poorly exposed, forming either a gentle saddle or a gentle slope between the Madison Group and the Quadrant Formation. The Amsden interval is everywhere littered with blocks of quartzite and yellowish-gray limestone from the overlying Quadrant Formation. Some of the limestone blocks may be part of the Amsden Formation, for Ruppel (1950, p. 52) found a conspicuous limestone and dolomite unit in the upper third of the formation in the nearby Limestone Hills.

The thickness of the Amsden Formation appears to vary but averages about 180 feet. The very poor exposures make the extent and nature of the variation uncertain. In the SE¼SW¼ sec. 7, T. 9 N., R. 1 W., the Quadrant Formation seems to lie on the Mission Canyon Limestone. The absence of the Amsden there may only be apparent, owing to poor exposures; or it may be real, owing to nondeposition, to faulting, or to erosion of the Amsden Formation before deposition of the Quadrant Formation.

QUADRANT FORMATION

The Quadrant Formation consists of about 400 feet of interbedded vitreous quartzite and limestone of Pennsylvanian age. In general, the quartzite of the formation is unmistakable, owing to the presence and, usually, abundance of spherical and ovoid masses which give the rock a spotted texture. Differential weathering generally produces a pitted or pock-marked surface.

The formation comprises four units; they are, from the base upward:

1. 200 feet of medium- to light-gray spotted vitreous quartzite.
2. 50 feet of very fine grained limestone in beds and as lenses and pods within quartzite beds. Some of the beds in the lenses are crumpled, although the enclosing quartzite is not similarly deformed.
3. 30 feet of spotted sandstone and calcareous siltstone and some beds of quartzite and dark shaly limestone.
4. 115 feet of spotted vitreous quartzite with local thin-bedded shale partings and limestone lenses.

The quartzite beds are nearly all light gray, medium gray, yellowish gray, or light olive gray and are very fine to medium grained. They are recrystallized quartz sandstone and contain as accessory minerals sparse amounts of small subrounded grains of zircon, apatite, and tourmaline. Some beds contain sparse grains of very fine grained quartzite, and some beds contain K-feldspar which is either authigenic or of metamorphic origin. Calcite, opal, or iron oxide minerals occur in some of the spotted varieties. Limestone beds and lenses are intercalated with the quartzite beds.

As seen under the microscope, the rock consists of an interlocking mass of sutured grains (fig. 4*B*), and the primary clastic texture has been obliterated. Thin sections of some rocks have narrow stringers of quartz having mosaic texture, which probably are recrystallized stringers of mylonite. All thin sections examined contain quartz grains that exhibit deformation lamellae. In many instances these lamellae pass without interruption across several sutured quartz grains, which indicates that the deformation lamellae formed in place and not during previous deformation in the source area.

The distinctive spotted texture (fig. 5) is due to the presence in the rock of small masses in which the quartz grains are cemented by a carbonate mineral or opal; some masses are entirely of quartz and are outlined by iron oxide rims. Spotted quartzite in the Quadrant Formation is interpreted to be metamorphosed quartz sandstone with original concretions cemented by ankerite or siderite (fig. 4*A*). After metamorphism the carbonate mineral in some concretions was replaced pseudomorphically by opal with rhomb and hexagonal shape.

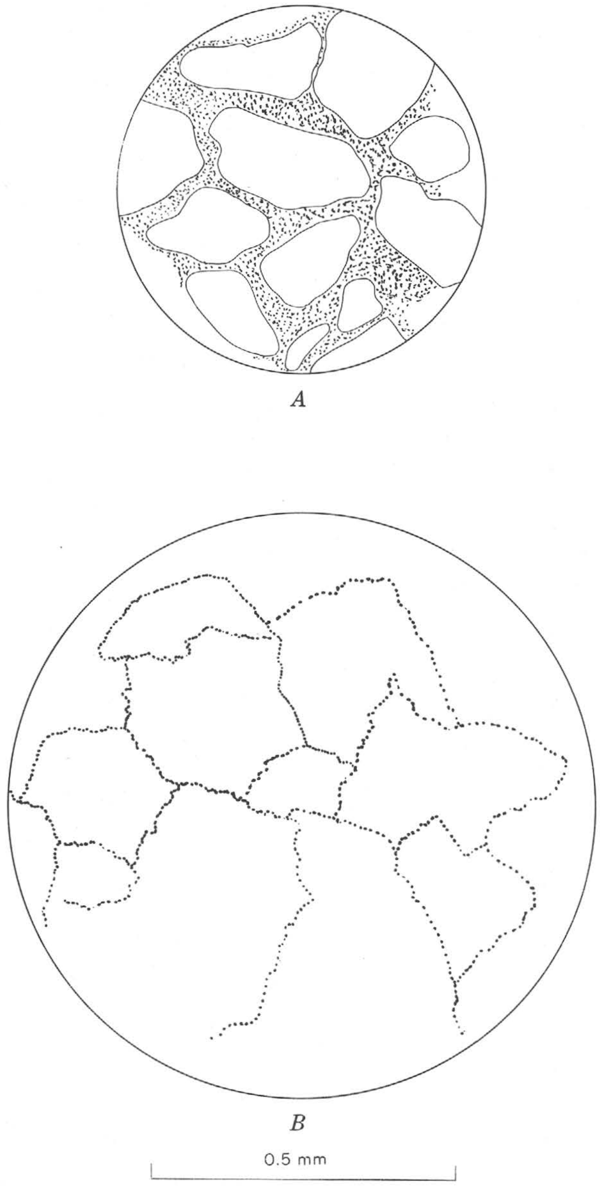


FIGURE 4.—Camera lucida drawings of quartzite of the Quadrant Formation. *A*, Part of a calcite-cemented spot showing original clastic texture of quartz grains. *B*, Nonspotted rock showing increased grain size and obliteration of primary texture.

PERMIAN SYSTEM

PHOSPHORIA FORMATION

A sequence about 90 feet thick of chert, quartzite, limestone, and phosphatic quartzite beds rests with apparent conformity on the Quadrant Formation. These beds are assigned to the Phosphoria Formation of Permian age. Phosphatic rock also is present in the Phosphoria Formation in the southern Elkhorn Mountains (Klepper and others, 1957, p. 22), but it is not known in strata tentatively assigned to the Phosphoria Formation in the Canyon Ferry quadrangle just northeast of the map area (Mertie and others, 1951, p. 28–29). The exposures in the map area are the northeasternmost outcrops of phosphatic rock known in the Phosphoria Formation.

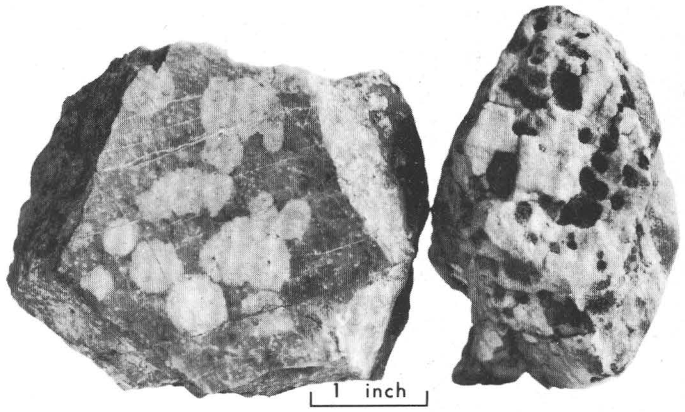


FIGURE 5.—Spotted quartzite of the Quadrant Formation.

The Phosphoria Formation can be divided into three distinct units: a basal unit of cherty quartzite and limestone, about 25 feet thick; a middle unit, about 40 feet thick, of chert, quartzite with bright green spots, and quartzite, some beds of which are conglomeratic; and an upper unit of about 25 feet of phosphatic quartzite.

A detailed stratigraphic section was measured on the prominent hill east of Corral Creek. A near-bedding fault passes through the middle of the Phosphoria Formation in that area; but the undisturbed lower and upper parts represent a slight duplication of beds, so that the entire section is present.

Section of the Phosphoria Formation west of Corral Creek in SE¼NW¼ sec. 14, T. 9 N., R. 2 W.

[Measured by H. W. Smedes and P. E. Myers]

	Feet
Jurassic:	
Swift Formation (part):	
19. Limestone, grayish-yellow-orange, medium-grained; shell fragments and calcite grains and abundant coarse grains of chert and quartz; poorly bedded; weathers very pale yellowish gray	15
Permian:	
Phosphoria Formation:	
18. Quartzite, grayish-orange, fine-grained; weathers pale yellowish brown	5
17. Concealed; probably underlain by rock similar to unit 16	6
16. Quartzite, grayish-orange, fine-grained, sparsely phosphatic; weathers pale yellowish brown	3
15. Quartzite, similar to unit 16 except highly phosphatic	4
14. Quartzite, similar to unit 16	4
13. Quartzite, similar to unit 15	1

Section of the Phosphoria Formation west of Corral Creek in SE¼NW¼ sec. 14, T. 9 N., R. 2 W.—Continued

	Feet
Permian—Continued	
Phosphoria Formation—Continued	
12. Quartzite, similar to unit 16. Sparse phosphate in irregular shapes, flecks, and ovoids (base of the phosphatic upper unit)	1
11. Quartzite, grayish-orange, weathers pale yellowish brown	4
10. Quartzite, olive-gray, medium- to fine-grained, conglomeratic, thick-bedded; weathers light gray	21
9. Concealed; probably underlain by green-spotted quartzite similar to unit 7	3
8. Chert, medium-olive-gray, thin-bedded, contorted and locally brecciated; contains patches, blocks, and layers of white chert; weathers very dusky yellow	1
7. Quartzite, light-olive-gray, medium- to fine-grained; locally calcareous with abundant limonitic streaks. Many moderate-yellowish-green spots of a soft material which is pseudomorphous after small equant crystals	3
6. Quartzite, light-olive-gray, very fine grained; commonly with chert interbeds and pods of green matèrial in upper part, as in unit 7, above	11
5. Quartzite, dusky yellow, very fine grained; includes chert layers; weathers same color (base of the middle quartzite unit)	1
4. Limestone, light-olive-gray, fine- to coarse-grained; contains angular fragments of quartzite and chert; commonly thin-bedded; weathers very light olive gray	6
3. Quartzite, medium-light-gray mottled with pale red; fine-grained and cherty; weathers white	1
2. Concealed; probably underlain by cherty quartzite and limestone	18
Total thickness of Phosphoria Formation	93
Pennsylvanian:	
Quadrant Formation (part):	
1. Quartzite, medium-light-gray, very fine grained	11

SPOTTED QUARTZITE

Special petrographic study was made only of the green-spotted quartzite, such as that of unit 7 in the stratigraphic section described above. These rocks are very fine to medium grained and of light olive gray color, though most are somewhat iron stained. Some of the spotted quartzite is calcareous, some is heavily stained with limonite, and all has been considerably altered. These rocks apparently represent selectively altered or metamorphosed shaly quartz sandstone which was calcareous in places.

The green spots were determined by X-ray study (Robert Gulbrandsen, written commun., 1957), to be mica which structurally is a mixture of 1-layer monoclinic and 2-layer monoclinic mica (1 M and 2 M of Yoder and Eugster, 1955). Gulbrandsen also reported (written commun., 1957) that the rock which is host to these green spots is composed principally of the same kind of mica and quartz.

Mica of the spots is in compact sectile masses pseudomorphous after some euhedral crystals. These pseudomorphs generally are of various hues of green including yellow green, yellowish green, grayish green, and brilliant green; a few are brown. They range in size from 1 to 8 mm; the majority are 2–4 mm across. Some are ovoid or rounded, but most have rather equant euhedral shapes which are easily seen on weathered surfaces where they have been etched out, leaving polyhedral casts, and on sawed surfaces. Sawed surfaces also reveal a color zonation of many of the pseudomorphs, with darker cores (generally green, rarely brown) and lighter rims.

Thin sections reveal that the matrix of the rock is a very fine grained mosaic of quartz and an irresolvable colorless material (mica). Abundant randomly oriented small rodlike masses occur throughout the matrix. The rods have nearly opaque central parts and hazy, ill-defined and dusty rims. The material of the rods is white to yellowish gray in reflected light and is probably largely leucoxene pseudomorphous after ilmenite or titaniferous magnetite.

Scattered throughout the siliceous matrix are the euhedral green mica pseudomorphs which in thin section are very nearly colorless. This mica has a very fine mosaic texture similar to that of the matrix, and under crossed nicols the two are nearly indistinguishable.

Crushed fragments of the pseudomorphs show the mica to occur both as fine fibrous aggregates and as equant grains in a mosaic texture. The birefringence is low, and the indices of refraction are between 1.58 and 1.59. The fibers are elongated parallel to the slow ray, and some are thick enough to show color and pleochroism. The maximum absorption is parallel to the elongation (=Z). Pleochroism is faint, with X=Y, pale yellow; Z, pale shades of blue green.

JURASSIC SYSTEM

The Jurassic System is represented in the Elkhorn Mountains by coarse highly calcareous cherty marine sandstone of the Swift Formation and by nonmarine siltstone and shale of the Morrison Formation, both of Late Jurassic age.

The Swift Formation lies on the Phosphoria Formation (pl. 1), not on the Quadrant Formation as shown by McKee and others (1956, pl. 2). In many places in the southern Elkhorn Mountains the basal bed of the Swift Formation is a thin chert pebble conglomerate which rests with slight erosional unconformity upon the Phosphoria Formation (Klepper and others, 1957, p. 23). In the northern Elkhorn Mountains no discordance was observed between the Swift and the underlying Phosphoria Formation.

According to McKee and others (1956), the dominant rock of Swift age in Montana and North Dakota is mudstone, with sandstone common in the western part, and conglomerate beds common adjacent to an inferred island or positive area that lay east of the Elkhorn Mountains in the region of the Big Belt Mountains. The chert conglomerate, coarse chert, quartz, and shell fragment facies of the Swift Formation in the Elkhorn Mountains is a coarse detrital shore or near-shore facies that clearly reflects the inferred positive area of the Big Belt island.

SWIFT FORMATION

Marine limestone about 50 feet thick lies between the Phosphoria Formation and the nonmarine Morrison Formation. Similar rocks in the same stratigraphic position in the southern Elkhorn Mountains are correlated with the upper unit of the Swift Formation of the Ellis Group of Late Jurassic age (Klepper and others, 1957, p. 23). The rocks of this interval in the map area also are considered to be part of the Swift Formation.

The Swift Formation consists of poorly bedded yellowish highly calcareous cherty sandstone with abundant coarse angular to subround quartz and chert grains and angular shell fragments. Upon weathering, the chert grains and many of the shell fragments stand out in relief and give the outcrop a very rough granular and pitted appearance. These rocks are easily eroded and thus tend to form gentle slopes or saddles between the ledges of the resistant phosphatic quartzite upper member of the Phosphoria Formation and the gentle rounded hills underlain by the Morrison Formation. Basal conglomerate present in the southern Elkhorn Mountains was not observed here.

MORRISON FORMATION

The nonmarine Morrison Formation consists of olive-brown, purple, and varicolored siltstone, shale, and sandstone. Some of the sandstone is calcareous. The formation makes gentle grassy slopes, low rock ribs marking the more resistant beds.

West of Mitchell Gulch, 600–800 feet of highly metamorphosed rock of the Morrison Formation lies between the Swift Formation and rock of the Boulder batholith. East of Mitchell Gulch the Morrison Formation is cut by strike faults, so that it is absent in places and is no more than 300 feet thick elsewhere.

The Morrison Formation grades upward into the Kootenai Formation.

CRETACEOUS SYSTEM

Cretaceous rocks of the Elkhorn Mountains have been divided into nine main map units (pls. 1, 2). These consist, from oldest to youngest, of the Kootenai Formation, three units of the Colorado Formation, two units of the Slim Sam Formation, and three units of the Elkhorn Mountains Volcanics. Two units of the volcanic rocks have been further subdivided in places. The six prevolcanic units have a combined thickness of as much as 3,100 feet, and the Elkhorn Mountains Volcanics are as much as 11,500 feet thick, making a total thickness of Cretaceous deposits of nearly 15,000 feet.

KOOTENAI FORMATION

The oldest Cretaceous unit in the Elkhorn Mountains is the Kootenai Formation of Early Cretaceous age. This formation is about 540 feet thick in the map area. For comparison, it is 529 feet thick in the Limestone Hills (Ruppel, 1950, p. 73) and ranges from 400 to 650 feet thick in the southern Elkhorn Mountains (Klepper and others, 1957, p. 24). It consists of yellowish-brown and gray cherty sandstone in the basal 70 feet, and sandstone, siltstone, and minor amounts of limestone in the remainder.

The lower part of the Kootenai Formation is characterized by a ledge-making succession of cherty "salt and pepper" sandstone beds. A marker unit consisting of two beds of fresh-water limestone separated by about 15 feet of red siltstone occurs near the top of the formation. These limestone beds are coarsely recrystallized coquinoid limestone with abundant fresh-water gastropods.

The top of the formation is placed at the base of the first siliceous sandstone bed above the upper limestone marker unit. The uppermost 30 feet of siltstone and sandstone have slaty, fine-prismatic, or splintery jointing and are irregularly and heavily limonite stained. Perhaps this staining represents weathering before deposition of the overlying Colorado Formation.

COLORADO FORMATION

A thick sequence of marine and nonmarine shale, siliceous mudstone, siltstone, and sandstone, assigned to the Colorado Formation, lies with apparent conformity upon the Kootenai Formation.

The Colorado Formation has been divided into three map units, as in the southern Elkhorn Mountains: (1) lower unit of sandstone and dark gray mudstone; (2) middle unit of sandstone and siliceous mudstone; and (3) upper unit of black shale.

The stratigraphy and paleontology of the Colorado Formation have been studied by W. A. Cobban and J. B. Reeside, Jr. Their opinions on correlation of these three map units in the southern Elkhorn Mountains are summarized in table 1. For the most part the same correlation is shown in correlation chart 10b prepared by the National Research Council Committee on Stratigraphy (Cobban and Reeside, 1952). The correlation chart is presumed valid for the northern Elkhorn Mountains.

TABLE 1.—*Correlation between the Colorado Formation as used in the Elkhorn Mountains and the reference sequence for the western interior United States*

Reference sequence for western interior [1]		Elkhorn Mountains [2]	
Upper Cretaceous	Telegraph Creek Formation	Slim Sam Formation (age at top unknown)	
Upper Cretaceous	Niobrara Formation	Colorado Formation	Upper unit of black shale
	Carlile Shale		Middle unit of sandstone and siliceous mudstone
	Greenhorn Limestone		
	Belle Fourche Shale		
Lower Cretaceous (part)	Mowry Shale		
	Newcastle Sandstone		Lower unit of sandstone and dark-gray mudstone
	Skull Creek Shale		
	Fall River Sandstone		

[1] Simplified from Cobban and Reeside (1952, chart 10b).
[2] Simplified from Klepper and others (1957, p. 26).

The basal sandstone may be a correlative of the Fall River Formation. Fossils were not found in the Colorado Formation in the map area, but they have been found in the southern Elkhorn Mountains where Klepper and others (1957, p. 27–28) reported that fossils characteristic of the Skull Cheek Shale occur in the middle and upper parts of the lower unit; that characteristic Mowry and Carlile fossils occur in the middle unit; and that fossils of earliest Niobrara age and of the next faunal zone in the Niobrara occur in the upper unit. No diagnostic Fall River, Newcastle, Belle Fourche, or Greenhorn fossils were found.

LOWER UNIT

The lower unit, about 215 feet thick, comprises siliceous, locally feldspathic, fine-grained sandstone, siltstone, mudstone, and shale that are mainly dark gray to black. The dark color is the principal basis for separating the Colorado Formation from the yellow and brown rocks of the underlying Kootenai Formation.

Feldspar in the upper third of the unit is in the form of euhedral and angular to subround crystals and fragments of andesine about 0.1–2.0 mm long. The andesine grains are in thin lenses and pods and in widespread laminae a few millimeters thick. Thin lenses and pods of the more rounded feldspar fragments are interpreted as pyroclastic material reworked by water; thin layers of well-formed crystals and angular fragments are interpreted as representing airborne pyroclastic material reworked only slightly or not at all.

MIDDLE UNIT

The lower unit appears to grade into the middle unit, about 580 feet thick, which is characterized by cherty and feldspathic (tuffaceous) sandstone and light-colored laminated very siliceous mudstone. This unit also contains dark siltstone and sandstone.

The siliceous mudstone of the Mowry Shale in the Black Hills, studied by Rubey (1929), is assumed to be equivalent in age to the lower part of this middle unit (see correlation chart, table 1). Rubey postulated that the large amount of silica was derived from the alteration of contemporaneous volcanic ash in alkaline water and was precipitated by decaying organic matter. Although the mudstone was not studied in detail for this report, a similar volcanic derivation of silica is quite probable, especially in view of the association with tuffaceous sandstone.

Petrography.—The feldspathic sandstone is coarse- to fine-grained graywacke and subgraywacke composed of abundant angular and subangular fragments of quartz, plagioclase, devitrified silicic porphyries, quartz-shard tuff, sandstone, and quartzite. Chert is abundant, in both angular and rounded grains. Sparse grains of angular to subround epidote, sphene, hornblende, biotite, muscovite, shale, and mudstone occur in most samples. The matrix consists of a fine paste of the same materials plus clay minerals. Some beds are in part cemented with calcite.

In thin section, the sandstone exhibits moderate to weak cataclasis marked by bending of mica and shale fragments around corners of grains, by deformation lamellae in many sand grains, by sand grains fractured or "exploded" with the parts only slightly separated and slightly disoriented, by strain shadows radiating out from (or more strongly developed against) points of contact with other grains, by wavy extinction, and by bent twin lamellae and cleavage. The deformation lamellae die out toward the present grain borders and were thus formed after the grains were deposited.

Outgrowths are limited to quartz and plagioclase, and on those grains they are restricted to microscopic crenulations and digitations extending into chert. The width of outgrowths is about 0.005–0.010 mm.

210-690 O—66——2

UPPER UNIT

Rocks of the upper unit are dark-gray to black shale, siltstone, and local mudstone. Small beds and lenses of sandstone occur locally. The thickness ranges from about 60 to about 130 feet, with an average of about 100 feet.

These rocks are not so resistant as are the sandstones above and below. Consequently, they seldom are well exposed and usually make a gentle slope or sag, covered by coarse debris from above. The best exposure of the upper unit is in a gentle sag in the N½NW¼ sec. 19, T. 9 N., R. 1 W. Presumably this upper unit is conformable with the overlying beds of the Slim Sam Formation, but the contact is nowhere exposed.

Section of the Colorado Formation measured along a broad gentle ridge, starting in the SE¼ of sec. 13 and ending in the center of the N½ sec. 24, T. 9 N., R. 2 W.

[Measured by H. W. Smedes and P. E. Myers]

	Feet
Cretaceous:	
Slim Sam Formation:	
Lower unit (part):	
39. Sandstone, light-olive-gray, medium-grained, clean; a few chert grains; thin discontinuous beds form conspicuous ledges 1–3 ft high; weathers moderate yellowish orange	24
Colorado Formation:	
Upper unit:	
38. Concealed; probably underlain by black mudstone, shale, and siltstone	66
Middle unit:	
37. Siltstone, dark-gray, splintery, slightly siliceous; weathers dark olive gray	4
36. Sandstone, medium-olive-gray, fine-grained; weathers olive gray	2
35. Sandstone and siltstone, medium-dark-gray to dark-gray, very fine grained, very siliceous; weathers medium gray, some beds medium greenish gray	12
34. Concealed; float is medium-olive-gray nonsiliceous siltstone and mudstone that weathers light olive gray	17
33. Mudstone, medium-gray, siliceous; weathers medium olive gray Uppermost 1 ft is dark-gray very fine grained sandstone that weathers medium dark gray	8
32. Concealed; float similar to unit 31	43
31. Siltstone, medium-gray to dark-gray; contains grayish-black fragments possibly of fossil plants; weathers dark greenish gray	7
30. Siltstone, greenish-gray; weathers medium olive gray	4
29. Concealed; float similar to unit 28	21

Section of the Colorado Formation measured along a broad gentle ridge, starting in the SE¼ of sec. 13 and ending in the center of the N½ sec. 24, T. 9 N., R. 2 W.—Continued

	Feet
Cretaceous—Continued	
Colorado Formation—Continued	
Middle unit—Continued	
28. Sandstone and siltstone, dark-gray, very fine grained; contains larger alined chips and plates of black shale. Close blocky fracture in lower and middle part, bladed in upper part; weathers medium olive gray	14
27. Siltstone, greenish-gray in upper part, dark-gray in lower part; broken into small angular chips and flat pencil-like fragments; locally thin bedded in upper part; weathers pale olive. Lower part massive, heavily limonite stained, weathers dark brownish black	54
26. Sandstone, medium-olive-brown, cherty and feldspathic; weathers dusty olive brown	3
25. Sandstone and siltstone, medium-gray to medium-dark-gray, very fine grained, cherty; weathers light olive gray	14
24. Sandstone, medium-dark-gray, salt-and-pepper; thin discontinuous bedding; weathers light olive gray	4
23. Siltstone, medium-olive-gray, siliceous; slaty to splintery fracture; weathers pale olive to pale olive brown	39
22. Sandstone, medium-olive-gray, fine- to medium-grained, highly feldspathic; contains a little chert and biotite; weathers olive gray	9
21. Sandstone and siltstone, medium-light-gray to medium-gray, very fine grained; a few interbeds of medium- to fine-grained cherty sandstone. Locally well bedded but typically poorly exposed; weathers medium greenish gray	17
Section is offset 1,000 ft east-northeast along top of sill (unit 20).	
20. Concealed; float of porphyritic andesite only, probably in place	(217)
19. Concealed; siltstone and mudstone float similar to unit 18	13
18. Siltstone and mudstone, medium-gray to medium-light-gray, siliceous; local thin beds of fine- to medium-grained sandstone; weathers light olive gray	16
17. Concealed; float similar to unit 16 but includes interbeds of medium-gray to dark-gray very fine grained sandstone and siltstone	9
16. Sandstone, medium-gray, salt-and-pepper, highly feldspathic with a little biotite and specks of other mafic minerals; breaks into small blocks and weathers medium olive gray	17

Section of the Colorado Formation measured along a broad gentle ridge, starting in the SE¼ of sec. 13 and ending in the center of the N½ sec. 24, T. 9 N., R. 2 W.—Continued

	Feet
Cretaceous—Continued	
Colorado Formation—Continued	
Middle unit—Continued	
15. Sandstone, medium-greenish-gray, fine-grained to very fine grained; weathers light olive gray	12
14. Concealed; sandstone and siltstone float similar to unit 13 but with addition upward of medium-grained feldspathic sandstone float	34
13. Sandstone and siltstone, dark-gray to grayish-black, very fine grained; weathers medium dark gray and medium gray to light olive gray. Upper 9 ft similar but weathers dark yellowish brown to moderate yellowish brown	65
12. Sandstone, medium-olive-gray, fine-grained, cherty and feldspathic, poorly bedded, blocky; weathers medium olive gray to light olive gray	18
11. Concealed; probably underlain by siltstone and siliceous mudstone, dark-gray to grayish-black	60
10. Siltstone, dark-gray to grayish-black, with some very fine grained sandstone; platy fracture; forms poor outcrop	32
9. Sandstone, olive-gray, fine- to medium-grained, feldspathic, with dark-gray to grayish-black siliceous mudstone matrix	4
8. Sandstone, medium-olive-gray, medium- to coarse-grained, very siliceous and slightly feldspathic; weathers olive gray	4
7. Sandstone, medium-olive-gray, medium- to fine-grained, cherty and feldspathic. Thick and indistinctly bedded blocky fracture. Makes conspicuous ledges; weathers dark yellowish gray	22
Total thickness of middle unit of the Colorado Formation	578
Lower unit:	
6. Concealed; abundant sandstone chips similar to unit 5	23
5. Sandstone, olive gray to dark-greenish-gray, fine- to medium-grained, locally feldspathic	39
4. Concealed; float consists of sandstone and siltstone similar to unit 3 and of medium-olive-gray and fine-grained siliceous graywacke, and dark-gray to grayish-black siliceous mudstone and shale. Mudstone weathers medium gray to medium dark gray	67

Section of the Colorado Formation measured along a broad gentle ridge, starting in the SE¼ of sec. 13 and ending in the center of the N½ sec. 24, T. 9 N., R. 2 W.—Continued

	Feet
Cretaceous—Continued	
Colorado Formation—Continued	
Lower unit—Continued	
3. Partly concealed; float and poor exposures suggest unit consists of medium-gray to medium-dark-gray siltstone and very fine grained sandstone, very siliceous. Sandstone beds are poorly bedded; weathers various shades of olive gray	46
2. Partly concealed; float and poor exposures suggest unit consists of medium-dark-gray to grayish-black siltstone, mudstone, and very fine grained sandstone; siliceous	37
1. Sandstone, medium-dark-gray, fine-grained, siliceous. Poorly exposed, blocky, weathers light olive gray	2
Total thickness of lower unit of the Colorado Formation	214
Total thickness of the Colorado Formation	858

Kootenai Formation (part):
Siltstone, dark-gray, slaty to splintery fracture; weathers medium yellowish brown (not measured).

SLIM SAM FORMATION

Overlying the Colorado Formation with apparent conformity is a sequence of marine sedimentary and nonmarine volcano-sedimentary rocks which has been called the Slim Sam Formation (Klepper and others, 1957, p. 28).

These beds have affinities with both the underlying largely marine sedimentary rocks and the overlying nonmarine volcanic rocks. This transitional sequence has been divided in the map area into a lower unit of cherty and feldspathic sandstone and siltstone, having intercalated siliceous laminated mudstone; and an upper unit of tuffaceous sandstone, tuff, and graywacke in most places, but locally of quartzose and cherty sandstone.

Measured sections of the Slim Sam Formation are presented below.

The lower unit and the tuffaceous facies of the upper unit of the Slim Sam Formation measured along the northeast-trending ridge in sec. 19, T. 9 N., R. 1 W.

[Measured by H. W. Smedes and P. E. Myers]

	Feet
Cretaceous:	
Elkhorn Mountains Volcanics:	
Lower unit (part):	
32. Ash-flow tuff, dark-gray to very dusky blue; characterized by sparse wispy	

The lower unit and the tuffaceous facies of the upper unit of the Slim Sam Formation measured along the northeast-trending ridge in sec. 19, T. 9 N., R. 1 W.—Continued

	Feet
Cretaceous:	
Elkhorn Mountains Volcanics—Continued	
Lower unit (part)—Continued	
32. Ash-flow tuff—Continued flattened fragments typically ½–6 in. long; makes prominent outcrop with blocky fracture; weathers various shades of olive gray	6
Slim Sam Formation:	
Upper unit, tuffaceous facies:	
31. Concealed; probably underlain by dark-gray to medium-dark-gray very fine grained sandstone and siltstone, obscurely bedded; weathers light grayish olive green and pale dusky yellow	17
30. Andesitic sandstone and lapilli tuff, medium-dark-gray to medium-olive-gray; sandstone is very crudely bedded and channeled	28
29. Siltstone and mudstone, medium-dark-gray to grayish-black; locally light-brown to moderate-brown; finely laminated to thin-bedded; weathers various shades of olive gray to greenish gray	15
28. Siltstone and shale, very dusky purple red; finely laminated with laminae commonly contorted due to contemporaneous deformation; slabby to splintery fracture with a few thin partings of fine-grained sandstone; weathers various shades of red purple to brownish gray	4
27. Coarse tuff and lapilli tuff with subordinate tuff breccia, medium-gray to medium-dark-gray, locally greenish-gray; thin-bedded, many changes in texture in a short distance; sparse blocks, as much as 5 in. long, in tuff breccia; poor outcrop	43
26. Concealed; sparse outcrop and float suggest unit consists of variegated tuff, lapilli tuff and fine- to coarse-grained, well-bedded andesitic sandstone	97
25. Sill, very dark greenish black to dark-olive-green, porphyritic hornblende andesite; weathers grayish olive green	(2)
24. Concealed; probably underlain by well-bedded tuff, lapilli tuff, and andesitic sandstone	45
23. Concealed; abundant porphyritic hornblende andesite blocks in float suggest irregular dike	(5)
22. Concealed	62

The lower unit and the tuffaceous facies of the upper unit of the Slim Sam Formation measured along the northeast-trending ridge in sec. 19, T. 9 N., R. 1 W.—Continued

	Feet
Cretaceous—Continued	
Slim Sam Formation—Continued	
Upper unit, tuffaceous facies—Continued	
21. Mostly concealed; underlain principally by dusky-purple lapilli tuff that contains lenses of andesitic siltstone and sandstone. Lapilli tuff contains fragments of porphyritic andesite in a crystal-lithic matrix. Sedimentary lenses exhibit erratic changes in grain size, local contemporaneous deformation, and minor scouring and channeling within lenses and of underlying beds	55
20. Andesitic sandstone, medium-dark to dusky-blue, coarse-grained to very coarse grained; consists of subround plagioclase grains and much dark lithic matter; local granule beds and a few widely spaced partings of shale to fine-grained sandstone. Coarse-grained sandstone is commonly cross-bedded and forms blocky outcrops; weathers very pale grayish yellow green	24
19. Tuff and andesitic sandstone, medium-gray to medium-dark-gray, coarse- to medium-grained; includes thin shaly bedding partings; forms rubble-covered outcrops	36
18. Andesitic sandstone and siltstone, medium-dark-gray, very fine grained, moderately well-bedded; weathers medium gray to medium greenish gray	8
17. Crystal-lithic tuff, dusky-greenish-gray, coarse-grained; unsorted and poorly bedded to massive; weathers dusky olive gray	24
16. Tuff and lapilli tuff, medium-light-gray to medium-dark-gray; contains abundant fragments of mafic crystals; coarser beds contain irregular large epidote pods; thick bedded; weathers olive gray to light olive gray	10
15. Andesitic sandstone and siltstone, dark-gray, very fine grained; weathers medium olive gray	2
14. Crystal-lithic tuff, medium-dark-gray, medium- to coarse-grained; weathers medium olive gray	7
13. Sandstone and siltstone, dark-gray, very fine grained with sparse larger fragments of dark aphanitic rock; weathers medium olive gray	3
12. Concealed; probably underlain by crystal-lithic tuff similar to unit 11	6

The lower unit and the tuffaceous facies of the upper unit of the Slim Sam Formation measured along the northeast-trending ridge in sec. 19, T. 9 N., R. 1 W.—Continued

	Feet
Cretaceous—Continued	
Slim Sam Formation—Continued	
Upper unit, tuffaceous facies—Continued	
11. Crystal-lithic tuff, dark-gray, coarse-grained, massive; weathers dark olive gray	7
10. Crystal-lithic tuff, medium-dark-gray to very dark greenish gray, coarse-grained; some beds are medium dark gray to moderate yellowish brown; weathers grayish yellow brown	15
Total thickness of upper unit of the Slim Sam Formation in this section, excluding intrusive rocks	508
Lower unit:	
9. Quartz sandstone, pale-grayish-green, fine-grained, very clean and free of chert, poorly bedded; weathers pale olive gray	55
8. Mostly concealed, but partly underlain by light- to dark-gray medium- to thin-bedded and crossbedded feldspathic and cherty sandstone	596
7. Siltstone, medium-dark-gray to dark-gray; close blocky fracture; weathers medium gray	12
6. Sandstone, medium-gray to medium-light-gray; with many chips of thin black siliceous shale, possibly in part stem fragments, and thin beds and streaks of similar shale; sandstone is heavily limonite stained; weathers pale olive gray	12
5. Concealed; probably underlain by medium-dark-gray siliceous shale and lighter colored siltstone and fine-grained sandstone	7
4. Siltstone and siliceous shale, medium-dark-gray; with interbedded olive-gray fine-grained sandstone	4
3. Siltstone and siliceous shale, medium-dark-gray; weathers dark greenish gray	9
2. Sandstone, light-olive-gray, medium-grained, clean; contains only small amount of chert grains; thin discontinuous beds form conspicuous ledges 1–3 ft high; weathers moderate yellowish orange	24
Total thickness of lower unit of the Slim Sam Formation	719
Total thickness of the Slim Sam Formation	1, 227

The lower unit and the tuffaceous facies of the upper unit of the Slim Sam Formation measured along the northeast-trending ridge in sec. 19, T. 9 N., R. 1 W.—Continued

	Feet
Cretaceous—Continued	
Slim Sam Formation—Continued	
Lower unit—Continued	
1. Concealed; probably underlain by black mudstone, shale, and siltstone	66

The lower unit and the sandstone facies of the upper unit of the Slim Sam Formation from near the northeast corner to the middle of the east edge of sec. 24, T. 9 N., R. 2 W.

[Measured by M. R. Klepper and R. A. Weeks, 1956]

	Feet
Cretaceous:	
Elkhorn Mountains Volcanics (part):	
4. Volcanic conglomerate with closely packed rounded pebbles and cobbles of several textural types of andesite porphyry and lapilli tuff; fragments as much as 6 in. long but most are 2–3 in.; no fragments of sedimentary rocks; matrix is silty to sandy volcanic debris	
Slim Sam Formation:	
Upper unit, sandstone facies:	
3. Alternating green tuffaceous sandstone and siltstone and hard siliceous mudstone similar to that of the middle unit of the Colorado Formation, with some quartz and chert sandstones devoid of, or low in, andesitic debris. Conglomerate bed with subangular to subrounded chert and quartzite cobbles near the top. Beds are in part thin bedded and even laminated; in part conspicuously crossbedded	200
Lower unit, sandstone facies:	
2. Mainly clean white to light-gray fine-grained quartz sandstone and some siltstone; many sandstone beds contain conspicuous chert and (or) quartzite grains. Distinctly bedded and in part laminated; form ledges and low cliffs	650
Total estimated thickness of the Slim Sam Formation	850
Colorado Formation:	
Upper unit:	
1. Dark-gray and black shale	130

LOWER UNIT

The lower unit of the Slim Sam Formation is characterized by sandstone, siltstone, and siliceous shale and is similar to the middle unit of the Colorado Formation. The thickness varies sharply in the map area from about 650 feet to about 1,150 feet.

Marine fossils of Niobrara age have been collected from high in the lower unit of the Slim Sam Formation in the southern Elkhorn Mountains (Klepper and others, 1957, p. 29), indicating that at least the lower part of the Slim Sam is equivalent to the upper part of the Colorado Group of the reference section of western interior United States (Cobban and Reeside, 1952).

In most places the upper black shale unit of the Colorado Formation is obscured by hillwash and talus, and the lower beds of the Slim Sam mistakenly appear to lie on rocks of the middle unit of the Colorado Formation. So greatly do the rocks of these two units resemble each other that they would be inseparable in the field without the presence of the upper black shale unit of the Colorado Formation. Under the microscope the distinction is clear cut, for the Slim Sam beds have an abundance of K-feldspar fragments, lacking in the Colorado, and also generally are richer in mafic minerals and magnetite. Chert is much less abundant in the Slim Sam than in the Colorado Formation.

Owing to poor exposures, the Slim Sam-Colorado contact is accurately located in only a few places.

The finer grained siltstone is dense, very hard, siliceous, and light colored. It rings when struck by a hammer and breaks with conchoidal fracture. The siltstone generally is thick bedded and forms conspicuous ledges and cliffs in the hills just south of the R. Dobler ranch in the N½ sec. 19, T. 9 N., R. 1 W. Many of the siltstone beds exhibit the effects of penecontemporaneous deformation, with coarser less siliceous feldspathic parts brecciated, crumpled, and strewn about in the finer grained siliceous matrix.

The coarser siltstone beds and the sandstone beds are thinner and make less prominent scarps and ledges. Their color is comparable to that of the dense siltstones, but they are more readily broken and produce a rough, irregular to hackly fracture.

Thin sections of the lower unit all contain abundant long angular quartz shards; some have axial ratios grater than 10:1. Angular K-feldspar and andesine and subangular to round recrystallized chert grains also are present. The matrix is largely recrystallized and comprises very fine grained quartz, calcite, granular zoisite, K-feldspar, and sparse epidote. Calcite also is present as large irregular patches and as small veinlets. The quartz grains exhibit very narrow outgrowth rims which engulf minute granules of zoisite. Zoisite has in some places developed subhedral crystals.

Both the siltstone and sandstone are highly siliceous. Much of the fine, almost unresolvable, siliceous matrix probably was derived from silicic volcanic ash as Rubey (1929) suggested to explain the origin of the siliceous Mowry Shale.

The sandstones within 100 feet of the top of the lower unit are fine- to medium-grained arkose, containing abundant angular to subangular grains of microline, orthoclase, and perthite.

Some beds which look like laminated siliceous mudstone actually are dense cordierite hornfels and, locally, spotted hornfels. Intercalated sandstones show virtually no mineralogic or textural transformation. The hornfels is low-grade thermally metamorphosed gray and black shale and siltstone from the upper part of the lower unit. Delicate primary sedimentary textures and structures commonly are preserved even in high-grade hornfels near the batholith contact. This feature makes it impractical to map the extent and distribution of metamorphic rock.

A representative hornfels is from the cuesta in the NE¼ sec. 22, T. 9 N., R. 2 W., just east of Corral Creek. It is delicately laminated, dark to light gray, very dense and hard; the laminae contain variable amounts of small spherules 2–3 mm across. These spherules are glomeroblastic aggregates of fine granular cordierite. The rock is now an epidote-calcite-zoisite-cordierite-quartz hornfels (fig. 6). The small quartz grains retain their clastic shapes, but high magnification reveals narrow crenulate outgrowths. Plagioclase is very sparse, but it is also clearly clastic and has outgrowths like those on the quartz. Very fine grained calcite, ferrian zoisite, and a little epidote occur throughout the rock; coarser crystalline aggregates of iron-free zoisite are disseminated sparingly. The glomeroblasts of cordierite contain abundant inclusions of the same minerals that make up the rest of the rock. Cordierite is difficult to distinguish in thin section except by use of the gypsum retardation plate, which clearly brings out the shape and sector twinning of the aggregates.

UPPER UNIT

The upper unit of the Slim Sam Formation has two contrasting facies: a sandstone facies and a tuffaceous facies. Although some reworked tuff undoubtedly is in the sandstone facies, those rocks are characterized by quartzose sandstone having conspicuous rounded to subangular grains of chert, quartz, quartzite, and plagioclase. The tuffaceous facies is composed of tuff and of tuffaceous rock with abundant grains of quartz, feldspar, mafic minerals, shale, and volcanic rocks, set in a matrix of finely divided particles of the same materials plus chert, clay minerals, sericite, and chlorite. Ankerite is common in irregular interstitial patches. The rocks of the tuffaceous facies include tuffaceous sandstone, andesitic sandstone, andesitic tuff, graywacke, subgraywacke (with less than 10-percent feldspar), and rocks completely devoid of quartz.

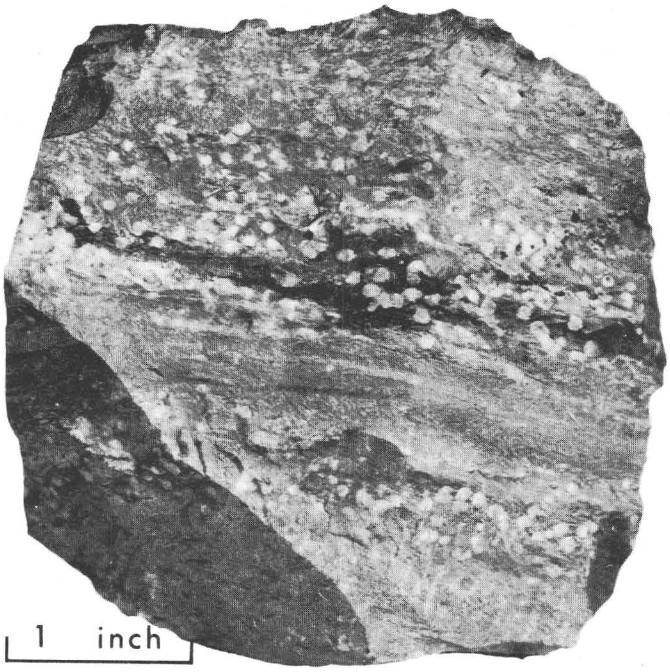


FIGURE 6.—Laminated cordierite hornfels from the upper part of the lower unit of the Slim Sam Formation. The small light-colored spherules are glomeroblasts of cordierite and are restricted to the original mudstone parts of beds. Fine bedding and silty texture are preserved.

The rocks of the upper unit are conformable on those of the lower unit and range in thickness from about 450 to about 1,100 feet.

TUFFACEOUS FACIES

The tuffaceous facies is the thicker and more prevalent one in the map area. The amount of airlaid tuff ranges widely. Locally, beds of the sandstone facies occur. In most places the change from lower unit to tuffaceous facies of the upper unit is abrupt, and rocks similar to those of the lower unit do not recur. In other places the change is equally abrupt, but beds like those of the lower unit recur repeatedly.

Crossbedding and other evidence of channeling and reworking are sparse in the tuffaceous facies. The deposits generally are poorly sorted to unsorted and range from poorly bedded and thick bedded to well bedded and, locally, laminated. Individual beds do not persist for more than a few hundred feet, probably owing to changes within the tuffaceous facies involving bedding, grain size, and relative proportions of constituents, and to changes toward the sandstone facies.

PETROGRAPHY

Rocks of the tuffaceous facies are of diverse types. Several representative rocks are described below; most others constitute mixtures of these types.

The lowest bed in the section, about 15 feet thick, is massive and unsorted greenish-gray coarse sandy crystal-lithic tuff; it weathers greenish gray and light olive gray. The chief constituents are coarse angular fragments of andesite porphyry together with fragments and unbroken crystals of andesine and hornblende. The groundmass of the andesite porphyry fragments blends subtly with the matrix of the tuff and, with the crystal debris and lack of sorting, gives the whole rock the appearance of porphyritic igneous rock. Angular grains of quartz, recrystallized chert (now a mosaic of quartz), sandstone, siltstone, and K-feldspar together constitute less than 15 percent of the rock; the presence of chert, sandstone, and siltstone debris indicates admixture of nonvolcanic material.

The matrix contains very fine grained andesine, oligoclase, mafic minerals, and clay, now largely reconstituted to a mat of interlocked and felted chlorite, actinolite, epidote, zoisite, magnetite, and some fine mosaic quartz which probably is recrystallized chert. Sphene is a common accessory mineral. Biotite occurs chiefly as small decussate patches interleaved with chlorite and actinolite.

Andesine crystals in the andesite porphyry fragments are similar to those that are free in the matrix; most likely they all came from the same source. The free andesine crystals generally are broken, but some are euhedral. Andesine crystals are netted by albite-oligoclase and locally also by K-feldspar, all of which are partly replaced by epidote, zoisite, a carbonate mineral, and sericite. In many places actinolite has replaced plagioclase along cracks and around rims. K-feldspar locally has replaced the cement of sandstone fragments and forms hazy, irregular streaks and patches in the matrix. The K-feldspar in plagioclase may have formed by exsolution; that in the groundmass may have been formed by recrystallization of kaolinic matter or from potassium released by the chloritization of biotite (Chayes, 1955). This K-feldspar is different from the detrital K-feldspar grains, which, in fact, have delicate outgrowths of the metamorphic K-feldspar.

The bed directly above the basal tuff is an unsorted dark-gray and olive-gray crystal-lithic tuff about 7 feet thick. This rock also superficially resembles a porphyritic igneous rock. It contains abundant crystals and fragments of hornblende and andesine and sparse fragments of andesite and andesite porphyry. Chert, quartz, sandstone, siltstone, and K-feldspar are absent from this tuff; otherwise the matrix of both rocks is the same. The upper tuff probably is purely pyroclastic air-fall debris.

A tuffaceous granule sandstone about 60 feet above the base of the upper unit contains abundant crystal fragments of angular to subangular andesine, subangular to round quartz, and some subangular to subround rock fragments. The rock fragments comprise fine- and medium-grained sandstone, coarse and fine andesitic tuff, andesite, andesite porphyry, and trachyandesite porphyry.

Cataclastic effects are weak to absent in nearly all the rock fragments. In contrast, the crystal fragments in this rock are intensely shattered in many places, but the shattered pieces have not been strewn apart. The shatter zones and delicate cracks in andesine controlled an extensive later albitization which resulted in a complex network of albite (fig. 7*A, B*). Some grains are not shattered but are bent, as shown by bent cleavage and twin lamellae. Mortar structure has developed along fractures and around the rims of quartz grains (fig. 7*C, D*). Deformation lamellae are common in many quartz grains; these lamellae generally die out toward the grain boundary, and their orientation is rather uniform. Undulose extinction is prevalent and reveals incipient shatter patterns. Outgrowths on some quartz grains are in optical continuity with the host, and they exhibit pseudostrain by their inherited undulose extinction patterns. Most quartz grains have no outgrowths or very small ones, but they are enveloped by a sheath of mortar which blends into the recrystallized matrix. All the mortar is a fine aggregate of recrystallized quartz which originally was fine pulverized quartz.

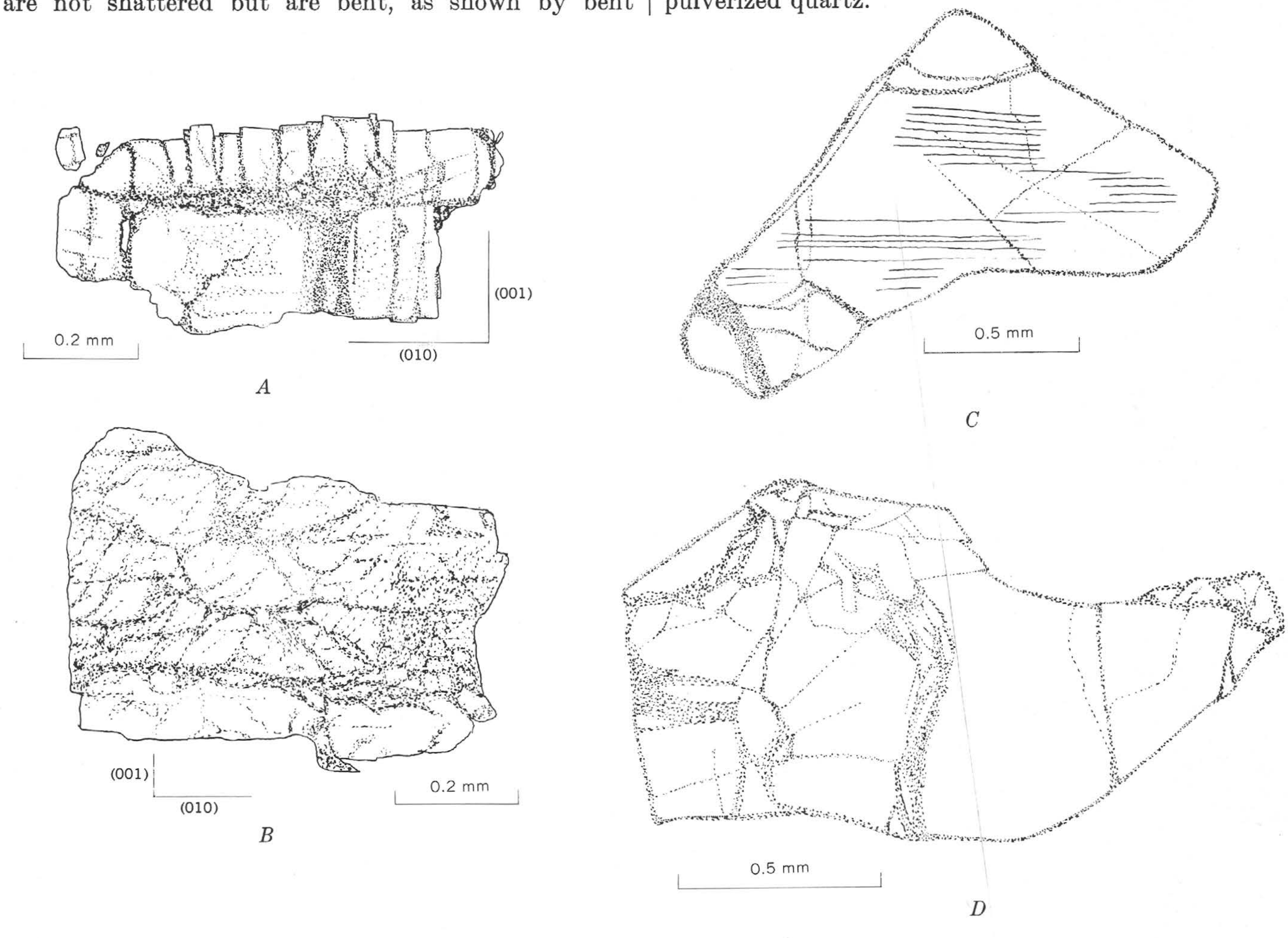


FIGURE 7.—Camera lucida drawings of andesine and quartz fragments from a tuffaceous granule sandstone of the upper part of the Slim Sam Formation. Albitization of andesine crystal fragments (*A* and *B*) controlled by shatter patterns. The distribution and relative intensity of albitization is shown by the density of stippling. The crystal fragment in *A* displays minute step faults with displacement along (001). Albitization is intense along the (001) cleavages and along (010) cleavages, especially just above the center of the grain. Weak albitization occurs along diagonal fractures as shown in the upper right corner. In *B* the most intense albitization is along (010), with the least along (001), and with moderate albitization in two diagonal directions. The quartz crystal fragments (*C* and *D*) have been shattered, with the development of mortar structure (stippled) around the rims and along cracks. The straight subparallel lines in *C* are deformation lamellae.

A few relicts of amphibole and mica occur as pyroclasts, but most are now pseudomorphs of felted masses of chlorite and sparse actinolitic hornblende, with abundant granules of magnetite and some sphene. The groundmass contains sparse chlorite, epidote, zoisite, and actinolitic hornblende, and much fine quartz and plagioclase in mosaic texture which probably represents recrystallized clastic and cataclastic "dust." Zoisite and lesser epidote also replace plagioclase on a small scale, along shatter zones. The metamorphic grade is that of the albite-epidote hornfels facies. This degree of metamorphism apparently was not sufficient to heal completely the effects of strain in the quartz grains.

The rock is locally transected by veinlets filled with K-feldspar and minerals of the epidote group, visible only at high magnification. K-feldspar also occurs as irregular streaks and patches throughout many of the plagioclase crystals; with albite in the shatter zones; as irregular rims of fine granules, blended with the recrystallized mortar of many quartz grains; and as scattered patches and granules in the groundmass.

A little metamorphic biotite occurs as small clusters of shapeless grains, as small plates along chlorite cleavages, and as rims around clusters of interlocked chlorite and actinolite.

A 2-foot bed of crystal tuff near the middle of the upper unit is intercalated with crossbedded tuffaceous sandstone. Except for a thin zone of gradation with the sandstone, this crystal tuff would be indistinguishable from fine-grained diorite. This tuff is grayish black to black, weathers dark gray to light olive gray, and contains abundant euhedral plagioclase crystals and mafic minerals. The grain size of plagioclase and mafic crystals is remarkably uniform. Even under the microscope the pyroclastic texture is not apparent at first.

The rock (figs. 8, 9) is composed of euhedral crystals and fragments of andesine, hornblende, and sparse augite. Rock fragments also are present; these are of porphyries with a texture that blends with the crystals and matrix, so that their outlines are difficult to discern. The matrix is fine andesite flour which is recrystallized and blends with the rock fragments.

Andesine has been netted to varying extent by albite and replaced by much actinolite and a little epidote and biotite. These replacement materials are more abundant in the calcic cores (fig. 9*A*), in calcic zones where the plagioclase has oscillatory zoning (fig. 9*B*), and in patterns suggesting those of former glass inclusions along pinacoids (fig. 9*C*).

Primary hornblende and augite occur only locally as cores of crystals whose outer parts have been converted to secondary amphibole, biotite, chlorite, and magnetite. The primary hornblende is pale green and has moderate birefringence. The augite remnants exhibit hourglass structure.

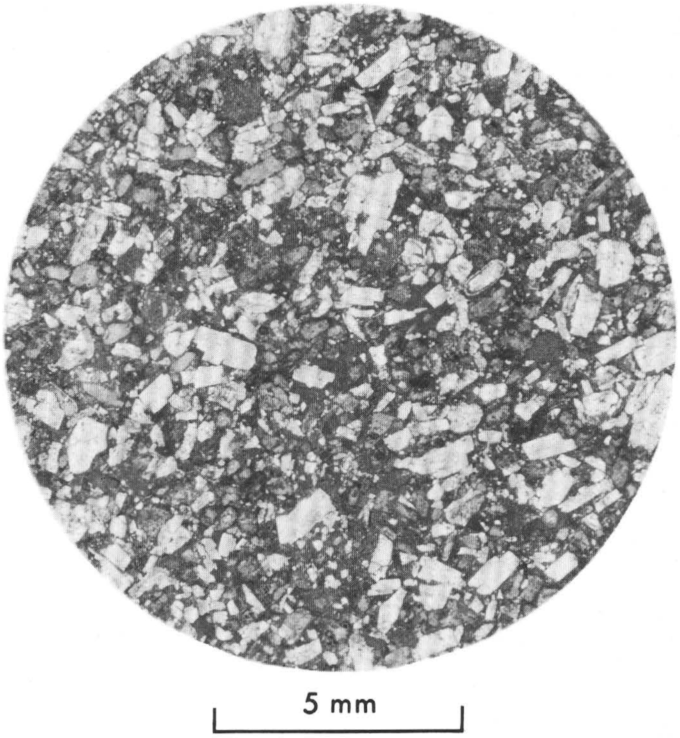


FIGURE 8.—Photomicrograph of crystal tuff from the upper part of the Slim Sam Formation. Crystals and fragments of andesine are light gray; hornblende and augite are dark gray. Plane polarized light.

The secondary amphibole has a peculiar fine fibrous structure and pronounced blue-green pleochroism. Some is pseudomorphous after euhedral pyroxene; some has, in turn, locally been converted to biotite along cleavages or around rims.

Biotite occurs as primary pyroclastic plates that are bent and partly converted to penninite and magnetite or to amphibole and as scattered patches where it forms an interlocked or decussate texture. Chlorite and magnetite have formed at the expense of both amphibole and biotite.

Pale-red-purple to light-brownish-gray apatite is very common in association with the blue-green amphibole, and forms small stout euhedral prisms, irregular granules, and nebulous patchy shapes; it commonly shows zonal structure.

K-feldspar is rare, mostly interleaved with the blue-green amphibole but also at random in the matrix in

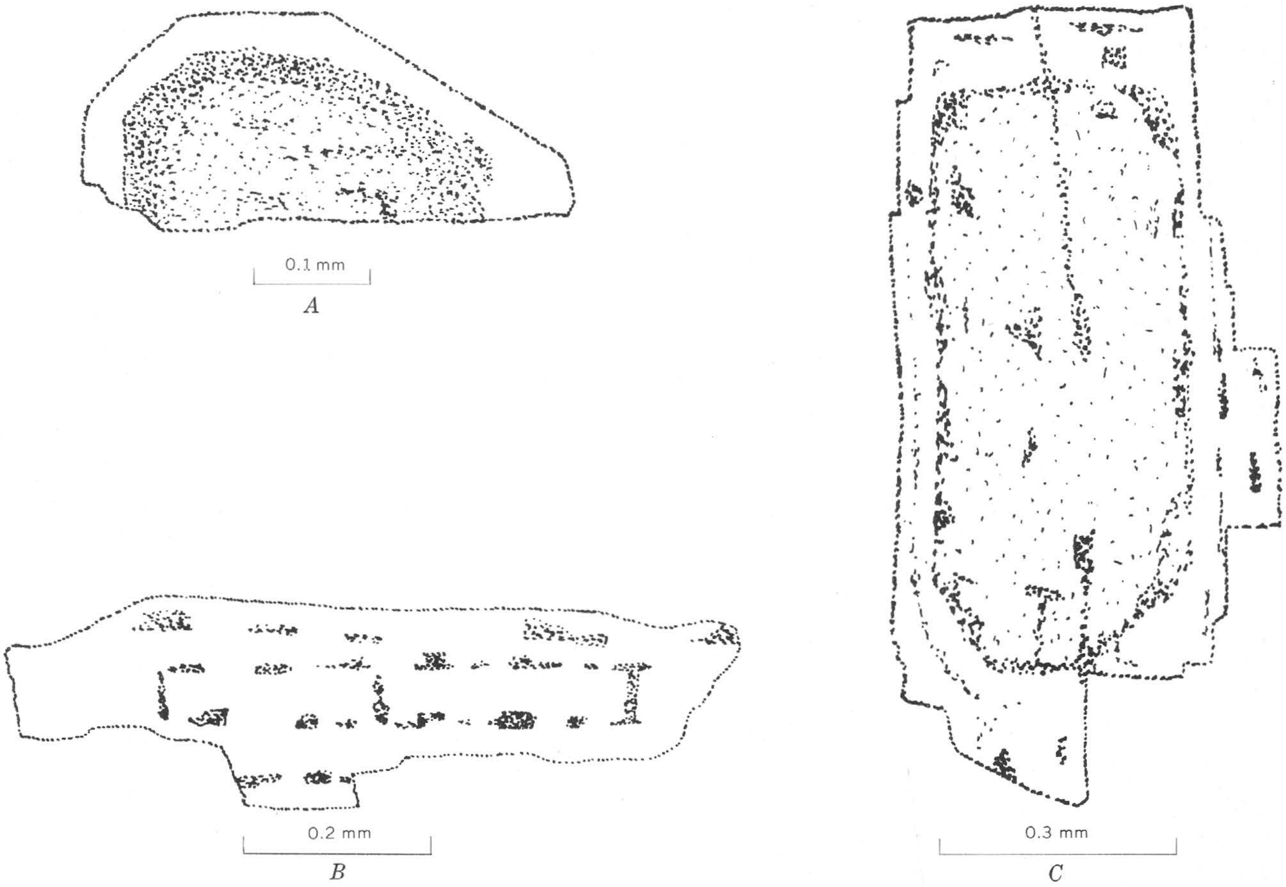


FIGURE 9.—Camera lucida drawings of andesine pyroclasts in crystal tuff from the upper part of the Slim Sam Formation. Stippling represents the distribution and relative abundance of felted masses of actinolite and lesser biotite and epidote. In *A*, the alteration is confined to the calcic core; in *B*, the plagioclase has oscillatory zoning and the alteration is most intense in a calcic zone near the periphery, although some actinolite has formed along cleavages. In *C*, the pattern of alteration is similar to that of the distribution of glass inclusions along pinacoids in plagioclase phenocrysts common in lava.

nebulous or amoeboid forms. Sericite and carbonate minerals are very sparse, and clastic K-feldspar and quartz are lacking.

HISTORY RECORDED IN MAFIC MINERALS

The matrix of this tuff has been recrystallized to a fine granular and felted mat of blue-green amphibole, purple apatite, and biotite.

The history recorded in the mafic minerals of this rock is interpreted as follows:

1. Magmatic crystallization of augite, amphibole, and plagioclase;
2. Possible deuteric alteration;
3. Explosive eruption and deposition as an ash fall;
4. Subsequent thermal metamorphism of low but rising grade, which converted augite, amphibole, and plagioclase to chlorite and blue-green amphible;
5. Increased degree of metamorphism, which led to formation of biotite at the expense of earlier minerals; and
6. Lower degree of metamorphism, which stopped growth of biotite and formed chlorite and magnetite from it.

Plagioclase was being converted to blue-green amphibole, epidote, and albite during episode (4), then to bitote during episode (5), then, slightly, to sericite and carbonate minerals.

Whereas the lower tuffs record only slight development of biotite, this tuff records significant development, which implies a slightly higher level of metamorphism.

SANDSTONE FACIES

The sandstone facies occurs only locally, along the crests of anticlines in the eastern part of the outcrop belt of the Slim Sam Formation. This facies is characterized by quartzose sandstone with conspicuous round to subangular grains of chert, quartz, and quartzite, and varying amounts of plagioclase. The cement is largely silica, usually as outgrowths on the grains; clay is rare. The beds are well sorted, exhibit cross-bedding, and have local seams and lenses of magnetite and mafic minerals—evidence of channeling and reworking.

Some of the beds have a small amount of clay matrix and varying amounts of hornblende, epidote, augite, and biotite in addition to feldspar, quartz, and chert. These beds represent admixtures of debris of the tuffaceous facies and include cherty subgraywacke and mafic-rich sandstone.

The more rounded feldspar grains in the sandstone probably were derived from tuff; the more angular feldspar grains and the mafic grains and local clay matrix, which are commonly associated, probably represent direct airborne tuff deposited with quartz, chert, and quartzite grains derived from erosion. No volcanic fragments of lapilli size (4 mm), or larger, are present, although chert and quartzite grains are of pebble size (4–64 mm).

This facies is very similar to that of the middle unit of the Colorado Formation, and the less tuffaceous beds closely resemble those of the lower unit of the Slim Sam Formation. The change from the lower unit to the sandstone facies of the upper unit is in a few places so gradual that the choice or even existence of a contact is in question. At such places, the truly volcanic lithology of the upper unit does not occur.

INTERPRETATION OF THE RELATION BETWEEN FACIES

Correlation between rocks of the sandstone facies and those of the tuffaceous facies is difficult because of the poor exposure and abrupt internal facies changes. The lithology of the basal part of the upper unit of the Slim Sam Formation differs from place to place owing to facies change, overlap, and (or) intraformational erosion. As a result, the boundary between upper and lower units of the formation probably has been placed at slightly different stratigraphic positions in different places.

In the western outcrops of the formation, the upper unit is the tuffaceous facies, and there is no evidence of unconformity with the overlying Elkhorn Mountains Volcanics. In the eastern part, the folded Slim Sam beds, which have local amplitudes greater than 300 feet, are overlain by beds of the Elkhorn Mountains Volcanics which are not folded. Along the troughs of the synclines, the upper and lower units of the Slim Sam Formation are thicker; the upper unit is coarser and of the tuffaceous facies. Along the crests of the anticlines, the upper and lower units are thinner; the upper unit is finer grained and of the sandstone facies.

The apparent restriction of the sandstone facies to the anticlinal areas strongly suggests contemporaneous deposition and folding. The sandstone facies may, however, be more widespread but concealed and may represent sand channels and lenses cut in, or intertongued with, tuffaceous deposits.

ELKHORN MOUNTAINS VOLCANICS

The eastern part of the map area (pl. 1) is underlain largely by Upper Cretaceous calcalkaline intrusive and extrusive rocks. These rocks lie in a broad north-northeastward-trending syncline and form a continuous belt that extends into the southern Elkhorn Mountains, where they have been given the name Elkhorn Mountains Volcanics (Klepper and others, 1957, p. 31). The Elkhorn Mountains Volcanics are remnants of a thick plateaulike or shieldlike accumulation exposed in an area of about 3,000 square miles around the Boulder batholith in the Elkhorn Mountains and the Boulder Mountains. The presence of similar rocks across the Jefferson River to the south and near Wolf Creek to the north suggests that the volcanic pile once covered as much as 10,000 square miles. This volcanic pile includes one of the largest ash-flow fields known (Smith, 1960a, p. 815).

The volcanic rocks are divided into three gross lithologic units: (1) a lower unit dominantly of andesitic, rhyodacitic, and basaltic pyroclastic and epiclastic volcanic rocks, autobrecciated lavas, and related mudflows, and a few thin partly welded quartz latitic ash flows; (2) a middle unit characterized by sheets of rhyolitic ash flows most of which now are welded tuff, and intercalated debris similar to that of the lower unit; and (3) an upper unit dominated by bedded and water-laid tuff and andesitic sedimentary rocks.

Quartz latitic welded tuff of the lower unit and rhyolitic welded tuff of the middle unit from in and near the map area have been analyzed (table 2). The proportions of normative quartz, orthoclase, and plagioclase in these rocks are shown on plate 3 (diagram 1), along with other volcanic and related intrusive rocks (data from unpub. analyses).

TABLE 2.—*Chemical and normative composition of*

	Elkhorn Mountains Volcanics, welded tuff			Sill with peperitic margins				Boulder batholith — Early stage	
	1	2	3	4	5	6	7	8	9
Analyses									
SiO_2	60. 7	71. 6	69. 4	49. 8	54. 8	53. 9	54. 4	57. 9	54. 5
Al_2O_3	16. 6	15. 4	15. 4	16. 1	15. 1	14. 9	14. 5	15. 4	12. 4
Fe_2O_3	1. 7	1. 2	1. 7	2. 5	2. 3	2. 2	2. 3	2. 3	1. 0
FeO	3. 5	. 73	. 86	5. 6	6. 0	6. 1	5. 4	4. 6	6. 8
MgO	1. 8	. 60	. 37	4. 8	5. 0	5. 1	4. 4	5. 1	11. 4
CaO	4. 2	1. 5	1. 6	9. 5	8. 1	7. 5	5. 3	6. 6	6. 8
Na_2O	2. 1	2. 6	2. 6	2. 3	2. 1	2. 0	2. 1	2. 6	2. 2
K_2O	5. 0	5. 2	6. 3	. 48	. 64	. 28	1. 9	3. 3	3. 2
TiO_2	. 74	. 4	. 56	. 96	. 90	. 90	. 86	. 64	. 59
P_2O_5	. 32	. 14	. 09	. 50	. 46	. 48	. 46	. 40	. 42
MnO	. 12	. 04	. 08	. 18	. 17	. 16	. 16	. 11	. 12
H_2O	--------	. 51	--------	3. 5	2. 8	3. 2	4. 2	. 81	. 68
CO_2	--------	. 08	--------	2. 9	1. 8	2. 5	3. 8	. 09	<. 05
Loss on ignition [1]	2. 3	--------	. 80	--------	--------	--------	--------		--------
Sum	99. 1	100. 0	99. 8	99. 1	100. 2	99. 2	99. 8	99. 9	100. 1
Sp gr	2. 65	2. 63	2. 52	2. 74	2. 76	2. 73	2. 72	[3] 2. 82	--------
Norms									
Quartz	17. 3	33. 0	27. 0	11. 7	14. 7	17. 2	16. 6	9. 4	0
Orthoclase	30. 2	30. 7	37. 3	3. 3	3. 9	1. 7	12. 2	19. 5	18. 9
Albite	18. 4	22. 0	22. 0	21. 0	19. 4	17. 8	19. 4	22. 0	18. 3
Anorthite	19. 7	6. 7	7. 2	34. 8	30. 9	32. 8	25. 3	20. 9	15. 0
Corundum	. 8	3. 1	1. 7	0	0	0	. 5	0	0
Wollastonite	0	0	0	0	3. 6	. 9	0	4. 1	6. 6
Enstatite	4. 5	1. 5	. 9	5. 1	13. 0	13. 5	12. 0	12. 8	23. 0
Ferrosilite	4. 2	0	0	12. 0	8. 3	8. 7	7. 4	5. 7	8. 8
Forsterite	0	0	0	0	0	0	0	0	4. 1
Fayalite	0	0	0	0	0	0	0	0	1. 6
Magnetite	2. 6	1. 2	1. 4	6. 5	3. 5	3. 3	3. 7	3. 3	1. 4
Apatite	. 7	. 3	. 3	1. 3	1. 0	1. 3	1. 3	1. 0	1. 0
Ilmenite	1. 4	. 8	1. 1	2. 0	2. 0	1. 8	1. 8	1. 2	1. 1
Hematite	0	. 5	. 8	1. 6	0	0	0	0	0
(Albite + anorthite) / Orthoclase	1. 3	. 9	. 8	16. 7	12. 9	29. 8	3. 7	2. 2	1. 8
Normative plagioclase	An_{50}	An_{22}	An_{24}	An_{61}	An_{60}	An_{63}	An_{55}	An_{47}	An_{44}

[1] Includes gain due to oxidation of FeO.
[2] Includes 0.45 percent organic matter; which prevented estimation of FeO; 0.44 percent SO_3; and traces of Cl, LiO_2, and BaO.
[3] Average of 8 samples which range from 2.64 to 3.06.

1. Quartz-latite; green wispy slightly welded ash-flow tuff of lower unit along the east flank of Elkhorn Mountains, about 5 miles southeast of mapped area in NW¼ sec. 19, T. 7 N., R. 1 E., Broadwater County. Collected by E. T. Ruppel and analyzed by rapid methods in 1953 by J. M. Dowd, K. E. White, and F. S. Borris. Lab. No. 53–77CW.
2. Rhyolite welded tuff of middle unit from north slope of East Fork of McClellan Creek, S½ sec. 14, T. 8 N., R. 2 W. Collected by H. W. Smedes and analyzed by rapid methods in 1954 by H. A. Phillips, P. L. D. Elmore, and K. E. White. Lab. No. 54–925C.
3. Rhyolite; composite sample of two blocks of welded tuff of middle unit from just east of the mapped area on ridge between Beaver and Pole Creeks, in NE¼SE¼ sec. 16, T. 8 N., R. 1 W., Broadwater County. This same sheet of welded tuff enters the mapped area in several places along the eastern edge. Collected by M. R. Klepper and analyzed by rapid methods in 1953 by J. M. Dowd. Lab. No. 53–72CW.

4–7. Andesite sill in upper unit of the volcanics from near the common cor. secs. 26, 27, 34, and 35, T. 8 N., R. 2 W. Collected by H. W. Smedes and analyzed by rapid methods in 1954 by H. A. Phillips, P. L. D. Elmore, and K. E. White.
 4. Basal zone of peperite. Lab. No. 54–927C.
 5. Central zone, not peperitic. Lab. No. 54–928C.
 6. Transitional between central zone and upper zone of peperite. Lab. No. 54–929C.
 7. Upper zone of peperite. Lab. No. 54–930C.

8. Quartz monzonite, near granodiorite in composition; composite of 8 samples of the Kokoruda Ranch complex. Collected by H. W. Smedes and analyzed by rapid methods in 1955 by P. L. D. Elmore and K. E. White. Lab. No. 143309.
9. Calcic melamonzonite from Kokoruda Ranch complex 60 ft northeast of the junction of McClellan Creek road and road to Economy mine, NE¼ sec. 21, T. 9 N., R. 2 W. Collected by H. W. Smedes and analyzed by rapid methods in 1961 by P. L. D. Elmore, I. H. Barlow, S. D. Botts and G. W. Chloe. Lab. No. 158777.
10. Syenodiorite from dike south of Antelope Creek stock 1⅛ miles east of mapped area, just south of dirt road in NE¼NE¼ sec. 4, T. 8 N., R. 1 W. Collected by H. W. Smedes and analyzed by standard methods in 1961 by E. L. Munson. Lab. No. G–3167.

11–12. Granodiorite of the Antelope Creek stock. Collected by M. R. Klepper and analyzed by rapid methods in 1953 by J. M. Dowd, K. E. White, and F. S. Borris.
 11. Typical of the main part of the stock, from low flanks of ridge south of Antelope Creek about one-quarter mile east of the mapped area in SW cor. sec. 33, T. 9 N., R. 1 W. Lab. No. 53–745CW.

some igneous rocks in the northern Elkhorn Mountains

Boulder batholith—Continued						Tertiary intrusive rhyolite			
Intermediate stage			Main stage Butte Quartz Monzonite		Late stage				
10	11	12	13	14	15	16	17	18	19
Analyses—Continued									
55.46	61.6	63.5	64.8	62.0	76.7	78.0	75.6	71.6	75.30
16.93	16.5	15.7	15.7	17.2	12.4	11.6	12.5	13.2	11.95
2.12	2.5	2.6	1.9	3.1	.6	.7	.6	.8	} 2.17
5.63	3.2	2.8	2.8	2.2	.77	.40	.51	.22	
4.01	2.6	2.4	2.2	1.6	.14	.36	.55	.02	.05
7.22	5.2	4.6	4.4	4.7	.81	.34	.44	.05	.62
3.01	3.4	3.3	3.1	4.1	2.2	4.0	2.4	3.4	3.09
3.18	3.0	3.2	3.9	3.3	5.8	4.0	4.0	5.0	4.69
.81	.53	.55	.60	.51	.13	.04	.01	.01	.17
.36	.22	.21	.19	.40	.90	.02	.02	.01	Trace
.16	.14	.14	.08	.15	.02	.02	.06	.07	Trace
.84	---	---	---	.56	.42	---	---	---	.97
.04	---	---	---	.05	.05	---	---	---	.45
---	.88	1.4	.57	---	---	1.0	3.8	5.7	---
99.8	99.8	100.4	100.2	99.9	100.9	100.5	100.5	100.1	[2] 99.5
---	2.73	---	---	2.73	---	---	---	---	---
Norms—Continued									
3.5	15.6	19.3	19.3	14.7	40.3	38.0	45.8	34.9	37.4
18.9	17.8	18.9	22.8	19.5	34.5	23.9	24.5	31.1	30.0
27.3	28.8	27.8	26.2	34.6	18.3	34.1	21.0	30.4	26.7
22.8	21.4	19.2	17.8	19.2	3.1	1.4	2.5	---	3.1
0	0	0	0	0	1.4	.2	3.4	2.6	.4
4.4	1.0	1.4	1.4	.6	0	0	0	0	0
10.1	6.5	6.0	5.5	4.0	.3	.9	1.4	0	.1
7.7	3.0	2.5	2.6	1.1	.7	.8	.4	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
3.0	3.7	3.7	2.8	4.4	.9	.9	.9	.7	0
1.0	.7	.3	.3	1.0	.3	0	0	0	0
1.5	1.1	.9	1.2	.9	.3	0	0	0	.3
0	0	0	0	0	0	0	0	.3	2.2
2.7	2.8	2.5	1.9	2.8	.6	1.5	1.0	1.0	1.0
An_{44}	An_{41}	An_{39}	An_{39}	An_{34}	An_{14}	An_{4}	An_{11}	An_{0} (Ab_{100})	An_{10}

12. Composite of 11 samples from all parts of the stock. Lab. No. 53–75SCW.
13. Quartz monzonite, coarse-grained, slightly porphyritic, from roadcut along east side U.S. Highway 91 between Shingle and Strawberry Creeks, N½SE¼ sec. 34, T. 9 N., R. 3 W. Rock is continuous with the type Clancy Granodiorite (Knopf, 1957) but is not the same as Knopf's porphyritic granodiorite (Knopf, written commun., 1962). Collected by R. W. Chapman and analyzed by rapid methods in 1953 by H. A. Phillips, K. E. White, and J. M. Dowd. Lab. No. 52–2116CW.
14. Granodiorite, medium grained, near quartz monzonite in composition, from small stock on north side of East Fork of McClellan Creek, NW¼ sec. 14, T. 8 N., R. 2 W. Collected by H. W. Smedes and analyzed by rapid methods in 1954 by H. A. Phillips, P. L. D. Elmore, and K. E. White. Lab. No. 54–926C.
15. Quartz monzonitic alaskite from near center NE¼ sec. 9, T. 8 N., R. 3 W., east side of U.S. Highway 91, 0.1 mile south of junction with Clancy Creek road, near south end of outcrop. Collected by R. W. Chapman and analyzed by rapid methods in 1954 by H. A. Phillips, P. L. D. Elmore, and K. E. White. Lab. No. 138309.
16. Porphyritic soda rhyolite from top of small plug on east side of U.S. Highway 91, 2¼ miles north of the mapped area, south of the middle of sec. 14, T. 9 N., R. 3 W., 0.90 mile (measured along highway) north of north end of railroad overpass (south of Montana City). Collected by R. W. Chapman and analyzed by rapid methods in 1953 by H. A. Phillips, P. L. D. Elmore, and K. E. White. Lab. No. 52–2114CW.
17–18. Rhyolite from narrow dike a few hundred feet west of mapped area, along west side of U.S. Highway 91, near middle of outcrop, NE¼ sec. 29, T. 8 N., R. 3 W. Collected by R. W. Chapman and analyzed by rapid methods in 1953 by H. A. Phillips, P. L. D. Elmore, and K. E. White.
  17. Aphanitic rock near center of dike; quartz latite very near rhyolite. Lab. No. 53–1859C.
  18. Rhyolite pitchstone near margin of dike. Lab. No. 53–1860C.
19. Porphyritic rhyolite, very near alkali rhyolite in composition, from summit of Red Mountain, about 10½ miles west of the mapped area in NW¼ sec. 10, T. 8 N., R. 5 W. Analysis published by Clarke (1910, p. 80, sample F). Collected by W. H. Weed and analyzed in 1899 by H. N. Stokes. Lab. No. 1787.

In the northwestern part of the map area (pl. 1) the lower unit of the volcanic rocks lies conformably on the Slim Sam Formation. In the northeastern part the volcanic rocks rest with angular unconformity upon the Slim Sam. Distinctive mappable units in the basal part of the Elkhorn Mountains Volcanics lap out against former topographic and structural highs. This is well shown in sec. 19, T. 9 N., R. 1 W., where thin partly welded ash-flow tuff beds (not mapped separately) lap up on the Slim Sam Formation.

In the southern half of the Clancy quadrangle, directly south of the map area (Klepper and others, 1957, pl. 1), the basal volcanic rocks rest directly on the Slim Sam Formation in the eastern part. Westward, however, the Slim Sam Formation sharply wedges out, and the upper and middle units of the Colorado Formation successively wedge out, so that a little west of the middle of the quadrangle the basal volcanic rocks rest directly on the lower part of the lower unit of the Colorado Formation. Klepper and others (1957, p. 34) interpreted this unconformity as representing a broad and deep valley cut across the preexisting rocks and into which the basal volcanic rocks were deposited. These basal volcanic rocks filled the trough and overflowed, leaving considerably thicker deposits along the trough than on either side. The inferred position of this valley coincides with the axis of a major syncline, and it may be that some late prevolcanic or early volcanic gentle folding occurred along this axis, and that streams guided by the syncline eroded a deep valley. Following deposition of the volcanic rocks, folding may have been renewed along the same axis, so that the thicker section of folded volcanics, the ancient valley, and the syncline now coincide.

The pattern of outcrop of the three units of the formation (pl. 1) outlines the broad synclinal structure. Interruptions by large irregular intrusive bodies and by faults make accurate measurement difficult, but it is possible that as much as 11,500 feet of Elkhorn Mountains Volcanics are preserved; the original thickness may well have been at least 15,000 feet.

The base of the Elkhorn Mountains Volcanics is placed at the base of the lowest volcanic breccia, lava flow, or ash-flow tuff, in accordance with regional usage. The base undoubtedly is at different stratigraphic levels in different areas because of the lenslike forms of some volcanic breccia, abrupt facies changes, the local lobate form of lava flows, removal of beds by erosion, and poor exposure. Of these factors, facies change probably is the most important.

LOWER UNIT

Rocks of the lower unit are dominantly pyroclastic and sedimentary debris, autobrecciated lava, and mudflow deposits. Included are monolithologic tuff and breccia, and polylithologic tuff, breccia, and conglomerate whose constituent fragments include a wide variety of textural types of rhyodacite, andesite, and basalt. Water-laid deposits of volcanic detritus are common in the basal part of the unit and also occur throughout, with various admixtures of airborne pyroclastic debris.

Volcanic breccia and conglomerate increase in abundance upward, as part of a general coarsening. The coarse fragments appear to be somewhat more rounded in the northeastern part of the area. Several thin partly welded ash-flow tuff beds are present in the northern part. The fragmental rocks and lava are rhyodacitic, andesitic, and basaltic; the ash-flow tuff beds are quartz latite.

A bed of calcareous tufa, similar to that described by Klepper and others (1957, p. 35) in the southern Elkhorn Mountains, is inferred to lie in the lower unit or in the lower part of the middle unit of the formation at shallow depth in the northeastern part of the map area. Reasons for this inference are given below (p. 64–66).

Although the fine-grained beds of the Elkhorn Mountains Volcanics are indistinguishable from many beds of the tuffaceous facies of the upper unit of the Slim Sam Formation, the lower unit of the volcanic sequence is distinguished by intercalations of coarse volcanic breccia and conglomerate, by a few thin beds of poorly welded or nonwelded ash flow tuff, and by a tendency toward massive bedding and gradation into crude lenses and channel fills. The effects of sorting and redistribution by water are abundantly displayed in the lower part but decrease upward, so that toward the top of the lower unit, bedding is obscure; where developed, it is probably due largely to ash showers, to zones within and on mudflows, and to zones in autobrecciated lava.

The only complete section of the lower unit in the map area is on the slopes of the northern tip of the Elkhorn Mountains (pl. 1), where it is about 2,200 feet thick. In the southwest corner of the area the lower unit is surrounded by faults and is cut by the South Fork intrusive mass; the thickness preserved is of the order of 4,000 feet. In the mountainous region along the middle of the south edge of the area, rocks of the lower unit are in fault contact with the middle unit to the north and are invaded by the batholith to the west and by the Moose Creek intrusive mass to the east. The thickness of strata in this block is at least 3,000 feet.

A generalized section of the lower unit is given below.

Stratigraphic section of the lower unit of the Elkhorn Mountains Volcanics

Section starts in the SW¼ sec. 19, T. 9 N., R. 1 W., ends in the N½ sec. 25, T. 9 N., R. 2 W., and is continuous with the section of the sandstone facies of the Slim Sam Formation described above.

[Measured by M. R. Klepper and R. A. Weeks, 1956. Thickness estimated]

	Feet
Middle unit (part):	
19. Welded tuff, very dark gray; closely spaced eutaxitic structure in homogeneous matrix of dense flintlike rock; abundant plagioclase crystals and small rock fragments; weathers light purplish gray	>500
Lower unit:	
18. Concealed; probably underalin by andesitic sandstone	35
17. Basalt porphyry; probably a sill, with massive base and peperitic top	(60)
16. Water-laid volcanic boulder conglomerate, consisting of about 75–80 percent fragments and 20–25 percent sandy matrix. Most of the fragments are round to subround boulders of several types of volcanic porphyry and nonwelded tuff; they are as much as 18 in. long, but most are 4–5 in	40
15. Concealed; covered by large slabs of partly welded tuff and porphyry	75
14. Tuff, in part massive, in part with irregular lensy bedding, in part laminated with silt, sand, and granule-sized fragments; includes some pebble and cobble beds with subround to subangular volcanic fragments and one boulder bed. Dominantly purplish gray in lower part and greenish gray in upper part. Thinly laminated beds and cobble beds are more common in upper half. Part is water laid, part probably is air-fall debris	325
13. Concealed; probably underlain by basalt of unit 12	(75)
12. Basalt porphyry, very fine grained; contains augite phenocrysts; slightly vesicular and amygdaloidal in basal 10 ft; dense to vaguely brecciated; looks slightly altered	(50)
11. Volcanic cobble and boulder beds, crudely layered; generally tightly packed, most fragments a few inches long, some well-rounded cobble conglomerate in float below outcrops; partly, if not wholly, water laid	50
10. Concealed by very coarse debris; probably landslide or mudflow material. Possibly a fault at base of covered interval	250

Stratigraphic section of the lower unit of the Elkhorn Mountains Volcanics—Continued

Section starts in the SW¼ sec. 19, T. 9 N., R. 1 W., ends in the N½ sec. 25, T. 9 N., R. 2 W., and is continuous with the section of the sandstone facies of the Slim Sam Formation described above.

	Feet
Lower unit—Continued:	
9. Lapilli tuff, tuff breccia, and volcanic conglomerate; crudely bedded; lower part mainly angular to subround lapilli in tuff matrix; in upper part some units are tuff breccia with fragments as much as 6 in. long. At least one bed in lower part is water worked, with well-rounded 1-in. pebbles. Most beds are nearly monolithologic. Cut by two thin sills (10–20 ft thick)	325
8. Ash-flow tuff, slightly welded, gray; contains wispy flattened pumice or glass clots and rock fragments, generally sparse and small but locally large and abundant. At base is a zone with angular fragments as much as 15 in. long. Caps crest of ridge	50
7. Poorly exposed interval mainly or wholly of andesitic sedimentary rocks, lapilli tuff, and fine-grained tuff breccia	300
6. Ash-flow tuff, slightly welded, with green wispy flattened pumice or glass clots; abundant rock fragments	20
5. Andesitic sandstone and siltstone with some granule beds, conglomerate, lapilli tuff, and tuff breccia; mostly olive gray; in part bedded and even laminated and in part massive	50
4. Ash-flow tuff similar to unit 6 above	40
3. Andesitic sandstone and siltstone similar to unit 5 above but with less coarse pyroclastic debris	100
2. Volcanic conglomerate with closely packed rounded pebbles of several porphyry types and lapilli tuff; fragments as much as 6 in. long, but most are 2–3 in.; no prevolcanic sedimentary rock fragments observed; matrix silty to sandy volcanic debris	500
Estimated total thickness of lower unit of Elkhorn Mountains Volcanics, excluding sills	2, 160
Slim Sam Formation:	
Upper unit (part):	
1. Alternating green andesitic sandstone and siltstone, and hard siliceous mudstone; some beds are quartz and chert sandstone with little or no andesitic debris	140

MIDDLE UNIT

The middle unit of the formation is characterized by rhyolite in welded tuff sheets interlayered with andesitic, rhyodacitic, and basaltic pyroclastic and epiclastic volcanic rocks; autobrecciated and massive lava; and mudflow breccia and conglomerate. Welded tuff forms nearly half the total volume. At least seven large welded tuff sheets are present in the southeastern and east-central parts of the area; these apparently merge to form two major composite sheets in the northeastern part (pl. 1). The pyroclastic rocks, lavas, and mudflows are similar to those of the upper part of the lower unit. Some beds of lapilli tuff and tuff breccia probably are nonwelded ash-flow tuff. In the map area the middle unit seems conformable on the lower unit, but near the south end of Bull Mountain, about 30 miles south-southwest of the map area, the middle unit seems to rest unconformably upon the lower unit and still older rocks (R. A. Weeks, oral commun., 1956).

The thickness of the middle unit ranges from about 3,300 to 7,500 feet. A complete section, 3,300–3,600 feet thick, is exposed in the southern part of the map area, south of Crazy Peak. In the northern part of the area the middle unit lies with apparent conformity on the lower unit, but it is separated from the upper unit by the Casey Peak intrusive mass, except in one small area where a few tens of feet of the upper unit remain; at least 4,000 feet of the middle unit is preserved there. East of the map area, along Beaver Creek, the middle unit is in fault contact with the Slim Sam Formation, but the remaining part extends without structural complication into the map area, to where it is truncated by the Casey Peak intrusive mass. The thickness of this remnant is 7,000–7,500 feet.

UPPER UNIT

The upper unit is dominantly water-laid thin- to medium-bedded mudstone; andesitic and basaltic siltstone, sandstone, and conglomerate; and bedded tuff. It also includes a few thin beds of volcanic breccia. Ripple marks, crossbedding, channel sandstone, and mud cracks in the finer grained strata give ample evidence of deposition by running or standing water. Many of the beds are rhythmically layered and resemble varved clay. Varvelike mudstone and siltstone may represent fine-grained ash that fell or was washed into lakes and ponds. Accretionary lapilli are common in these fine-grained strata. Some mudstone is very light colored and porcelaneous. Fossil plant remains were found in some thin beds of siltstone and fine-grained andesitic sandstone.

Outcrops of the upper unit mark the crest of the northern Elkhorn Mountains.

The thickest preserved section of the upper unit, about 2,000 feet, is near High Peak. Northwestward, probably two or three times that thickness is preserved, but structural complexities prevent accurate measurements.

AGE AND CORRELATION

The volcanic rocks of the Elkhorn Mountains are indistinguishable from similar rocks in the Boulder Mountains and near MacDonald Pass, to the west; in Bull Mountain and along the northern flanks of the Highland and Tobacco Root Mountains, to the south; and near Wolf Creek, to the north. The volcanic rocks in all these areas are considered to be part of the Elkhorn Mountains Volcanics.

In the Elkhorn Mountains the volcanic rocks lie on strata as high as the upper part of the Slim Sam Formation and as low as the lower part of the Colorado Formation. In the map area fossils have been found only in the upper unit, in one locality. This locality is at the head of Beaver Creek, on the east slopes of High Peak on the boundary between secs. 34 and 35, about 500 feet south of their common north corner, and just below the lower of two mapped sills. The fossils are plant remains in gray, olive-gray, and dusky-blue andesitic siltstone and fine-grained sandstone. The first material found was submitted to Roland W. Brown and identified by him (written commun., 1953) as a cone scale, *Dammara* sp., of Cretaceous age, probably Judith River. Brown later collected additional material himself and reported (written commun., 1954) that—

> The plants from this locality are few and very fragmental. In the 1953 shipment * * * I identified a cone scale, *Dammara* sp. and assigned a Late Cretaceous age to the strata. The 1954 collection has a portion of a coniferous twig that may be *Androvettia* or *Libocedrus*; and a fragment that may be the cone scale of a fir *Abies*, or a small ginkgo leaf. As all of these pieces are fragmentary, I hesitate to make definite identifications. If the first cone scale is really a *Dammara*, I would have no doubts about its Cretaceous age. If, however, it is merely a battered cone scale of *Abies*, * * * then these cone scales plus the *Androvettia* or *Libocedrus* would suggest a younger age, Paleocene or a little later.

Elsewhere, fossil plants have been collected from the upper unit of the Elkhorn Mountains Volcanics in Mullevy Gulch along the east flank of Bull Mountain and from the lower unit at Tebay Springs on the west flank of Bull Mountain, south of Boulder. The material was identified by Brown who reported (written commun., 1954) that "these two localities yield definitely Upper Cretaceous plants that are comparable to those of Judith River age."

Volcanic debris in the Livingston Group, far southeast of the Elkhorn Mountains, is similar to material of the Elkhorn Mountains Volcanics, and most likely is detritus washed out from the Elkhorn Mountains. No other possible source area is known. This volcanic debris is intercalated with beds as old as the Claggett Shale equivalents (A. E. Roberts, written commun., 1961). The abundance of welded tuff in this detritus strongly suggests that the middle unit of the Elkhorn Mountains Volcanics had already been deposited and was being eroded during Claggett time.

Near Wolf Creek and northward along the Rocky Mountain front, volcanic rocks correlated with the middle and upper units of the Elkhorn Mountains Volcanics occur as a member of the Two Medicine Formation.[1] This volcanic member is overlain by the St. Mary River Formation containing *Ostrea glabra* beds (Schmidt, 1963); these beds are equivalents of the Horsethief Sandstone (W. A. Cobban, written commun., 1956).

The age of the Elkhorn Mountains Volcanics is thus rather closely bracketed; deposition probably began after Niobrara but before Claggett time, and ended before Horsethief time. The formation probably is the time equivalent of the Eagle Sandstone, Claggett Shale, and Judith River Formation. This interval corresponds with the Campanian Stage (Cobban and Reeside, 1952, chart 10b).

DESCRIPTION OF ROCK TYPES

Many rock types occur repeatedly throughout the volcanic section; only a few are restricted to a single unit. Therefore, description of the rocks is made on the basis of lithology rather than stratigraphic position.

All the rocks have been thermally metamorphosed and have been altered in other ways. Primary textures and minerals in the volcanic rocks have been obliterated in a narrow inner contact zone of high-grade thermal metamorphism along the Boulder batholith contact. Elsewhere, primary textures are preserved, and in the aureole of low-grade metamorphism some of the primary minerals also are preserved as relicts in rocks which have been partly recrystallized to very fine grained epidote, albite, actinolitic hornblende, chlorite, carbonate minerals, opaque minerals, and quartz.

In addition, some beds in the low-grade metamorphism aureole exhibit textures and minerals which are interpreted as relicts of prebatholithic deuteric and hydrothermal alteration. These relict minerals generally are the same as those formed during the late low-grade thermal metamorphism, as well as clinozoisite and zeolites. All apparently were stable under the conditions of the ensuing metamorphism; they differ from the fine-grained ubiquitous metamorphic minerals in being coarser grained and restricted to certain beds, parts of beds, or irregular fracture-controlled zones.

[1] Viele, G. W., 1960, The geology of the Flat Creek area, Lewis and Clark County, Montana: Utah Univ., unpub. Ph. D. dissertation.

The pervasive metamorphism and alteration have imparted a distinctive color to many of the rocks. Most rhyolitic welded tuffs of the middle unit are grayish black to medium gray; some are of more conspicuous shades of red and reddish brown. Quartz latitic ash-flow tuff of the lower unit is various shades of green and greenish gray. The dominant hue of the pyroclastic rocks, lavas, and sedimentary debris is dark greenish gray to grayish black, blue and red being prominent locally.

Although quartz and K-feldspar are abundant in the sheets of rhyolitic welded tuff in the middle unit, these minerals and biotite are sparse in sandstone, tuff, and breccia, which contain, instead, abundant crystals and fragments of plagioclase, pyroxene, and amphibole.

Plagioclase ranges from oligoclase to bytownite; most is andesine and labradorite. Some tuff beds contain only andesine as the feldspar, others only labradorite, and still others contain heterogeneous mixtures of feldspar with a wide range of composition.

BRECCIA AND CONGLOMERATE

The Elkhorn Mountains Volcanics include large quantities of polylithologic and monolithologic volcanic breccia and conglomerate; that is, coarse-grained deposits whose fragments are either all of the same rock type or of a variety of rock types. Many deposits with coarse angular fragments grade laterally or vertically into deposits with well-rounded debris; others have lenses, beds, or irregular zones marked by well-rounded debris. Some of these deposits are conglomerate, others may be agglomerate or autobrecciated lava whose particles were rounded by attrition in a vent or during the flow of lava. For these reasons, the volcanic breccia could not be clearly separated from conglomerate in this study.

Monolithologic breccia and conglomerate probably include talus, mudflow, and landslide debris from homogeneous source areas (such as lava flows and domes); agglomerate; rubbly ash-flow deposits; and autobrecciated lava and derived mudflows.

Polylithologic breccia and conglomerate probably include talus, mudflow, and landslide debris from heterogeneous source areas, and alluvial-fan and channel deposits.

These coarse-grained deposits are most abundant in the lower unit of the formation, where they occur in beds as much as 600 feet thick. They occur in the middle unit where they are not so thick or so coarse, and in the upper unit only as local beds of polylithologic conglomerate less than 10 feet thick.

The most common kinds of fragments are porphyritic basalt, andesite, rhyodacite, and lithic tuff; andesitic sandstone and siltstone, breccia, and welded tuff are only locally abundant. Fragments of nonvolcanic rocks are rare in the lower unit and apparently are absent elsewhere.

Most fragments are dense or microvesicular; scoria and pumice are rare. Matrix fills nearly all pore space, and where scoria is present, the cavities generally are invaded by matrix (fig. 10).

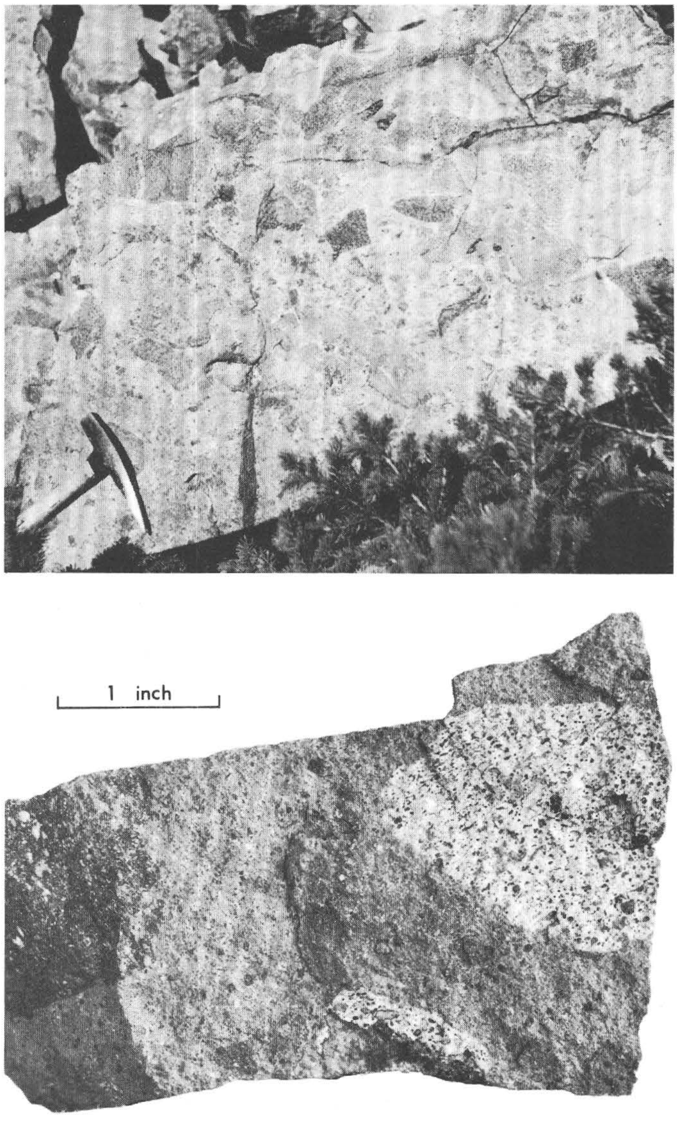


FIGURE 10.—Volcanic breccia. Upper, Monolithologic andesite porphyry blocks in a polylithologic matrix of andesitic siltstone and sandstone. In places, banding in the matrix is contorted (as in the photograph, near the middle right edge). Lower, Polylithologic volcanic breccia showing penetration of ash matrix into vesicular and scoriaceous blocks of basalt. Only vesicles not already filled with ash received amygdaloidal fillings later.

Many breccias in the lower and middle units are for the most part monolithologic and contain coarse to very fine fragments of angular to subround porphyritic basalt or andesite. The largest blocks observed are about 3 feet long. To the north and northeast the fragments are in general more rounded, and the deposits contain a higher proportion of ash or mud matrix. These deposits resemble glacial till, in which coarse, medium, and fine particles are mixed. Sorting and bedding are lacking in most deposits, and where present, they are generally obscure and discontinuous.

Monolithologic breccia and conglomerate are widespread and sheetlike. Beds commonly are 50 feet or more thick; some are nearly 600 feet thick. Several sheets were traced for more than 2 miles without appreciable change in thickness or lithology. The original extent of these sheets could not be determined because of interruption by faults, intrusions, and cover. Attitudes of strata above and below and of sparse crude internal bedding are parallel and indicate that the deposits had low primary dips.

The sheetlike form, fine matrix, lack of sorting and grading, and absence of explosive features, such as tapered bombs and scoria, suggest that these monolithologic breccias are material comminuted by the autobrecciation of slowly moving lava, much of which may have been redistributed as mudflows, as described by Curtis (1954).

Polylithologic breccias are in general not so thick or abundant as the monolithologic breccias, but they are coarser. Some blocks are about 8 feet long. These breccia beds are not so extensive as those of monolithologic type, although one bed was traced for more than a mile without apparent change in thickness. The fragments are of dense and porphyritic andesite and basalt; some are highly vesicular and amygdaloidal. They grade from angular to well rounded, the latter usually clearly water laid and more properly referred to as volcanic conglomerate. Some polylithologic breccia has very little matrix, and the blocks are packed tightly together; some has a high proportion of matrix, and the blocks are very loosely packed.

Some beds consist of angular monolithologic blocks embedded in a silty to sandy polylithologic matrix (fig. 10). These may be talus, slightly reworked agglomerate, mudflows, extrusive peperite, or landslides. In some breccia the tuff matrix shows supratenuous folds which were formed as the breccia blocks first were surrounded and then covered by ash. Other beds exhibit blocks that fell into thin finer grained beds and produced bedding sag.

One coarse bed of polylithologic breccia about 100 feet thick occurs between the 2 sills near the saddle of the ridge that connects High and Casey Peaks. It contains abundant blocks of vesicular basalt, some of which are scoriaceous. The matrix has penetrated into some of the scoria and broken vesicles around the rims of some blocks (upper fig. 10). In the interior of these blocks, the cavities were filled as amygdules. Because of penetration by the matrix, the blocks are hazily defined and thus superficially resemble partly assimilated inclusions. The amygdular filling must have occurred after the breccia came to rest, and then only in the interior of the blocks, where ash matrix had not previously filled the vesicles. Parts of the ash matrix were porous, and their voids are now lined and filled with the same minerals as in the amygdules. Other blocks in this bed of breccia acquired amygdules before deposition; these blocks exhibit broken amygdules and are not penetrated by the matrix.

ASH-FLOW TUFF

Ash flows are interpreted as having been emplaced by an avalanche or flow of hot gas-laden ash, the heat of which in many places caused softening of glass fragments, and the weight of which caused collapse and flattening of the softened fragments, which then welded together into compact sheetlike masses bearing some resemblance to both lava and tuff. The welded parts are properly called welded ash-flow tuff—a term here shortened to welded tuff, in conformity with the terminology of Smith (1960a). Some include sufficient coarse debris to warrant the full name ash-flow tuff breccia, but again for conformity are called ash-flow tuff.

The characteristics of ash-flow tuffs have been summarized by Smith (1960a) and Ross and Smith (1961).

The ash-flow tuffs (figs. 11–15) consist of fragments of pumice and other rocks in a matrix of small rock shards which probably once were glass; irresolvable material which probably is altered fine-grained ash; and euhedral and broken crystals of feldspar, quartz, hornblende, pyroxene, biotite, and magnetite.

Rock fragments include ejecta which are termed "essential," "accessory," and "accidental," following the usage of Wentworth and Williams (1932). The essential fragments are of direct magmatic origin. Accessory fragments are from previously consolidated rocks of the Elkhorn Mountains volcanic pile. Accidental fragments include chips of fine-grained felsic and cherty rocks and dense green, maroon, purple, and black rocks which may have been derived in part from the underlying prevolcanic strata and in part from rocks of the lower unit of the formation. These fragments are very sparse in the middle unit, but locally they are abundant in the lower unit.

Accessory fragments are largely of fine-grained and porphyritic basalt, andesite, and rhyodacite indistinguishable from similar rocks that make up much of the volcanic pile; and pieces of welded tuff similar to the enclosing rock or similar to the essential fragments, except that the accessory blocks clearly were collapsed and deformed earlier and appear to have been compact and solid during emplacement of the host sheet of welded tuff. Fragments of earlier welded tuff are abundant in nearly all the ash flows.

Fragments considered to be of essential ejecta generally are ½–8 inches long, but locally they are more than 6 feet long; they occur as discs which lie parallel to the plane of the sheet. Axial ratios of essential fragments generally are between 1:2 and 1:5 in rocks of the lower unit and commonly are about 1:15 to 1:20 in welded tuff of the middle unit, where extreme ratios of 1:60 locally attain. Some essential fragments are pumice, but others may represent former clots of lava or glass that did not vesiculate. They both appear to be of the same composition as the matrix, and, in fact, in welded tuff they generally cannot be distinguished except on a favorably weathered surface or under the microscope in plane polarized light.

Except in the nonwelded ash flows, most of the essential fragments have at least incipiently digitate or wispy margins (figs. 11*B*, 13*B*), and in the more intensely welded deposits, the fragments are bent or draped around the compact accessory and accidental rock fragments and crystals (Figs. 12, 13*A*). The wispy margins and the curved cross sections indicate that at least part of the discoid or plate form is due to flattening of pumice fragments by collapse; in general, the more thorough the welding, the flatter the essential fragments. However, essential fragments in some nonwelded ash flows are inequidimensional and indicate that the primary fragmental shape of some pumice ejecta may have been platelike, with axial ratios of as much as 3:1. Such plates do not have wispy margins.

The essential fragments appear to have been deformed more than the shards in the matrix in slightly to moderately welded tuff, and apparently were less viscous than the shards. Similar relations were noted by Ross and Smith (1961, p. 41). This assumed lower viscosity of the larger fragments may be due to their having had more volatiles, or higher temperature, or slower rate of cooling because of their smaller ratio of surface area to volume.

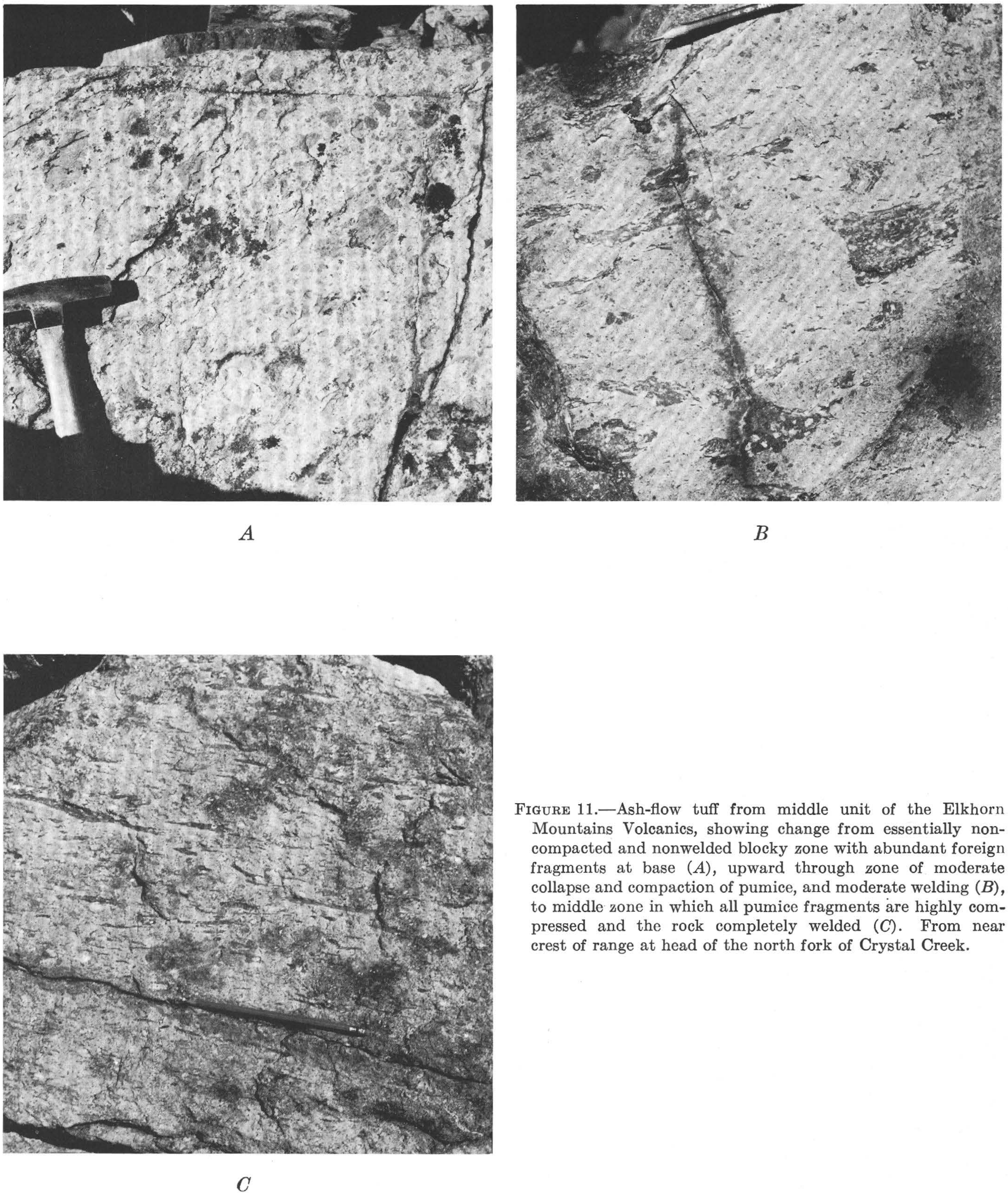
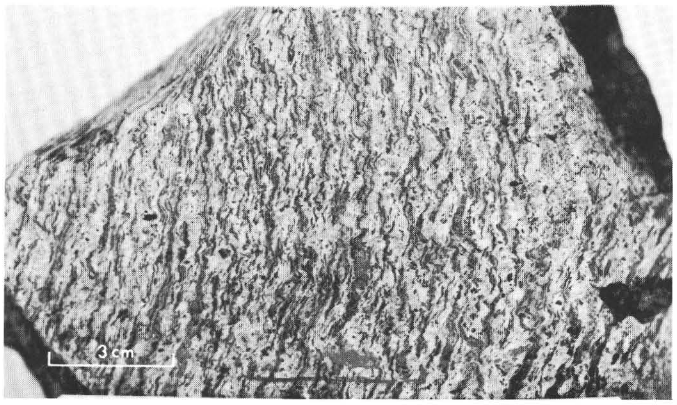
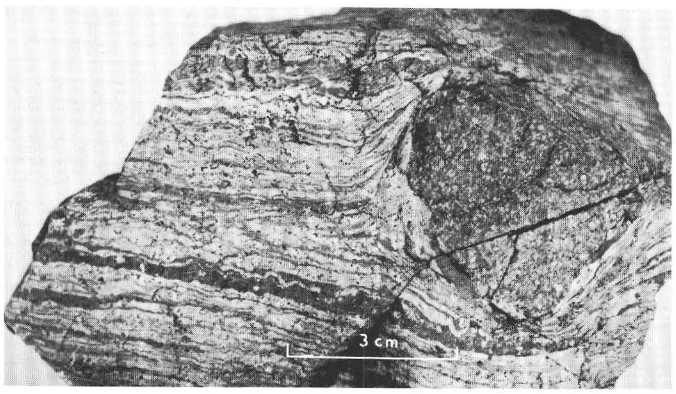


FIGURE 11.—Ash-flow tuff from middle unit of the Elkhorn Mountains Volcanics, showing change from essentially noncompacted and nonwelded blocky zone with abundant foreign fragments at base (*A*), upward through zone of moderate collapse and compaction of pumice, and moderate welding (*B*), to middle zone in which all pumice fragments are highly compressed and the rock completely welded (*C*). From near crest of range at head of the north fork of Crystal Creek.

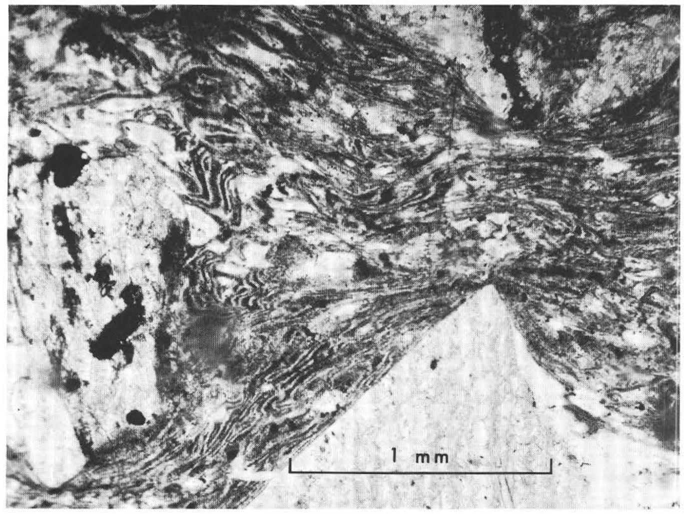


A

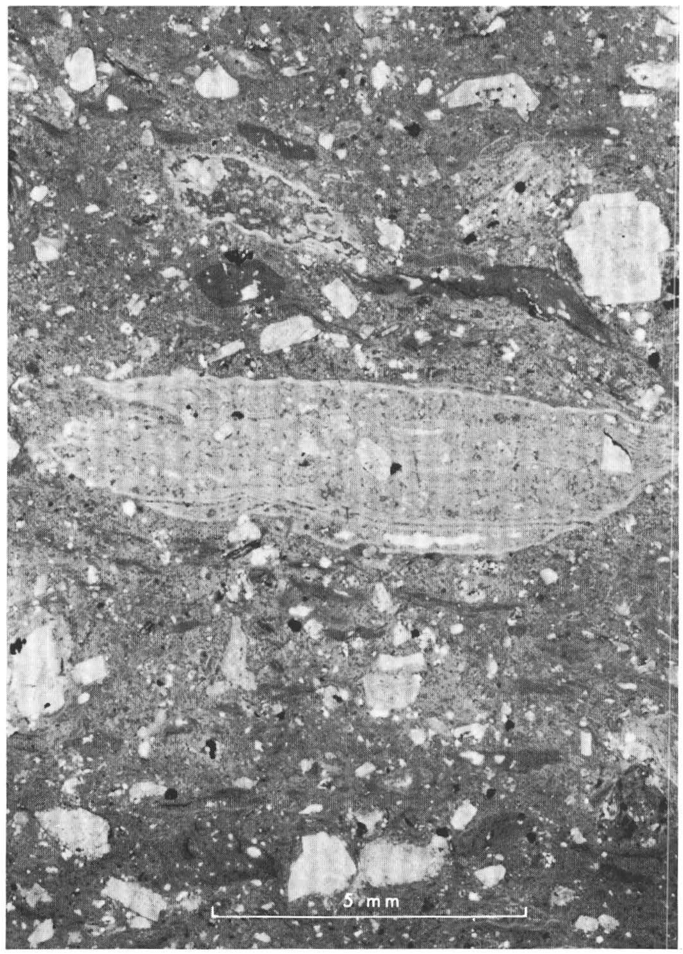


B

FIGURE 12.—Welded tuff showing contortions around obstacles. Collapsed pumice fragments have crinkled appearance where draped over plagioclase crystals (*A*). Sharp deflections are produced around large cognate fragments (*B*), which were dense and solid at time of welding.



A



B

FIGURE 13.—Welded tuff. *A*, Glass shards (dark gray, outlined by clear rims) are highly compressed between two crystals on right side and are less compressed but contorted in pressure shadow region next to crystal on left side. *B*, Collapsed pumice disc with bleached margin showing characteristic digitate rims. Plane polarized light.

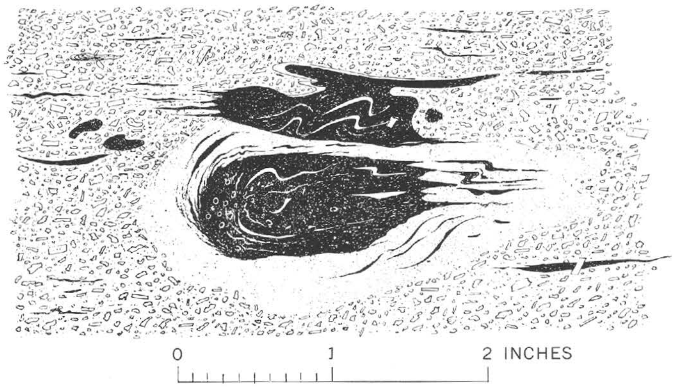


FIGURE 14.—Partly flattened pumice fragments in welded tuff. Alteration halo shown by light stipple. Drawn to scale from cut slab.

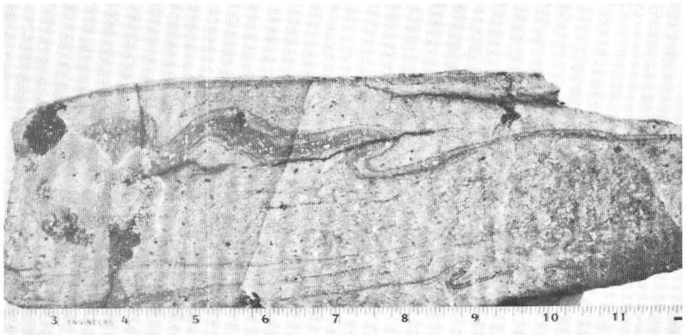


FIGURE 15.—Welded tuff with contorted eutaxitic structure. Some layers are relict devitrified flattened pumice; others may represent lateral extensions of this devitrification into the matrix.

The preferred orientation of the platy essential ejecta gives the rock a planar structure. Ash-flow deposits in the middle unit, especially, exhibit all gradations from loose structureless tuff and tuff breccia to compact highly welded rocks with conspicuous streaky flowlike appearance (fig. 11). This streakiness, or eutaxitic structure, is the most diagnostic field feature of the welded tuffs and is lacking in the nonwelded rocks.

The ash flows are poorly sorted and vary in texture; most have gradational to tabular zones of different texture, marked by differences in size or abundance of fragments and by degree of welding and compaction (fig. 11). These are similar to the zones described by Smith (1960b). Maximum collapse and highest degree of welding occur in the middle. Those ash-flow layers in which the essential fragments are not flattened closely resemble airborne ash; many of these may have gone unrecognized as ash-flow deposits. Similarly, where essential fragments are lacking or are blended with the matrix, there is no apparent eutaxitic structure, and the rocks resemble nonwelded ash-flow tuff or airborne tuff. Where accessory and accidental fragments also are lacking, sparse, or inconspicuous, the rocks resemble fine-grained crystal tuff or porphyritic lava.

Ash-flow rocks in the lower unit probably are quartz latite; those in the middle unit are rhyolite, but near quartz latite in composition. No ash flows were observed in the upper unit.

Many of the rocks have been propylitized, and all have been thermally metamorphosed by the Boulder batholith and its satellite bodies. The effects of metamorphism are discussed on pages 82–85.

QUARTZ LATITE ASH FLOWS

Ash-flow tuff has been observed in the lower unit only in the northern part. At least 4 beds crop out, ranging from homogeneous nonwelded tuff to partly welded wispy-looking rocks in deposits a few feet to about 50 feet thick. Several of these beds in a narrow zone in sec. 23, T. 9 N., R. 2 W., were mapped separately. Elsewhere, they were not mapped. Their aggregate thickness probably is only about 100 feet.

At least three sheets of similar thin partly welded to nonwelded ash-flow tuff occur in the lower unit several hundred feet above the base of the volcanics southeast of the map area. A chemical analysis of one of those (sample 1, table 2) indicates that the rock, in Rittman's classification (1952), is quartz latite near rhyolite in composition. Very likely the ash flows in the lower unit of the volcanics in the mapped area also are quartz latite.

The matrix of quartz latite ash-flow tuff is gray or green. Essential fragments generally are less than one inch across, are various dark shades of green or gray, and have all been chloritized to some extent. Accessory and accidental fragments and plagioclase crystals generally are abundant; crystals of other minerals are sparse. Plagioclase phenocrysts in essential fragments are sodic labradorite and calcic andesine (An_{60-48}), whereas those in rhyolite of the middle unit are more sodic (An_{50-32}).

The basal zone of the uppermost ash-flow tuff (unit 8, in the middle of the measured section) has abundant angular accessory fragments as much as 15 inches long. In contrast, the welded tuff at the base of the volcanics (unit 32 of the measured section of the tuffaceous facies of the Slim Sam Formation) is nearly devoid of accessory and accidental fragments.

A representative specimen of quartz latite of ash-flow origin similar to that of the chemically analyzed sample (1, table 2) is described below. It is from the medial welded part of an ash flow that is about 20 feet thick.

The rock is a streaky tuff with grayish-green and grayish-olive-green wispy discs and plates of essential ejecta 2–35 mm long and about one-half to one-third as thick, set in a yellow-green to pale-olive matrix of fine-grained ash. The essential fragments, about 25 percent of the rock, contain scattered phenocrysts of turbid plagioclase. Accessory and accidental fragments, about 5 percent, are of grayish-red fine-grained porphyritic augite andesite and pale-olive chert or very fine grained tuff in equant chips as much as 5 mm long. The matrix, 70 percent, consists of about one-third plagioclase crystals as much as 1 mm long and two-thirds devitrified and altered flattened grayish-green shards which curve partly around accidental and accessory fragments and larger crystals.

The matrix contains numerous grains of andesine and sodic labradorite 0.01–1 mm long, sparse fragments of augite crystals, and closely packed moderately deformed rock shards that probably were glass originally. In plane polarized light the shard texture is clearly discernible, but under crossed nicols it is nearly obliterated because pervasive devitrification and alteration have produced a camouflage of aggregate- and mosaic-textured intergrowths of quartz, plagioclase, and K-feldspar and larger granules and flakes of epidote, chlorite, and sericite. Similar changes have rendered the essential fragments nearly indistinguishable from the matrix, the principal distinction being the smaller proportion of plagioclase crystals in the fragments. In plane polarized light the fragments appear slightly darker than the matrix and exhibit a streaky and somewhat lacy appearance because of collapse of vesicle walls in pumice. The digitate margins are of delicately attenuated strands which are crenulated and distorted on a small scale because of compaction over small crystal fragments; their subparallel billowing sinuous forms somewhat resemble a lock of hair. These oriented flattened fragments collectively give a eutaxitic structure to the rock.

Small colorless grains of porphyroblastic cordierite less than 0.05 mm across occur irregularly throughout the rock and locally are very abundant in the marginal parts of essential fragments. These minute grains, which are almost universally cyclic twins (sixlings), have complex crenulated rims.

Original vugs in some larger essential fragments are now filled with clear quartz and crystals of epidote.

RHYOLITE ASH FLOWS

Throughout the Elkhorn Mountains volcanic field, the middle unit is characterized by sheets of welded rhyolite tuff (table 2), which constitute about 50 percent of the unit. In the map area there are at least seven sheets of welded tuff in the middle unit (pl. 1). The specific gravity of the rocks ranges from 2.43 to 2.63, with an average of 2.54. These sheets are of relatively uniform thickness and broad extent. The intercalated beds of pyroclastic rocks likewise are rather uniformly thick. The result is a plateaulike accumulation. These distinctive sheets of welded tuff provide marker units for mapping structure within the volcanic pile and for correlating the volcanics between fault blocks. Conspicuous exceptions to the continuity of sheets are the gap in a sheet on the ridge between Staubach and North Pole Creeks in the NW¼ sec. 17, T. 8 N., R. 1 W., and the wedgeout southward of the next higher sheet, at the head of Sawmill Creek. Whether the gap and wedgeout are due to nondeposition or to erosion is not known.

North of the head of Antelope Creek, the middle unit comprises two main sequences of thick composite sheets of intensely welded tuff and minor unmapped lenses and thin beds of pyroclastic debris, separated by a thick sequence of breccia. The lower sequence of welded tuff is 1,500–1,800 feet thick, the breccia is as much as 2,000 feet thick, and the upper sequence of welded tuff is more than 2,800 feet thick (map estimates). The aggregate thickness of welded tuff in these 2 sequences is far greater than in any other part of the map area and amounts to at least 70 percent of the middle unit.

Even though the stratigraphy of the volcanics in the northern part is complicated by faulting, enough of the section can be pieced together between faults to warrant the conclusion that at least twice as many welded tuff sheets occur there as occur across the fault that trends northward from the head of Staubach Creek to Antelope Creek. This suggests major lateral displacement on the fault.

The lowest sheet exposed in the Beaver Creek area is about 900 feet thick and more than 4 miles long. It may have been much longer, for it is cut off by the Antelope Creek stock on the north and by a large fault at the south, just east of the map area. Despite its thickness, this sheet seems to be a single flow. In the south, the sheet comprises nearly 800 feet of homogeneous nonwelded ash-flow tuff which grades upward within 3 or 4 feet into 120 feet of poorly to moderately compacted and welded tuff. Northward, the thickness of the welded upper part steadily increases, and between Staubach and Antelope Creeks the sheet is moderately to intensely welded throughout. The aggregate thickness of welded tuff in that area from Beaver to Staubach Creeks amounts to about a third of the total thickness of the middle unit. In the southern part of the map area, sheets of welded tuff make up about half of the total.

The bottom and top parts of some ash-flow tuffs are nonwelded and grade into a central zone of moderately to intensely welded tuff. In most ash flows the welded zone makes up more than three-fourths of the deposit; in others this zone makes up a third or so of the total and is a little below the middle. In many deposits where an upper nonwelded zone is lacking, the welded zone extends to the top. In several deposits of this type it could be determined, by the presence of remnants, that an original nonwelded zone had been eroded. Probably all the sheets originally had a nonwelded upper zone.

Some rhyolite ash-flow tuffs have abundant blocky accessory or accidental fragments in their basal part;

others have zones of coarse material elsewhere. In a few single sheets of welded tuff there occur zones of intensely collapsed pumice fragments alternating with zones of moderately collapsed pumice. As Smith (1960b) suggested, these zones may indicate that several separate ash flows were emplaced so rapidly that they cooled as a single unit.

The matrix of ash-flow tuff in the middle unit generally is dark gray in the nonwelded and poorly welded zones and bluish gray in the welded zones. Essential fragments are mostly dark gray and dark bluish gray, but locally they are shades of yellow, brown, orange, and rarely purple, but not green. Microscopically, the welded tuffs are characterized by flattened and deformed Y-shaped shards or streaks of devitrified glass which are bent around other rock fragments and crystals (fig. 13*A*). Wisplike lapilli and small shards of the matrix are bent and draped about these fragments, resulting in an apparent contorted flow structure of small scale. Plagioclase crystals in essential pumice fragments in rhyolite welded tuff are andesine (An_{50-32}), whereas those in quartz latite of the lower unit are more calcic (An_{60-48}).

A few accessory fragments of intensely welded cordierite-bearing tuff were observed in ash-flow tuff that otherwise has no cordierite and is only weakly chloritized and epidotized. Primary cordierite or the cordieritelike mineral osumilite occur in some peraluminous lavas (Miyashiro, 1953, 1956), and it may be that the so-called cordierite in the Elkhorn Mountains Volcanics actually is osumilite and of primary magmatic origin. Or perhaps the cordierite was produced by thermal metamorphism of older welded tuff in the vent of the younger ash-flow eruption. Either way, the presence of cordierite or a cordieritelike mineral in these volcanic rocks shows that cordierite is not formed only by thermal metamorphism related to large intrusions such as the Boulder batholith.

In many sheets of welded tuff, haloes surround the essential blocks that were not highly flattened. These haloes are formed by an abundance of fine-grained epidote, calcite, and bleached mafic minerals (fig. 14). They are interpreted as due to alteration by the gas trapped in the fragments.

Two samples of welded tuff from the middle unit were analyzed chemically (2 and 3, table 2). Both are rhyolite in Rittman's classification (1952). They are closely similar to each other petrographically as well as chemically; both also are similar to analyzed welded tuff in the middle unit in other parts of the volcanic field (Knopf, 1913, p. 26, and 1957, p. 84; Klepper and others, 1957, p. 34; and unpub. analyses).

The chemically analyzed rocks are medium gray and medium bluish gray, weather medium dark gray, and form conspicuous ledges and slopes strewn with blocky rubble. Sample 3 (table 2) is from the most intensely welded zone of a thick sheet that probably is the same sheet shown in figure 11*C*. On fresh surfaces the rock appears to be structureless and homogeneously dense, but on weathered surfaces essential fragments stand out conspicuously as olive-gray wisps and streaks, a few millimeters to nearly 1 meter long and one-fourth to about one-fifteenth as thick. Larger fragments are more intensely compressed than smaller ones. Accessory and accidental fragments were not observed. Plagioclase crystals 1–3 mm long make up about 5–8 percent of the matrix and about 3 percent of the compressed essential fragments.[2] A petrographis description follows:

Thin sections show that the welded tuff texture has been obliterated by devitrification and subsequent grain growth. The entire rock has a highly variable and heterogeneous texture marked by aggregates and mosaics of K-feldspar, quartz, and plagioclase and by larger porphyroblastic clusters of the same minerals. Larger essential ejecta can now be recognized only because the recrystallization was coarser in those fragments than in the matrix and smaller pumice chips. Even in plane polarized light the large fragments are only hazily defined because crystallization has taken place throughout the rock without regard for boundaries of fragments.

Plagioclase phenocrysts in the essential pumice fragments are andesine (An 42–50). Plagioclase fragments in the matrix have a wide range in composition, indicating that many of them were derived from fragmentation of porphyritic andesite and related rocks which are the prevalent accessory ejecta in the ash flows, as suggested by Ross and Smith (1961, p. 35). K-feldspar appears to be confined to the mosaic in the groundmass where it occurs mostly as untwinned clear crystalloblastic grains. Quartz occurs in the aggregate- and mosaic-textured groundmass and as irregular lenses, pods, and streaks of coarser grained clear masses scattered in rough alinement.

Scattered plates of biotite make up less than 1 percent. They have been irregularly bleached, dusted with iron oxides, and rimmed with granules of magnetite. The relict parts are pleochroic from moderate brown and dusky yellowish brown to grayish yellow. Where bent partly around plagioclase crystals, the biotite was recrystallized to polygonal arcs.

Sparse fragments of amphibole occur, especially as inclusions in biotite. They are pale colored and pleochroic from neutral or yellowish gray to grayish green. Epidote and zoisite occur as scattered irregular large grains, mostly as replacement of plagioclase.

Sheets of welded tuff exposed along the ridge that trends southeastward from the summit of Crazy Peak, in the N½ sec. 1, T. 7 N., R. 2 W., and xenoliths of welded tuff in the small basalt plug in the NE¼ sec. 25, T. 8 N., R. 2 W., show the least alteration and recrystallization. Megoscopically, these

[2] Although some of the crystals probably are accidental or accessory, they must differ from the essential plagioclase by less than 18 mol percent anorthite, which is the total range in plagioclase composition; their contamination effect on the bulk composition of the rock would be slight. Even if as many as one-fourth of the crystals were accidental or accessory, and had composition as calcic as An_{50}, they would affect the composition by less than 0.25 percent CaO and less than 0.15 percent Na_2O.

rocks are no different from others, but in thin section they display better preservation of primary texture and structure.

They consist of wispy essential fragments of compressed pumice (fig. 13 B), as long as 30 mm and one-fourth to one-tenth as thick, and sparse accessory chips of andesite and rhyodacite embedded in a fine-grained matrix of deformed shards and plagioclase crystals (fig. 13 *A*). Essential fragments constitute about 20 percent, accessory fragments less than 3 percent, and plagioclase and very sparse bleached biotite crystals, as much as 3 mm in diameter, make up nearly 15 percent of the rock.

Under the microscope the relict form of distorted shards is clearly visible in plane polarized light (fig. 13 *A*). The core of each shard is a mass rich in K-feldspar that crystallized in aggregate texture, and appears dark; the rim of each is an almost irresolvable aggregate, apparently of quartz and plagioclase.

Minute crystalloblastic grains of quartz less than 30 microns across occur in some of the less intensely compacted pumice fragments, which are now largely chlorite. These quartz grains all possess wedge-shaped or cyclic twin sectors (threelings and sixlings) that very closely resemble the habit and twinning of tridymite. They may be quartz paramorphs after tridymite.

From studying suites of sections from gradational zones, I infer the following relations: By the time there was sufficient heat and compaction to deform the pumice fragments, the glass shards had already been deformed, compressed together, and slightly welded. In slightly to moderately compacted and welded tuff, the formerly sharp edges of shards are rounded, and the shards are deformed into wrinkles and contortions and are bent around the edges of crystals. In the same rocks the pumice fragments were compressed, so that the ratio of their thickness to their length changed from 1:1 to 1:3 or flatter, and they are slightly bent around compact fragments. As compaction and welding proceeded, the shards were more and more deformed (fig. 13*A*) until, in intensely welded tuff, they were compressed into mere films which lost all shard form, but which may be outlined by turbid or dusty coating. In extreme cases the shards were obliterated, apparently by homogenization of the glass matrix. Accompanying these changes, the essential fragments were compressed, so that they have axial ratios of at least 1:20, and in extreme cases more than 1:60. According to Ross and Smith (1961, p. 25), flattening of pumice fragments beyond the 1:20 ratio cannot be due to simple loss of pore space through compaction; it also requires stretching of the structure.

The pumice fragments developed small-scale recumbent and overturned drag-fold wrinkles by being draped and stretched over and down the sides of the compact accidental fragments. The same relations hold, reversed, for fragments that lie below and are deformed around the lower part of compact obstacles. In many welded-tuff sheets, these small-scale drag folds are overturned away from the obstacle in all directions in the plane of compaction.

In some welded tuff, porphyritic pumice fragments have been compressed to such an extent that they are thinner than their contained phenocrysts. In these fragments the phenocrysts either caused local swelling in the pumice disc around the internal obstacle, or they pierced the disc and now lie approximately normal to the plane of compaction, as shown in the lower right corner of figure 14.

These relations, plus the fact that the compressed fragments generally are equant in the plane of compaction rather than elongated, indicate that the compaction was accomplished in most sheets after the flow came to rest. The vertically arranged sheetlike gradational zones likewise are attributed to the effects of compaction and loss of heat and volatiles in an otherwise static mass.

Only locally is the eutaxitic structure contorted so that is does not conform with the general planar form of the sheet. Such contortions are conspicuous in the central part of the thick sheet which forms the long flat part of the ridge in the NW¼ sec. 25, T. 9 N., R. 2 W. Contortions in this same sheet are exposed on the ridge west of the Chicago mine in the NW¼ sec. 26, T. 9 N., R. 2 W.

In section 25, each of the ledges, which are 20–30 feet long and as much as 10 feet high, appears to have planar eutaxitic structure throughout. However, the attitude of the eutaxitic structure is highly discordant from one outcrop to the next, varying as much as 90° in the strike and dip. The eutaxitic structure is discordant with the attitude of the sheet, and there apparently are no faults that could have caused the jumbling.

In section 26, the true nature of the jumbling is evident because, in addition to the gross variations from one outcrop to another, there also are local sharp contortions within an outcrop and even within a hand specimen. These contortions are in the form of asymmetrical, overturned, and recumbent flow folds, as shown in figure 15. Some of the recumbent folds have parallel limbs which are less than half an inch thick and more than 4 feet long. In some specimens and small exposures the two limbs appear to be two separate bands with no suggestion of the intense contortions. Such strongly deformed layers commonly lie between unfolded or feebly wrinkled layers, indicating that the movement was accommodated more readily within certain zones—although some of the recumbent folds may have been sheared off, resulting in apparently nonfolded bands. There is no consistent directon of overturning of the folds.

Away from the intensely contorted zone the only evidence of contortion is minor crumpling or wrinkling of the streaks. A little farther away these wrinkles have incipient fracture cleavage across the wrinkled eutaxitic structure. These folded layers probably represent smaller scale drag on the limbs of larger flowage folds. The amplitude of the larger features would have to be 20–30 feet or more to explain the regularity of eutaxitic structure within a 20–30 foot outcrop and its extreme variance with that of the next outcrop 20–30 feet away. Many of the flowage features are similar to those exhibited by contemporaneous deformation and intraformational contortions of soft sediments.

These contorted structures may have been formed during the initial movement of the ashflow, but it is more likely that the thick ash flow came to rest, pumice blocks collapsed, and then, owing to renewed movement, the still hot plastic part of the unit was thrown into erratic flow folds of large amplitude. Flowage drag along the limbs of these larger folds produced wrinkling, strong folding, recumbent folding, and severe stretching of the flattened pumice fragments.

The abrupt thickening and thinning of the flattened blocks and their attenuated form attest to the highly plastic but tenacious condition of the rock at the time of deformation. This deformation must have occurred during the optimum heating of the central part. The marginal zones of weak crumpling probably were cooler, and those parts where fracture cleavage is superimposed on crumpled flat fragments must have been just above the plastic threshold when deformation started, and must have cooled below this threshold before deformation ceased, so that the recorded deformation is that of flowage of viscous material, which passed into shear of brittle material.

BEDDED TUFF AND ANDESITIC SEDIMENTARY ROCKS

An almost endless variety of bedded volcanic rocks is present in the map area. Such rocks are the principal characterizing feature and constituent of the upper unit of the volcanics and make up a significant part of the lower unit. They are very sparse in the middle unit, being virtually absent from it in the northern part of the map area and occurring only as scattered thin beds and lenses in coarser deposits elsewhere.

It would be impracticable to describe the many textural, structural, and mineralogic varieties, but they include many combinations of the following sets of physical features:

1. Channeled and crossbedded to evenly bedded and laminated.
2. Very fine grained to very coarse grained.
3. Virtually all crystal fragments to virtually all rock fragments:
    - A. Crystals dominantly plagioclase to dominantly mafic and opaque minerals.
    - B. Rock fragments monolithologic to polylithologic.
4. Unsorted to well sorted.
5. As partings or laminae, to some beds more than 6 feet thick.

Some of these features are shown in figure 16.

Some beds are unsorted deposits of crystals, rock and crystal fragments, and ash or rock flour; others are well sorted; some have graded bedding. Many deposits in the upper unit are of fine-grained green or gray ash in beds a few inches to less than an inch thick; they resemble varved clay. Some sequences of these thin-bedded deposits are at least 30 feet thick. Some display subtle graded bedding, and some contain accretionary lapilli but lack any other structure and are interpreted as airborne ash. The accretionary lapilli consist of a core that is the same as the host rock or slightly coarser, and a rind of very fine grained ash, commonly in several concentric shells. Many of these lapilli have been selectively epidotized and now stand out as conspicuous knots on weathered surfaces.

Particle size in many beds is distinctly bimodal, the rock consisting of mud, silt, sand, or ash matrix with larger lithic or crystal fragments. Some of these bimodal rocks exhibit scour or channel bedding, mud cracks, and related structures which clearly indicate that the matrix was water laid; in others the matrix is structureless and may be of airborne ash. The bimodality probably is due to mixing of airborne with waterborne materials.

Many of the fragments in these beds are of intrusive rocks; others clearly were derived from preexisting tuff, from welded tuff, and from sedimentary rocks. The sedimentary rocks include dense siltstone, mudstone, and fine-grained tuffaceous sandstone that could have been derived from the volcanic pile or from the underlying Slim Sam or Colorado Formations. Clean quartzite, chert, limestone, and other kinds of sedimentary rocks were not observed. A few beds contain conspicuous amounts of small fragments of K-feldspar crystals; other beds locally contain crystalloblastic K-feldspar which apparently formed during metamorphism of the volcanic rocks by the batholith.

Calcite occurs sparsely as detrital grains, but it is widespread as cement, healing ruptured fragments, and in the groundmass. Locally, the cement is ferruginous clay, now partly chlorite, or silica. Fine-grained siliceous tuff is porcelaneous. Generally, clay "paste" is the chief bonding medium.

Some beds consist essentially of crystals of plagioclase and mafic minerals which are so evenly mixed and sufficiently well formed that, lacking large outcrops, the rock might be mistaken for diorite. Similar "pseudodiorite" has been described from the upper unit of the Slim Sam Formation (fig. 8).

Bedded deposits characteristic of the lower unit of the volcanics are shown in figure 16*B*, those of the middle unit in figure 16*A*, and typical bedded deposits of the upper unit in figure 16*C*.

The weight of overlying beds on semiconsolidated tuff apparently caused penecontemporaneous deformation, crushing many crystals and fragments. These local deformed beds generally are more altered than the enclosing nondeformed beds.

The bulk of these rocks have been worked by water. Minor disconformities appear in most outcrops, marked by channels and by lens-shaped and wedge-shaped deposits. Mud cracks, crossbedding, ripple marks, and mud-flake breccias locally are present, especially in rocks of the upper unit. Some rare crossbedding appears to be the result of wind action. Thin lenses and seams of magnetite and augite are commonplace features.

Fossil leaves, fragments and stems of twigs, and macerated woody matter occur in andesitic mudstone and siltstone of the upper unit in the High Peak area.

MASSIVE CRYSTAL AND LITHIC TUFF

The relatively few massive beds of tuff present are 6–40 feet thick and free of internal layering; otherwise they are similar in texture and appearance to the bedded deposits. They occur principally in the lower unit, sparsely in the middle unit, and apparently are absent from the upper unit, of the volcanics.

The tuff beds are of three principal types:

1. Deposits of unsorted ash containing a wide variety of rock types as fragments. These are the finer grained counterparts of polylithologic breccia or conglomerate and probably are mudflows.
2. Fine- to medium-grained crystal tuff with andesine and pyroxene crystals and fragments of crystals set in a fine-grained ash matrix. These appear to have been airborne.
3. Deposits of crystals and fine-grained rock debris which closely resemble the intrusive rocks and lavas. One bed of this type in the Beaver Creek area seems to grade northward into monolithologic breccia which, in turn, grades into an autobrecciated lava flow.

LAVA FLOWS

Lava flows are relatively abundant in the lower and middle units of the volcanics, but are absent from the upper unit. Most lava flows are autobrecciated and casually seem to be part of the succession of pyroclastic deposits. Many of these monolithologic breccias, however, are lava flows that grade laterally from massive or incipiently autobrecciated lava through zones of rubbly breccia to mudflow conglomerate with lenses of fine-grained material, or to medium-grained massive crystal-rich deposits of highly comminuted matter. The autobrecciated lavas are similar to autobrecciated intrusive rocks which are described below.

Most of the lavas are dusky-blue to medium-dark-gray porphyritic rocks which weather grayish blue to medium light gray; some are dark shades of greenish gray. Crystals of andesine and labradorite 3–10 mm long, and larger clusters of those crystals making up 10–15 percent of the rock, are set in an aphanitic groundmass broken by networks of fractures in which calcite, epidote, and quartz have formed. Generally, the fracture network is discernible only on weathered surfaces.

The plagioclase phenocrysts are strongly and complexly zoned and are partly altered to epidote and calcite. In some rocks the shapes and distribution of altered parts suggest that they represent altered former inclusions of lava or glass which were trapped along pinacoid planes during growth of the crystals. Andesine and oligoclase microlites less than 0.5 mm long and smaller granules of magnetite and of epidote-chlorite pseudomorphs after mafic minerals make up the groundmass. The microlites generally are well alined in an even flow structure that is deflected in whorls around phenocrysts; locally, contortions on a larger scale occur.

The matrix is crisscrossed by ramifying networks of fractured rock along which are many microscopic streaky vesicular patches now filled with a mixture of quartz, a carbonate mineral, epidote, chlorite, and hematite. In rocks that are considerably brecciated, the fractures are wider zones of altered comminuted rock and crystal debris, and they outline irregular blocks of nonbrecciated and only slightly altered lava. Generally, the angularity and size of the blocks are inversely proportional to the degree of development of the fracture networks and to the width of the comminuted fracture zones.

A few lava flows are conspicuously flow banded. These flows range from a few feet to about 20 feet thick. The upper parts of the flows are brecciated, the central two-thirds or more is characterized by contorted flow banding, and the bottom part generally is massive, though in some flows it is banded and in some, brecciated. Underlying sedimentary and tuffaceous debris was churned up into the basal part of some flows of this type. None of these banded lavas could be traced more than about 600 feet, and they probably have lobate rather than sheetlike form.

A lava flow beneath the welded tuff in cliffs north of Beaver Creek in the NW¼ sec. 29, T. 8 N., R. 1 W., may be taken as representative. It is about 15 feet thick, and olive black, with small white phenocrysts of plagioclase in tablets as much as a quarter of an inch long. Weathered surfaces are grayish purple to brownish gray and exhibit small-scale brecciation; these structures are not so conspicuous on fresh surfaces. The microscope shows the rock to contain andesine phenocrysts set in a fine-grained groundmass of slender oligoclase-andesine prisms oriented parallel with the flow banding. Low-grade

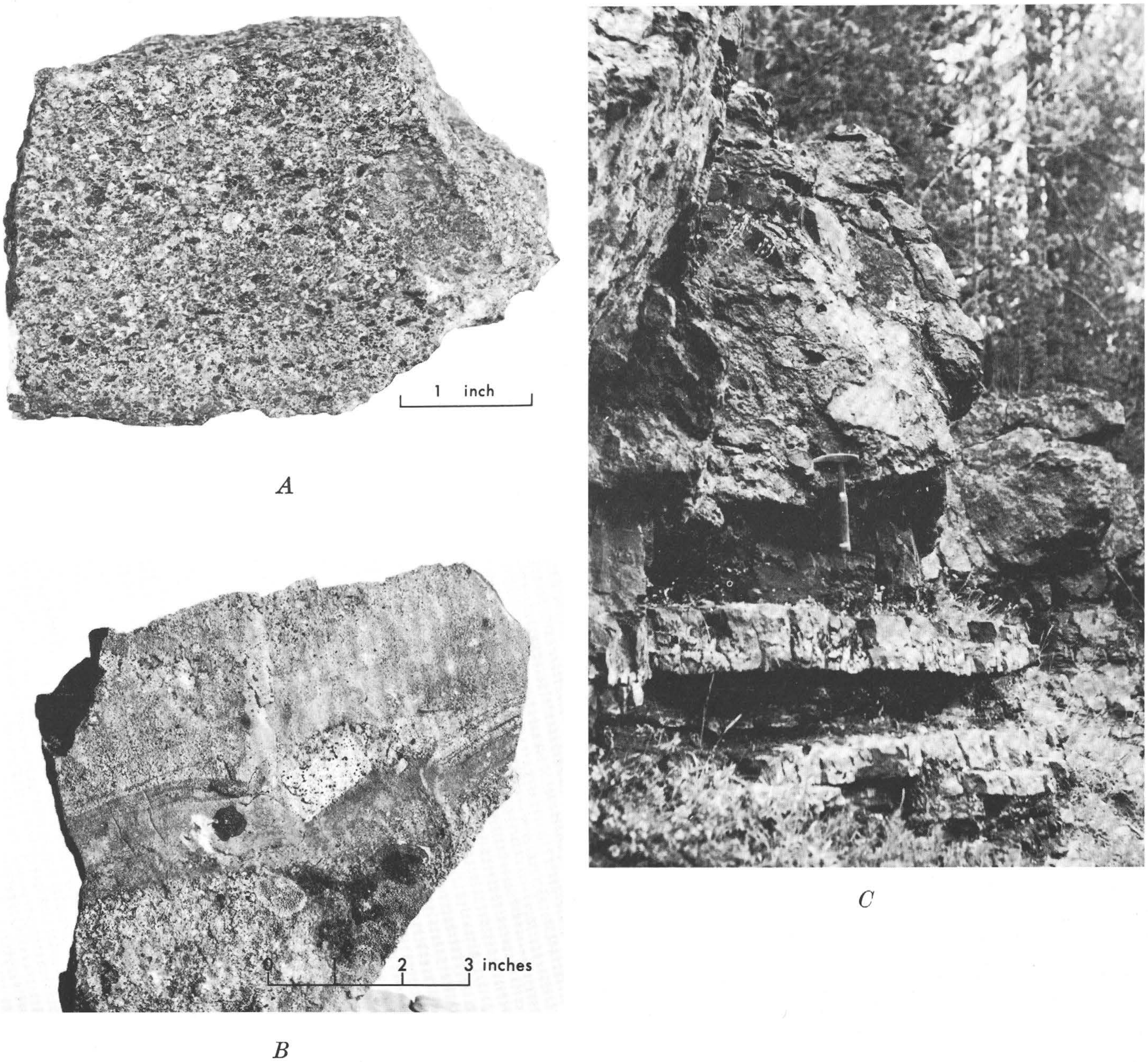


FIGURE 16.—Bedded tuff and andesitic sandstone.

A. Unsorted lithic tuff with faint horizontal layering produced by orientation of flat or elongate rock chips.

B. Sag created in andesitic siltstone by block of amygdaloidal basalt. Lower part of specimen is unsorted polylithologic lapilli tuff, disconformably overlain by well-sorted andesitic sandstone; channel bedded in upper part and grading upward into crystal-lithic tuff.

C. Thin-bedded andesitic mudstone, siltstone, and sandstone overlain by a 6-foot bed of block and ash conglomerate probably of mudflow origin. The conglomerate and some of the sandstone beds have been strengthened by epidotization and stand out as ledges. Hammer handle, 1 foot long, gives scale.

thermal metamorphism has completely converted the original mafic crystals into decussate patches of biotite with or without quartz, epidote, chlorite, and a carbonate mineral. Minute plates of biotite and granules of epidote are disseminated throughout the groundmass and in the phenocrysts. The biotite is of two colors: one pleochroic ranging from yellowish gray to moderate green or dark yellowish green, and the other pleochroic ranging from yellowish gray to moderate yellowish brown or dark yellowish brown. Magnetite occurs as euhedra and granules distributed at random and concentrated in the altered mafic phenocrysts.

INTRUSIVE ROCKS

Numerous bodies of andesitic and basaltic composition cut the volcanic rocks and all older rocks (pls. 1, 2). Fragments of similar rocks occur in tuff and tuffaceous sedimentary rocks of the Slim Sam Formation and profusely throughout the volcanic section both in the map area and elsewhere in the Elkhorn Mountains. Evidence suggests that some bodies were intruded into moist semiconsolidated sediment. The intrusions probably were partly contemporaneous with the Elkhorn Mountains Volcanics, and the depth of cover must have been slight.

The close mineralogic and textural similarity suggests that the intrusive rocks represent the source and feeders of the extrusive rocks. Some intrusive and extrusive monolithologic breccias could not be separated in the field, probably because they are part of single intrusive-extrusive masses.

The intrusives occur in a multitude of textural, lithologic, and morphologic types and include dikes, sills, laccoliths, plugs, and irregular bodies. Some are simple, some are compound, and some composite. Many bodies are too small to show on the map. Small bodies generally have more regular shape than larger bodies, which have digitate margins or margins outlined by numerous short straight edges abutting against each other as though block stoping were responsible for the emplacement.

The shape of the intrusive is influenced by the preexisting structure, the bedding, and the texture of the host strata. True sills abound in bedded water-laid volcanic mudstone and siltstone, at the base or top of welded tuff, and in prevolcanic sedimentary strata. In coarse or poorly bedded volcanic deposits the sills tend to diverge and branch, and irregular intrusive masses predominate. Large composite irregular bodies with marginal sills and irregular apophyses lie along the axis of a broad syncline and appear to represent major centers of intrusion. Some large dikes and the margins of some irregular masses were controlled by preexisting faults.

DIKES

Dikes are few considering the total number of intrusive bodies. Some sills have crosscutting connecting links, offshoots, and feeders; others locally deflect to different stratigraphic levels by means of dike segments. Some intrusive masses are dikelike for part of their extent and elsewhere bulge out irregularly along bedding to form embryonic laccoliths (fig. 17) or short wedges and sills. Many dikes are apophyses of large irregular masses.

Complex swarms of small dikes and sills were mapped as units (pl. 1). Such swarms are in the region between Casey and High Peaks, on both sides of the Jackson Creek lobe of the Boulder batholith, and in the southeast corner of the map area.

Two large dikes of augite basalt porphyry are along nearly east-west faults in the lower unit of the volcanics at the head of the South Fork of Warm Springs Creek (pl. 1). These dikes probably are related to the Moose Creek intrusive mass (pl. 2).

The eastern margin of the Moose Creek intrusive mass was controlled by a major fault. A dike offshoot from the larger mass extends northward along the fault and cuts up into the upper unit of the volcanics near Crazy Peak.

Smaller dikes along faults were mapped on the crest of the range at the head of Spokane Creek, and south of Tepee Creek. Still other dikes may be fault controlled, but displacement has not been demonstrated along the fractures which the dikes occupy.

Two arcuate segments of basalt around the margins of the Antelope Creek stock are interpreted as remnants of a composite cone sheet (pls. 1, 2). One of these dikes lies in the northeastern part of the map area, between Antelope and Sheep Creeks, and is as much as 600 feet thick and about 1¾ miles long; the other segment, half a mile east of the map area, is as much as 1,600 feet thick and about 1½ miles long. Both dikes include three distinct textural types of augite labradorite basalt: with phenocrysts of labradorite only, augite only, and both labradorite and augite. These dikes contain inclusions of volcanic rock and, locally, marble. The base of the basalt dike in the map area locally (near the Buzz mine) dips 30° toward the stock. One exposure of the dike east of the map area indicates very low dip. Elsewhere, the attitudes of the bodies could not be determined.

Flow structures generally are pronounced in narrow dikes and along margins of many of the wider dikes. The flow structure usually is parallel with the margins of the dike but is contorted locally. Streaked-out vesicles, most of which are now amygdules, produce a lineation in the rocks that ranges from vertical in some dikes to as low as 20° in others, indicating that in some dikes the flow probably was directed outward from the source as well as upward.

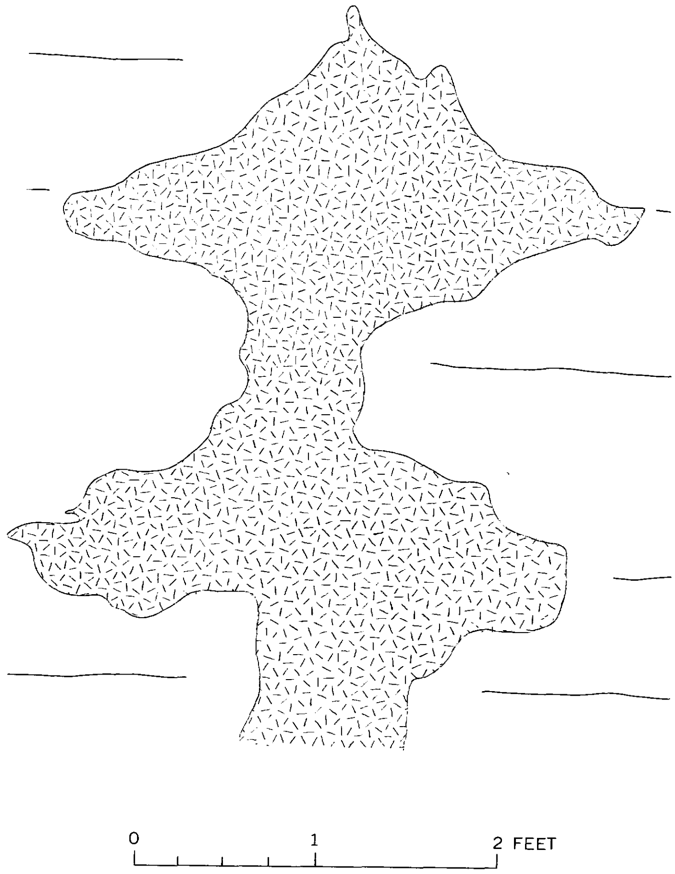


FIGURE 17.—Sketch of vertical exposure of basalt dike apex, High Peak area. Host rock is thinly banded siliceous mudstone.

Country rocks rarely are deformed by dikes, and the thermal effects of intrusion appear to be restricted to zones of baking and bleaching no more than a few inches wide. The dikes commonly have narrow chilled selvages.

PLUG

A plug of porphyritic basalt and andesite occurs at the upper fork of Beaver Creek, in the NE¼ sec. 25. This body lies just west of the juncture of two main fault zones (pl. 1). The contacts are very steep, and the rock is brecciated in many places. The rock contains phenocrysts of plagioclase (ranging from An_{30} to An_{65} in different parts of the mass), augite, and hornblende. The mass is profusely littered with inclusions of a great range of size and shape. The inclusions are mainly welded tuff, coarse-grained hornblendite, melanocratic hornblende diorite, and large partly resorbed hornblende crystals.

Inclusions of plug material in basalt of the nearby Casey Park intrusive mass show that the plug is older. The inclusions are porphyritic basalt and andesite. Diagnostic among these are fragments which are themselves full of coarse hornblendic inclusions indistinguishable from those in the plug. These diagnostic inclusions occur only near the arcuate septum of rock that separates the two intrusive bodies. They probably were torn off the walls of the plug at lower levels by the rising Casey Peak mass. Ring faults apparently controlled emplacement of the plug and probably also resulted in the arcuate septum of country rock separating the plug from the Casey Peak mass. The brecciated parts of the plug probably represent both autobrecciation and brecciation by the later intrusions.

SILLS

Throughout the Elkhorn Mountains, sills are abundant in sedimentary rocks of late Precambrian to Late Cretaceous age and in the Elkhorn Mountains Volcanics of Late Cretaceous age. In the map area sills were not observed in rocks older than Cretaceous, although they are present in older strata to the west.

One or more sills, 1–3 feet thick, occur at the top of the Kootenai Formation. They are very close together and are mapped as a unit. Another sill lies about a third of the way up in the middle unit of the Colorado Formation. It is thicker but less continuous than those in the Kootenai. Near the head of Corral Creek it is only a few feet thick, but just west of the Broadwater County line it is about 215 feet thick.

In the Elkhorn Mountains Volcanics, sills are abundant and of varied size and shape. They are most abundant and best displayed on the east slopes and cliffs along upper McClellan Creek in secs. 27, 33, and 34, T. 8 N., R. 2 W. The sills there clearly are offshoots of the Casey Peak intrusive mass.

Sill contacts are of three distinct types, controlled by the nature of the country rock: (1) sharp and straight; (2) blended by autobrecciation of sill material; and (3) irregular and marked by mixing of magma and country rock, resulting in intrusive peperite. Some sills have all three kinds of contacts at different places.

SHARP CONTACTS

In prevolcanic sedimentary strata, sills have sharp regular contacts and apparently are entirely concordant. In the Elkhorn Mountains Volcanics, sills with sharp regular contacts occur mainly in fine-grained thin-bedded water-laid tuff and andesitic siltstone or sandstone (fig. 18) and at the top or base of welded tuff sheets.

Contact effects are restricted to baking, bleaching, or both, for less than an inch. The top and base of most but not all sills are slightly finer grained than the central part. Some sills are vesicular or amygdaloidal in zones along their upper part or lower contacts or both; some are autobrecciated along contacts or throughout.

Locally the magma dislodged and carried along or lifted slabs and blocks of the country rock. These fragments separated along bedding and behaved in a rigid manner. In general, country rocks are more severely deformed along sills that have sharp contacts than along other types of sills.

CONTACTS BLENDED BY AUTOBRECCIATION

Some sills intrusive into fine-grained bedded deposits have sharp contacts, as described above, and also have thick marginal zones of autobrecciated sill material. Where autobrecciated sills intrude monolithologic tuff and breccia that do not in other ways contrast with the sill, the contact cannot be located accurately and appears blended.

Most sills are brecciated only along the margins, but a few are brecciated throughout. The degree of brecciation ranges from incipient ill-defined fracture systems visible only on favorably weathered surfaces to intensely brecciated and rounded fragments in a matrix of consolidated crystals and finely comminuted and altered rock flour.

A representative example of blending due to autobrecciation is the sill at the ridge crest near the boundary between secs. 7 and 8, T. 7 N., R. 1 W. The sill intrudes monolithologic augite andesite breccia for more than a third of a mile southwestward from the South Fork intrusive mass. Near its connection with the South Fork intrusive, the sill appears to be a homogeneous rock body with local flow alinement of phenocrysts, and there is only microscopic evidence of autobrecciation. There, narrow irregular dike offshoots from the top and base of the sill penetrate into the host breccia, and fragments of breccia occur as scattered inclusions near the margins of the sill. However, as this sill is followed southwestward, it becomes more and more thoroughly brecciated, and its contacts with the country rock breccia become less and less distinct.

The basal part of the sill is porphyritic augite-hornblende andesite, with conspicuous black hornblende phenocrysts alined in a flow structure. In thin section this basal part exhibits pronounced dikytaxitic texture (Fuller, 1931, p. 116; 1938, p. 162; 1939, p. 304) which consists of loosely interlocked crystals of sodic andesine, hornblende, and augite, without groundmass. The original irregular angular polygonal voids have been coated with silica, or filled with chlorite and silica, or locally filled with fibrous masses of clinozoisite. The silica is now spherulitic chalcedony, but it may originally have been opal. Augite and hornblende phenocrysts are slightly chloritized and are rimmed

FIGURE 18.—Sharp contact (at hammer head) of porphyritic augite basalt sill with underlying bedded fine-grained andesitic sedimentary rocks. Locally the margin of the sill is vesicular and appears light colored, as in the middle of the photograph where the vesicular margin is about 8 inches thick.

by magnetite and ilmenite. Plagioclase is sodic andesine partly replaced by epidote and calcite.

The basal diktytaxitic zone grades upward into a vaguely brecciated middle zone, with irregular netting by chlorite and epidote. In thin section, the rock is seen to be altered (probably deuterically) to a higher degree than in the basal zone.

The vaguely brecciated middle zone grades upward into distinctly brecciated rock of the upper zone, where there is no suggestion of diktytaxitic texture. The rock here is more highly altered than in the zones below and contains granular quartz and K-feldspar in the groundmass and K-feldspar as patchy replacement masses in some plagioclase crystals.

In the field, the overlying monolithologic breccia cannot readily be distinguished from the upper zone of the sill. Under the microscope it can easily be distinguished from the sill by its lack of K-feldspar, chlorite, granular quartz groundmass, and hornblende.

The beginning stages of autobrecciation are clearly recorded in many sills (fig. 19). Macrovesicles are sparse or absent, microvesicles are widespread. In the beginning stages of brecciation (fig. 19*A*) the fractures are discontinuous and ill defined. They are marked mostly by lines and zones of chloritized and carbonatized groundmass that appear to link together strings of microvesicles. As the degree of brecciation increases, the fractures become wider and filled with secondary minerals (fig. 19*B*), mostly chlorite, epidote, quartz, and calcite. As brecciation continues, plagioclase crystals become involved and are broken down into small chips, whereas the mafic crystals, especially hornblende, tend to remain intact (fig. 19*B*).

Irregular branching, looping, and joining of fractures commonly results in a pattern resembling stylolites (fig. 19*C*). Advanced stages are monolithologic breccia or tuff bearing a disquieting resemblance to extrusive pyroclastic deposits but characterized by the presence of euhedral hornblende crystals in the matrix. In extreme autobrecciation (fig. 19*D*), the accompanying movement of the solidifying rock mass apparently created additional crushing and streaking out of particles, so that the hornblende crystals also were destroyed.

The sparcity of macrovesicles, the abundance of microvesicles, the pervasion of the brecciation, and the presence of diktytaxitic texture support Curtis' (1954) explanation of autobrecciation, summarized below:

1. Viscous magma, already partly crystallized but so low in volatiles that small confining pressure keeps them in solution, moves upward or sideways from its parent intrusive mass.
2. Vesiculation begins as confining pressure is reduced, perhaps by faulting, and the viscosity of the magma is so increased that it can no longer flow.
3. The partly solidified magma must adjust to continuing stress by fracturing.
4. Differential movement along small irregular fractures causes slight dilation, resutling in loci of reduced pressure.
5. Gas in vesicles adjacent to the fracture, under confining pressure of the overlying rocks, expands explosively toward the reduced-pressure region of the dilated fracture, resulting in spalling of the partly solidified magma along both fracture surfaces. The spalling sets some crystals free, and they become embedded in fragmental debris.
6. Additional very slight movement results in continued spalling, and the entire mass may become pervasively and intensely brecciated very quickly.

Following initial autobrecciation, further movement of the intrusive mass results in comminution by attrition, rounding of the fragments (fig. 19*D*), and hydrothermal alteration by the hot condensed fluids acting on pulverized rock.

The broad horizontal and vertical extent of the effects of autobrecciation in the northern Elkhorn Mountains, both in sills and in lava flows, and other features described above, lead me to believe that this autobrecciation was effected principally by increase in viscosity due to drop in pressure. The resulting rock is distinctly different from brecciated rocks formed by increase in viscosity due to drop in temperature, as described from the Bearpaw Mountains of Montana by Pecora (1941, p. 845). In both the Elkhorn and the Bearpaw Mountains types, additional brecciation and comminution could be accomplished during the forceful shouldering aside of the country rocks during intrusion.

PEPERITE AT SILL CONTACTS

Peperites are rocks formed by mixing of magma or lava and moist sediments (Michel-Lévy, 1890; Wentworth and Williams, 1932); they are common along contacts of basalt and andesite sills in the Elkhorn Mountains Volcanics. Although peperitic sills are abundant, they rarely are well exposed. Exceptionally good exposures were found in the High Peak fault block at the head of Beaver Creek. Typical peperitic margins in that area are shown in figures 20 and 21.

Peperitic sill margins represent a thorough mixing of magma and country rock, with each retaining its identity even on a microscopic scale. Shreds, stringers, loops, ribbons, blocks, spindles—all imaginable shapes and sizes of fragments and connected country rock pieces—are strewn through the marginal parts of the sill (fig. 20). Dikes and fragments of sill matter are embedded in country rock adjacent to the sill, and the country rock is contorted on a small scale (fig. 21).

Peperite material is restricted to the marginal 20 feet or less, so that sills as much as 40 feet thick may be strewn with country-rock fragments throughout. Thicker sills have central parts free of inclusions, but with top or base, or both, of peperite.

In addition to having irregular base and top, on a small scale, these sills also commonly have very irregular terminations, such as shown in figure 22, and generally have deformed the country rocks into gentle folds, domes, and depressions with amplitudes as much as 15 feet, and small-scale contortions. Clastic dikes of country rock and, locally, of comminuted sill matter cut the sills in places, but apparently not the country rocks.

Vesicles, now largely filled with secondary minerals, are abundant in the peperites, and similarly filled cavities are common in bordering country rocks; they are absent in the central part of thick sills.

Some sills deflect from one level where they are in contact with fine-grained thin-bedded deposits to other levels where they are in contact with lapilli tuff, breccia, or sheets of welded tuff. Other sills are in contact with different kinds of rocks along strike because of changes in facies of the country rocks.

Peperitic margins are present only where the sill is in contact with fine-grained thin-bedded rocks. Rocks in peperite margins of sills are high in H_2O and CO_2. This, coupled with the localization of vesicles, strongly suggests that some of the water was derived from the enclosing rocks.

The interpretation that these sills were intruded into moist semiconsolidated sediment implies shallow cover at the time of intrusion and suggests that the intrusives were only a little younger than the enclosing strata.

LACCOLITHS

Five bodies were mapped as laccoliths, because they have a lenslike shape and have bulged the surround-

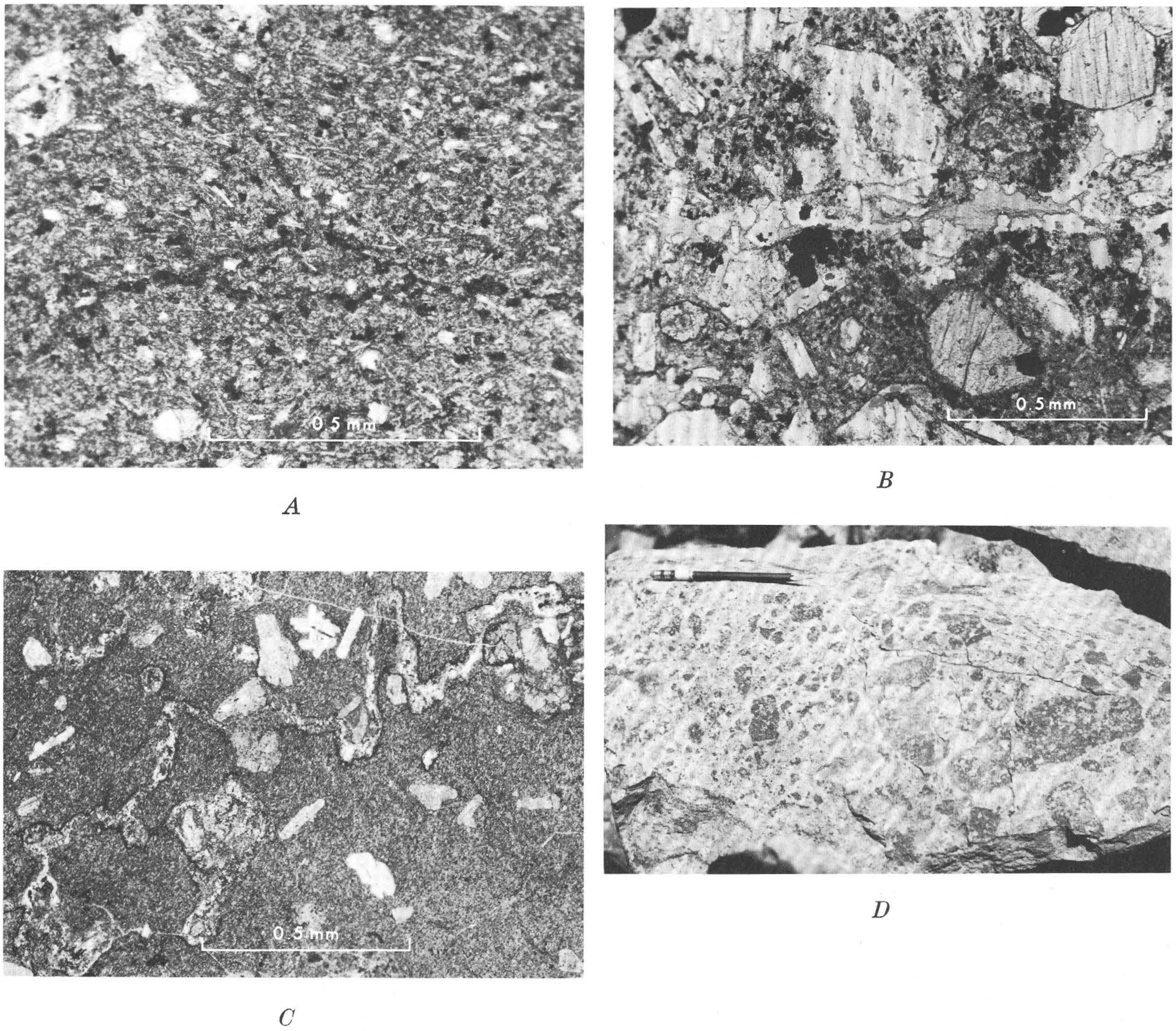


FIGURE 19.—Stages in the development of autobrecciated andesite and basalt. In incipient stage, *A*, the fracture is discontinuous. In the next stage, *B*, the fracture is wider and filled with secondary chlorite; the fracture tends to be deflected around crystals, as in the upper right corner, but locally the crystals are also broken, as in the center of the figure. In a slightly more advanced stage, *C*, the fracture has looped and branching parts and is filled with comminuted rock matter and secondary minerals. *D*, Intrusive autobrecciated andesite porphyry with fragments rounded owing to attrition. View is normal to the plane of streaky flow banding of fragments, which can be seen along the top of the block. The fragments are all of the same type and similar to the matrix which differs only in being highly altered.

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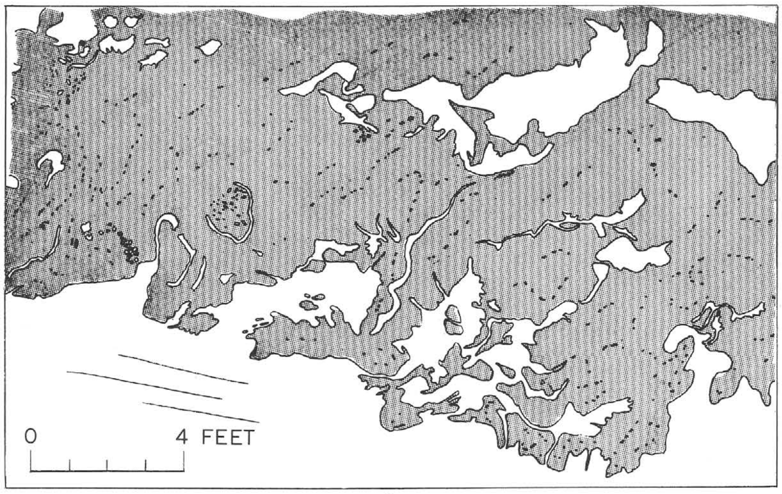
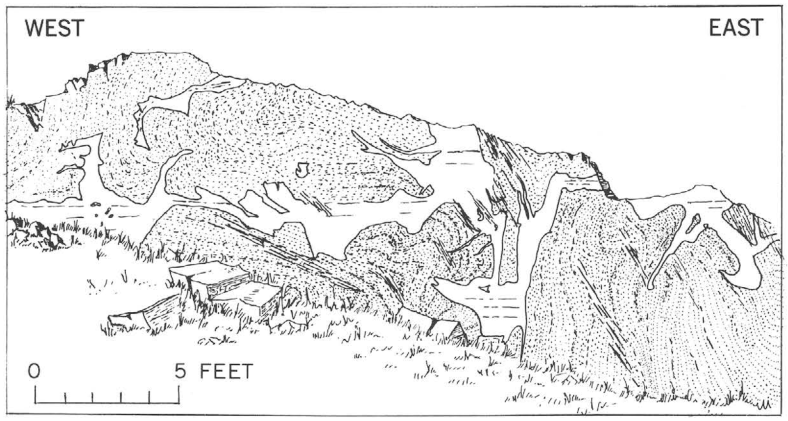


A



B

FIGURE 20.—Sketches of vertical exposures of peperitic part of andesite sill in the High Peak area. Stippled parts represent vesicular andesite showing trace of flow-streaked vesicles by dashes. Clear areas represent volcanic siltstone and mudstone, with bedding shown by subparallel ruling. *A*, Basal part. *B*, Middle part. Zones of shearing shown by closely spaced subparallel lines.

ing strata in order to make space for themselves. Some, and perhaps all, are marginal parts of the nearby Casey Peak mass.

A large laccolith southwest of Horsethief Park in sec. 19, T. 8 N., R. 1 W., appears to have formed by the merging of the two sills from the Casey Peak mass. It is 1⅓ miles long and as much as 300 feet thick. A large septum of country rock lies above the middle in the western part of this laccolith. Dikes from the base of the laccolith, or auxiliary feeder dikes, extend eastward along the ridge crest.

One laccolith about a mile long and as much as 600 feet thick is near a ridge north of Sawmill Creek in secs. 17 and 20, T. 8 N., R. 1 W. A small laccolith about ⅓ mile long and 140 feet thick occurs farther up this ridge in the E½ sec. 18.

All three laccoliths described so far occur just above sheets of welded tuff in the middle unit of the volcanics. One very small laccolith, about 800 feet long and 100 feet thick, lies at the contact between rocks of the middle and upper units of the volcanics near the center of sec. 15, T. 8 N., R. 2 W.

The fifth laccolith, in the lower part of the upper unit of the volcanics, is exposed on the mountain slopes west of Casey Meadows in secs. 14 and 15, T. 8 N., R. 2 W. It is only about 100 feet above the last small laccolith mentioned. Thin-bedded andesitic siltstone and tuff lie below the laccolith, and gray lapilli

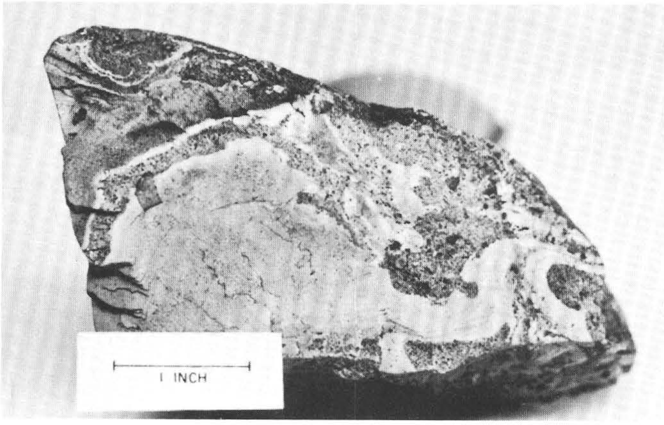


FIGURE 21.—Andesite peperite from the upper peperite zone of the sill shown in figure 20. The very fine grained light- and medium-gray parts are inclusions of mudstone, with bleached rims; coarser darker parts are andesite with amygdules appearing very dark gray.

tuff and coarse-grained lithic tuff lie above. The laccolith is an asymmetrical body whose upper surface is an elongated arch trending about N. 60° W. The northwestern part is especially asymmetrical: the floor, sides, and roof on the north dip gently south, but the floor and sides on the south dip steeply north and vertical. The south side of the laccolith is steep and blunt; the north side tapers northward, resulting in a cross section like a teardrop. In the central and southeastern part the body is more symmetrical. This laccolith is fed by, or has offshoots of, three dikes at its south end. All the margins exhibit intense small-scale crumpling; small slabs of the floor country rocks have been lifted to become inclusions. Small folds and dikes in the country rocks around the southeastern part of the laccolith suggest that late movement of magma in the dikes there caused the enclosing volcanic strata to buckle into a weak east-west arch, which resulted in tension fractures parallel to the axis of the arch and into which magma squirted to form still younger dikes.

LARGE INTRUSIVE MASSES

Several large highly irregular intrusive masses occur in the Elkhorn Mountains in the southeast quarter of the map area (pls. 1, 2). The larger of these masses are compound and composite; that is, they were formed by multiple injections of magma of a single composition and also by injections of magmas of different composition.

Large parts of some of these masses are autobrecciated and brecciated by subsequent intrusions. Their forms vary and include parts and offshoots which are sills, dikes, laccoliths, lopoliths, and plugs. Some parts appear to have been emplaced by injection dilation, some by piecemeal stoping, and some by large-scale block stoping owing to foundering of large blocks of country-rock volcanic strata. Deformation of the country-rock roof and walls ranges from intense to none.

The large masses are interpreted as magma reservoirs high in the crust which were principal centers of extrusive activity. These inferred reservoirs are further interpreted as having risen higher and higher into the accumulating volcanic pile, partly through foundering of the volcanics. The large bodies probably were the sources of the smaller intrusive masses.

The term "chonolith" (Daly, 1912, p. 719–720) fits these bodies well, but it is not applied here because it has fallen into disuse. The term "stock" and, to many geologists, the term "pluton" imply plutonic (that is, deep seated and coarse grained) rocks, and might be misleading. Accordingly, I refer to these bodies as "intrusive masses" or, more simply, "masses." The largest is the Casey Peak mass, followed in size by the Moose Creek, South Fork, and Crazy Peak masses. Several or all of these masses may actually be interconnected as parts of a common magma chamber at depth, but they are considered separately.

These masses intrude rocks of all three units of the Elkhorn Mountains Volcanics, but they are not in contact with older rocks at the present level of exposure. Similar masses southeast of the map area are in contact with rocks as old as Jurassic.

Except for the South Fork mass, the distribution of the intrusive masses—and large-scale block foundering probably related to them—appear to have been controlled by the regional syncline which passes diagonally northeastward through the volcanics (pl. 1). However, the forms of the masses are controlled by local structure, by lithology, and perhaps by depth.

CASEY PEAK MASS

The main part of the Casey Peak mass lies northeast of Casey Peak along the trace of the northeast-trending regional syncline, but this intrusive complex includes offshoots of sills and irregular bodies from Casey Peak to High Peak and extending westward (pls. 1, 2). The entire area is about 13 square miles. To the west the mass is invaded by the Boulder batholith in McClellan Creek canyon; to the north it is invaded by the Jackson Creek lobe of the batholith. It is in contact with rocks of the middle and upper units of the Elkhorn Mountains Volcanics. Faults separate this mass from the other large intrusive masses to the south and southeast.

This mass appears to consist of a steep-walled central plug flanked by a complex array of laccoliths and sills in a form somewhat similar to the intrusives in the Henry Mountains in Utah (Hunt and others, 1953). The pluglike core lies northeast of Casey Peak. The northern and northeastern contacts of the mass are steep, but they flare out upward, tending to become concordant at higher levels (pl. 2). Along the northern contact near the head of Antelope Creek, the intrusive mass follows the boundary between the middle and upper units of the volcanics. A large roof pendant of the upper unit is preserved just south of the contact, and flat-lying beds of tuff along the ridge crest in the northern part of the mass probably are additional remnants of the roof.

The northwestern part of the mass is a large irregular body which is connected with the main part of the Casey Peak mass by a sill and dike complex. The roof of this northwestern portion is comformable at least in its southeastern part. Many of the interleaved country-rock septae have been disrupted; several of these were mapped on the north canyon wall of Tepee Creek. Many smaller slabs of bedded volcanic rocks also occur. Although these slabs appear to be completely engulfed, the relatively undisturbed attitude and parallelism of many suggest that they may actually have been attached to the walls (pl. 2).

At the head of the East Fork of McClellan Creek there are several large bedding-plane slabs of country-rock volcanics within the intrusive. These slabs are of rock of the upper unit of the volcanics and stand nearly vertical; they probably represent a large block of foundered country rock.

The mass is mostly augite basalt, but it includes trachybasalt in all but the northeastern part, and andesite. Large parts of the mass are breccia. In general,

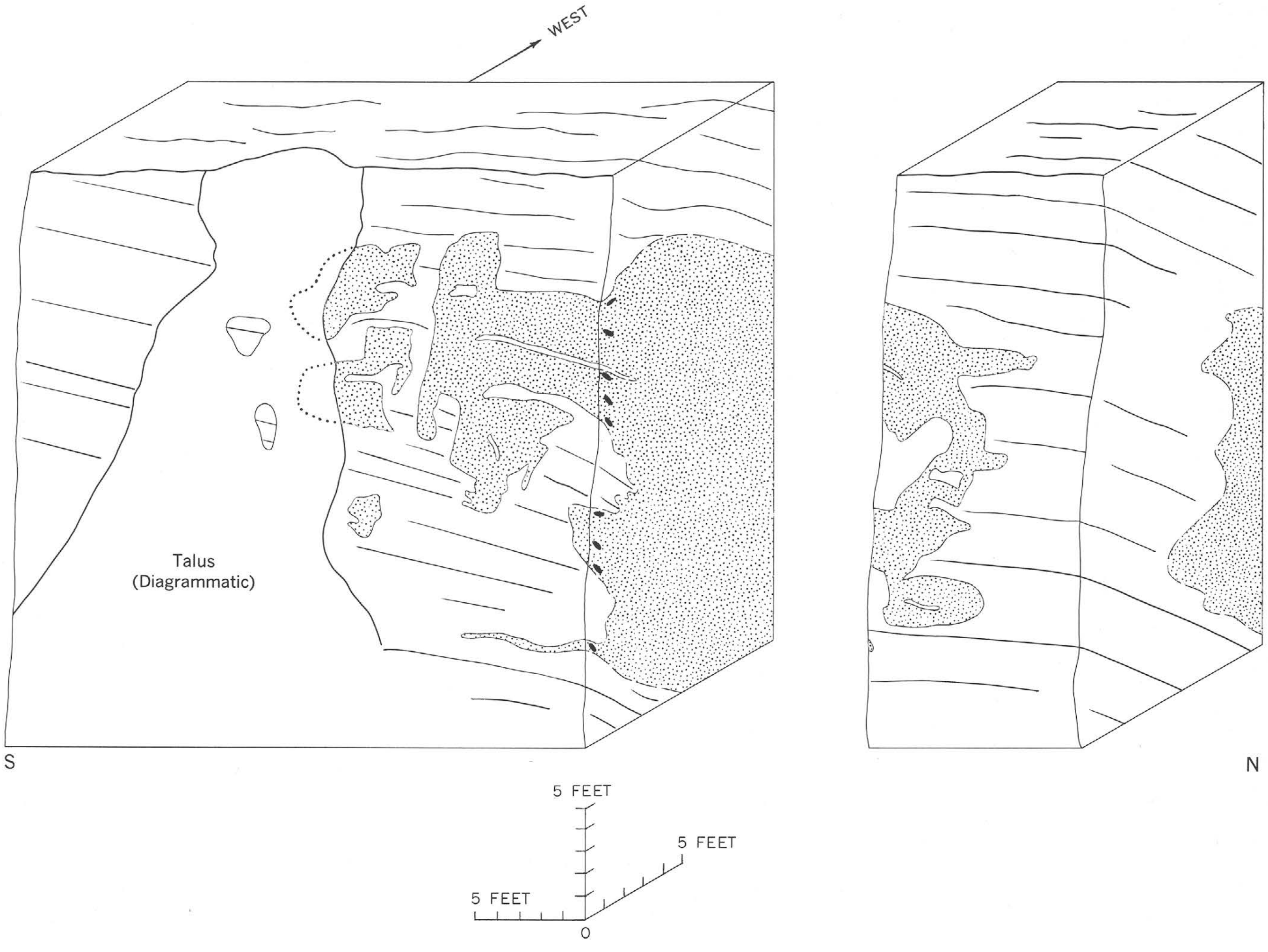


FIGURE 22.—Block diagram of a cliff face showing distal edge of a basalt sill with peperite margins. Lightly ruled parts represent andesitic siltstone and mudstone; stippled parts represent amygdaloidal basalt with trend of flow-alined amygdules shown by dark ovals in section view.

the areas richest in breccia are the eastern part north of Sheep Park and that part between Casey Peak and the older plug just south of Sheep Park. Some of the breccia is interpreted as due to autobrecciation caused by vesiculation, some probably is protoclastic breccia, and some was produced by subsequent intrusion. Several distinct periods of intrusion of magma of differing composition clearly occurred, but their products could not be separately mapped.

The position of the Casey Peak mass probably was controlled by the northeast-trending syncline. The mass may also have been emplaced along the northeast-trending fault mapped at the head of Staubach Creek. However, the age relations of the fault, syncline, and intrusive mass are not clear; the fault may have been older than the intrusive and perhaps related to the syncline; or the fault may have been younger and offset the northeastern margin of the mass.

MOOSE CREEK MASS

The Moose Creek mass, along the southern edge of the map between Moose and Clear Creeks, occupies about 4 square miles. An additional three-quarters of a square mile lies to the south (Klepper and others, 1957, pl. 1). Breccia is abundantly, though irregularly, distributed throughout the Moose Creek mass. Quartz, jasper, and hematite occur in large irregular bodies associated with some of the breccia. Peperite breccia is absent.

Roof pendants and inclusions are more abundant in this mass than in any of the other masses in the map area, but only two are large enough to be shown (pl. 1). The largest roof pendant, along Moose Creek, consists of highly altered welded tuff, tuff, and lapilli tuff of the middle unit of the volcanics. The other pendant mapped is a distinctive tuff breccia near the western edge. This inclusion is a large slab of a single thick bed, in structural continuity with the same bed in place to the north, across the contact.

This mass was emplaced along north-trending faults of large displacement. Several west-northwest-trending faults have been invaded by the Moose Creek mass along its west and northwest margins. The northern edge appears to have been in part controlled by an extension of the northwest-trending fault at the McClellan Creek-Moose Creek divide. The mass is not visibly cut by faults; all faults apparently were preintrusive or contemporaneous with the intrusion.

The northwest-trending fault along the ridge at the head of McClellan Creek and Moose Creek cirques was invaded by the Moose Creek mass, but it truncates a sill offshoot of the Casey Peak mass. Another sill, apparently an offshoot from the Casey Peak mass, is truncated by the north-trending fault along which the eastern part of the Moose Creek mass was injected, east of Clear Creek. Five other northwest-trending faults lie along the western margin of the Moose Creek mass, south of this large fault. Three of these were also truncated by the intrusive mass, and two were invaded by wide dikes which apparently are offshoots of the mass. In four of these faults the displacement was determined; the north side was dropped relative to the south, the same as the displacement across the northwest-trending fault already noted.

The structural relations indicate that the Moose Creek mass is younger than the Casey Peak mass and that the two were separated in time by a period of faulting. This faulting probably was block subsidence that followed emplacement of the Casey Peak mass and permitted emplacement of the Moose Creek mass.

Nevertheless, the two bodies may be the shallow and the deep parts of a single large mass, the Casey Peak mass and its country rock representing the sheeted roof part which subsided into the still-liquid deeper part now represented by the Moose Creek mass. The Moose Creek mass lies mostly in rocks of the lower unit of the volcanics, but it has inclusions or pendants of the middle unit. It has no peperite or other features to suggest that the country rock was moist or semiconsolidated at the time of intrusion, and it has truncated and invaded many faults. The Casey Peak mass occupies higher stratigraphic positions, has many peperite parts, which testify to a shallow depth of emplacement, and is cut by many faults.

The nature of offset across the faults at the west margin of the Moose Creek mass suggests a regular slipping or foundering of blocks in steplike manner. All but the northeastern part of the Casey Peak mass has been faulted down in a complex triangular block. These relations also strongly suggest foundering of the Casey Peak mass and imply that a large part of the Moose Creek mass lies below the exposed part of the Casey Peak mass.

Petrographic similarity also points to close relationship between the two masses.

SOUTH FORK MASS

In the southeast corner of the map area the South Fork intrusive mass has irregularly invaded rocks of the lower unit of the Elkhorn Mountains Volcanics. The mass underlies about 1½ square miles in the map area and extends east and southeast for at least another quarter of a square mile. It extends south of the map area for an unknown, though probably short, distance; along the southern part of the map area the mass is largely a complex of anastomosing dikes.

Four large sheetlike inclusions of tuff were mapped in the central and eastern part of the mass (pl. 1);

many smaller unmapped sheets also occur. The relatively flat and undisturbed attitude of these sheets suggests that they are country rock which remained attached to the walls and that the mass is partly a complex sill (pl. 2).

Foundered blocks of country rock are common in the western part of the mass; only the larger ones are mapped. Sill and dike offshoots connect separate parts of the mass and give it a highly irregular margin.

The most distinctive feature of the South Fork mass is the blending of intrusive contacts by brecciation. Peperite is locally abundant in the upper parts but lacking in the lower parts. Xenoliths in the upper part commonly are bent and deformed in a manner which strongly suggests that they were semiconsolidated at the time of detachment.

The South Fork mass is thus similar in its lower part to the Moose Creek mass, similar in its upper part to the Casey Peak mass, and may represent an intermediate level of intrusion. The South Fork mass is cut by faults which also cut sills tentatively correlated with the Casey Peak mass.

CRAZY PEAK MASS

The Crazy Peak intrusive mass is an elongated body that extends from southeast of Crazy Peak northwestward about one mile, mostly in sec. 35, T. 8 N., R. 2 W. Contacts are steep on all sides except the southeast, where the intrusive spreads laterally and has a fairly flat base conformable with the strata just above the base of the upper unit of the volcanics (pl. 2). This intrusive mass has severely deformed the host rock for several hundred yards.

The intrusive rock is so highly altered that the feldspar can only locally be identified. Those rocks that could be determined range from basalt (An_{72}) to andesite (An_{33}). The deeper parts of the mass are augite trachybasalt with plagioclase of about An_{70}. The upper part of the mass contains abundant jasper, quartz, chlorite, hematite, epidote, carbonate minerals, and locally garnet, in irregular bodies as much as 4 feet across, and as vesicle fillings.

This intrusive mass is elongated parallel with a zone of northwest-trending faults which it has invaded (pl. 1). The mass is also younger than a north-trending fault which probably is the feathered-out northern part of the zone of faults which controlled the eastern edge of the Moose Creek mass. The Crazy Peak mass is cut by a fault at its northwestern end.

The form and structural relations of the Crazy Peak mass suggest that magma rose vertically along the northwest-trending fault zone and spread laterally southeastward as a laccolith or sill.

DEFORMATION EFFECTS OF INTRUSIVE BODIES

Minor folds and crumpled rocks occur only locally near the intrusive bodies, where they are restricted to volcanic strata. The trends of fold and crumple axes are either parallel with the intrusive contact or wildly erratic; they bear no relation to the trends of similar structures around other intrusive masses or to the regional structure pattern. Clearly, this deformation is the direct result of the injection of the adjacent intrusive body.

The Crazy Peak mass induced more severe deformation of the country rock than did any other intrusive body. Country-rock strata along the entire western half of the mass were tightly and erractically folded and faulted by the force of intrusion. Fold axes range from horizontal to vertical, but they are too closely spaced, erratic, and discontinuously exposed to map separately. The northwest-trending fault zone along which the Crazy Peak mass was emplaced consists of three main strands which bound two slices of country rock. A low-angle thrust fault in the southwestern slice, about 1,500 feet east of the summit of Crazy Peak, has brought a sheet of welded tuff up onto a trachybasalt sill which is older than the faults and the Crazy Peak mass. Because the thrust is only in one of the fault slices and was directed away from the Crazy Peak mass, it probably formed in response to local lateral spreading of magma in the upper part of the Crazy Peak mass. The stress was taken up within the one fault slice and produced several zones of mylonite 2–6 inches thick (fig. 23). These mylonite shear zones are connected by diagonal steep distributive planes which separate many small imbricate slices (fig. 23).

Sills with sharp contacts and those with peperitic margins have, in general, deformed the host strata more than have other types of sills. The greatest deformation known is in the High Peak area. Deformation there is illustrated in figure 24.

Strata have been crumpled above and below many sills. The blunt south end of the sill along the crest of the range southwest of High Peak has induced crumpling around vertical axes in the surrounding country rock.

Some sills locally had a bulldozing effect on the underlying beds, plowing up blocks and slabs of the thin-bedded strata. At the base of the thick sill on High Peak (second sill from the summit), dusky red andesitic silt was locally thinned in some places, piled up in other places, and drawn up into the basal part of the sill (fig. 25) as clumps and individual silt and sand grains. Near the contact the basalt is colored dusky red by these disseminated grains. The particulate behavior of the silt suggests that it was unconsolidated

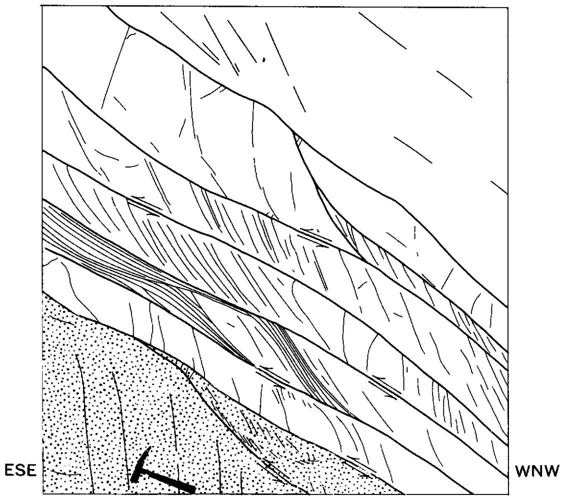


Figure 23.—Thrust fault zone in floor of Crazy Peak intrusive mass southeast of Crazy Peak. View looking south-southeast, sketched from a photograph. Welded tuff in the upper plate was sheared and thrust east-southeastward (to the left) over a trachybasalt sill in the lower plate (stippled), producing zones of mylonite (dipping gently to the right) which are connected by imbricate shears (dipping steeply to the right). Hammer handle is about one foot long.

or only partly consolidated. Distribution of vesicles in the basalt strongly suggests that they were produced by water from the silt.

Along some other sill contacts in the High Peak area, thin-bedded fine-grained rocks are crumpled, contorted, and deformed into convoluted structures resembling those of penecontemporaneous deformation. These beds also may have been only partly consolidated at the time of intrusion.

In the three small probable roof remnants in the northeastern part of the Casey Peak mass, sec. 13, T. 8 N., R. 2 W., beds of tuff were deformed into a number of small scallops—gently arched anticlines separated by sharp V-shaped synclines. Along the crest of the arches the beds are thinned, resulting in a structure resembling supratenuous folds.

Xenoliths in the South Fork intrusive mass are of bedded tuff, lapilli tuff, and, locally, volcanic sandstone. Many are deformed. In some, the deformation may have occurred before the rocks were incorporated as xenoliths, but in others, the deformation appears to have occurred while they were enclosed in the intrusive mass, as illustrated in figure 26. As in the peperitic sills, these inclusions were deformed by bending and distortion; some were further deformed by rupture. The upper xenolith of figure 26 shows very strong distortion of the lower beds only, which apparently was followed by hardening of the xenolith and subsequent

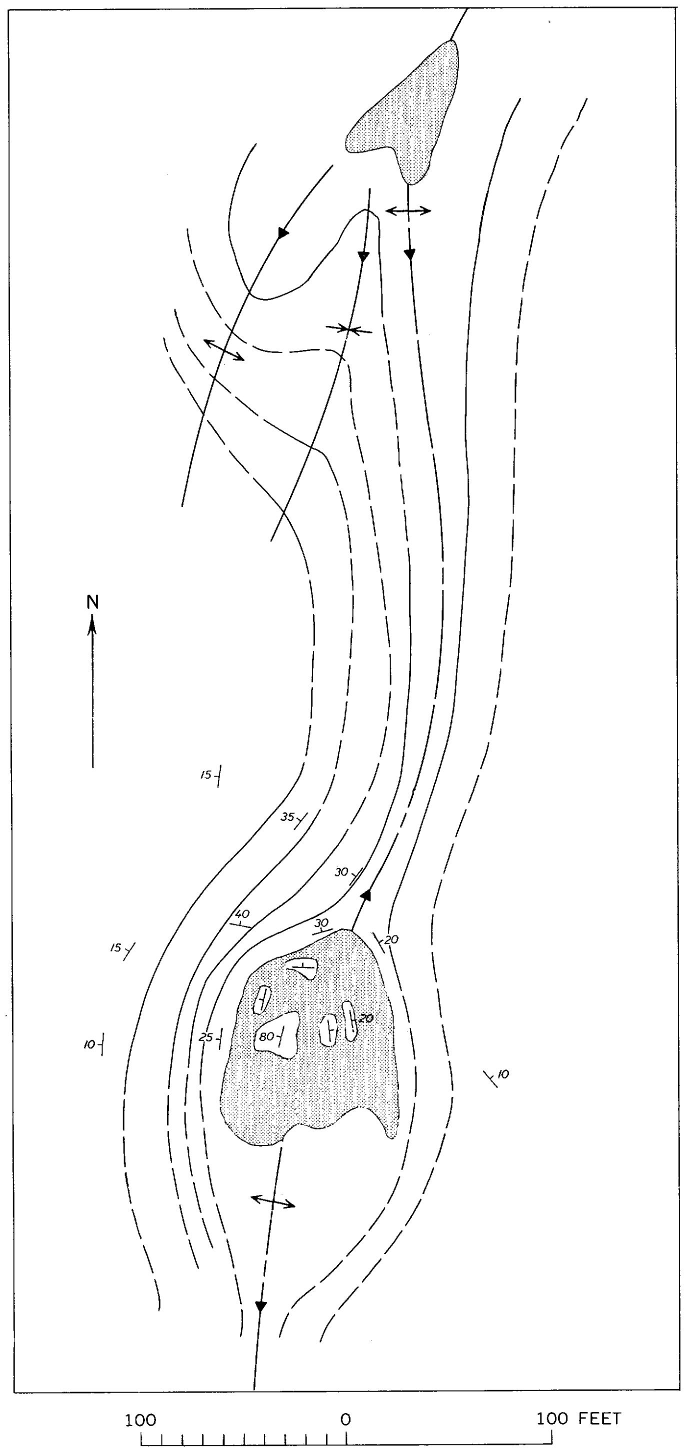


Figure 24.—Sketch map of deformed country rock above bulges in trachybasalt sill in the High Peak area. Parallel curved lines represent contacts of marker beds in the upper unit of the volcanics; sill shown by stipple. Two inliers of trachybasalt represent domal high parts on the rolling top of a sill.

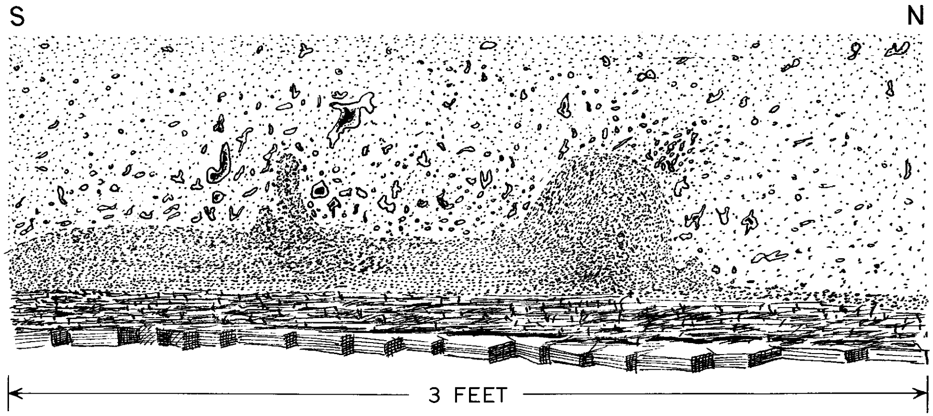


FIGURE 25.—Deformed silt bed at base of basalt sill in High Peak area. Blebs represent amygdules. Sketched from outcrop.

deformation by rupture which produced the slightly displaced pointed end and truncated downfolded protuberance. This xenolith appears to have been deformed partly by compression normal to the bedding, which caused thinning of the beds by stretching to the left. The xenolith complex shown in the lower part of figure 26 appears to have been formed by injection of the beds and intense crumpling without subsequent rupture.

Porphyritic trachybasalt occurs as part of the Moose Creek mass along the ridge crest east of Moose Creek in secs. 3 and 4, T. 7 N., R. 2 W. It is cut locally by small dikes of basalt $\frac{1}{16}$–2 inches wide. Along several of these dikes the edge is raised into a series of parallel ridges with irregular crests and triangular projections, whereas the host-rock wall is smooth and planar. This suggests that the walls pulled apart while the dike material was tacky. Some of the dike ridges and projections are asymmetrical, suggesting some displacement parallel with, as well as normal to, the walls. These projections are closely similar to the shark's-tooth projections described by Nichols (1939) from a lava flow in New Mexico. The only significant difference between the two rocks is that in the present example the projections were formed by movement of hard country rock against tacky basalt, whereas in the New Mexico example they were formed by tacky basalt pulling apart along a crack within the basalt.

METAMORPHISM

Basaltic and andesitic intrusives associated with the Elkhorn Mountains Volcanics caused low-grade metamorphism of parts of the volcanic pile. The metamorphic effects are irregular in intensity and are not everywhere clearly distinguishable from those produced by deuteric processes or by the batholith. Minerals of the albite-epidote-hornfels facies (epidote, albite, calcite, chlorite, biotite, quartz, actinolite, and garnet) formed to some extent almost everywhere. Zeolites occur sporadically in both intrusive and extrusive rocks and include thompsonite, phillipsite, and chabazite. This metamorphism produced hornfels which is typically very fine grained and even textured; spotted hornfels is not common. Generally the hornfels texture is recognizable only under the microscope, but the metamorphism is evidenced by the green color imparted by epidote, chlorite, and actinolite. The minerals formed by this thermal metamorphism are the same as those formed by deuteric processes in the penecontemporaneous intrusive masses which are considered to have been the chief source of heat and

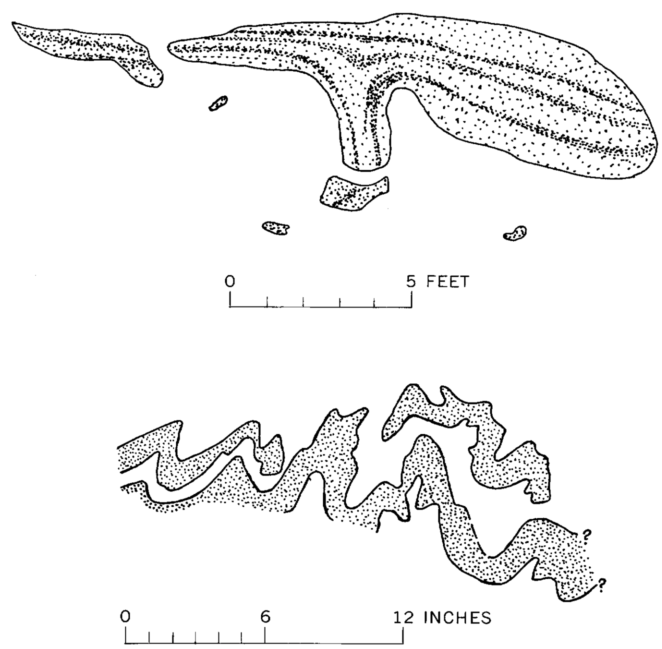


FIGURE 26.—Sketches of deformed xenoliths (stippled) in basalt (blank) in the upper part of the South Fork intrusive mass. Heavier stippling in upper figure indicates bedding, which is accentuated by selective epidotization.

fluids for the metamorphism. These effects are described on pages 57–58.

CORRELATION

Field relations indicate several periods of injection of basaltic magma alternating with injections of andesitic magma, so that basalt is older than andesite at one place and younger at another. Injections of basaltic magma in one place may have been synchronous with injections of andesitic magma in some other place. Therefore, a strict chronology of these intrusive rocks cannot be compiled. The following relative ages have been established or can reasonably be inferred:

1. The Casey Peak mass is oldest, the South Fork mass perhaps is of intermediate age, and the Moose Creek and Crazy Peak masses are younger. The differences probably are only slight; the main difference is that the older bodies are the shallow parts and the younger bodies the deeper parts of a complex and dynamic magma chamber.
2. The plug near Sheep Park composed of andesite and basalt is older than at least part of the Casey Peak mass of basalt and trachybasalt.
3. In the South Fork mass, a dike of porphyritic augite-hornblende andesite cuts a large body of olivine-augite basalt. The distribution of rock types indicates that the upper central trachybasalt parts of the mass are older, and the basalt and andesite marginal parts are younger.

RELATION BETWEEN INTRUSION AND REGIONAL FOLDING

In the map area the sills and larger intrusive masses appear to be closely related. The sills follow bedding even where the beds are folded. However, the folds are not very sharp, and the sills probably could have been emplaced before or during folding. In the southern Elkhorn Mountains, folds locally are very tight; yet in several folds, sills follow around the plunging noses and along the flanks without change in thickness, which led Klepper and others (1957, p. 45) to conclude that intrusion was accomplished before folding. In addition, in that area tear faults probably related to the folding contain no dike offshoots, further suggesting that the intrusions preceded the main period of folding.

It has been noted that most of the large intrusive masses lie along the axis of a broad syncline. This relation may indicate that the intrusions are younger and were guided by the fold; that folding and intrusions were synchronous; or, that the intrusions were slightly older than the folding but synchronous with regional horizontal compressive stresses that later produced the folds.

The intrusions have been shown not to be younger than the syncline and, in general, probably are older. However, the occurrence of episodes of moderate local folding suggests that folding and intrusion may have been synchronous locally. Folding occurred locally, for example, during deposition of the Slim Sam Formation in the northern part of the map area and during the interval between the lower and middle units of the volcanic rocks in the southern Elkhorn Mountains (Klepper and others, 1957, p. 32, 60). Lifting of beds by this postulated compression would allow sills to form without having to lift the entire weight of the overlying section, which is more than 10,000 feet thick in places.

A similar hypothesis has been presented for the Pando area, Colorado, by Tweto (1951, p. 529): "intrusion took place early in the Laramide revolution * * * before the rock had been deformed and only shortly after the close of Cretaceous sedimentation, when the load was at a maximum." He postulated (p. 530) that "the spread of the viscous Pando and Elk Mountain magmas in relatively thin, widespread, and uniform sills was aided by the lifting action of laterally compressed competent beds." Tweto's concluding statement (p. 530) is also thought to be applicable in the Elkhorn Mountains: "Local irregularities and small-scale doming of sills * * * is attributed to differential compaction of the lenticular host rocks, and the large-scale doming or swelling to laccolithic proportions is attributed to rapid supply of magma near source vents."

The positioning of younger intrusives and structures is partly controlled by the pattern of older intrusives and structures, and these younger features may, in turn, modify the older ones, making it very difficult to analyze the resulting complex.

PETROGRAPHY AND PETROLOGY

Many textural and mineralogic varieties of intrusive rocks occur repeatedly throughout the Elkhorn Mountains Volcanics. They are indistinguishable from many rocks which occur as fragments in the extrusive deposits of the volcanics.

The following rock types were recognized in the course of microscopic study of the composite intrusive masses; similar rocks also occur as sills, dikes, laccoliths, and in the plug near Sheep Park:

- Casey Peak mass:
  - Augite basalt
  - Augite-hornblende andesite
  - Coarse-grained augite trachybasalt ranging to coarse-grained augite latite
- Moose Creek mass:
  - Augite basalt
  - Augite trachybasalt
  - Coarse-grained hornblende trachybasalt

South Fork mass:
- Augite basalt
- Hornblende-augite basalt
- Augite trachybasalt ranging to hornblende-augite trachybasalt
- Augite andesite
- Augite-hornblende andesite
- Olivine-augite-hornblende andesite (lamprophyric)

Crazy Peak mass:
- Basalt (mafic minerals too altered to identify)
- Augite trachybasalt
- Andesite (mafic minerals too altered to identify)

The different petrographic types were not mapped separately. The general locations of studied samples are shown in an earlier publication (Smedes, 1962b).

The varied rocks share several features. One is alteration; another is the presence of microvesicles; still another feature, probably related to microvesicles, is the widespread autobrecciation.

Nearly all the intrusive rocks are porphyritic; some are porphyries. Phenocrysts are of plagioclase, hornblende, or pyroxene and occur alone or in combination. Some bodies and parts of apparently single intrusive masses have hornblende or pyroxene, or both, as phenocrysts, but not plagioclase; these rocks are called lamprophyre in the descriptive sense of Knopf (1936, p. 1748–1749).

In the Moose Creek mass, porphyritic trachybasalt grades from hornblende trachybasalt through augite-hornblende trachybasalt to augite trachybasalt. The plagioclase phenocrysts are as calcic as An_{82} in the augitic part and An_{64} in the hornblendic part.

Other rock bodies exhibit gradations from parts which have phenocrysts only of plagioclase to those which have phenocrysts only of mafic minerals, with plagioclase and mafic mineral phenocrysts of comparable size between.

Intrusive rocks are dominantly shades of gray, blue, and green, principally medium gray to dark gray, bluish gray, and greenish gray to greenish black. Red, brown, and purple hues are associated only with altered intrusive rocks. Phenocrysts of mafic minerals commonly stand out on weathered surfaces, and the rocks break into platy, slabby, or blocky fragments on frost-heaved slopes or in talus.

Only a few rocks are entirely aphanitic; most have a hiatal texture and consist of an aphanitic or very fine grained crystalline groundmass studded with phenocrysts. The phenocrysts are mostly euhedral, but some are subhedral owing to partial resorption or to cataclasis. Flow alinement is common and is marked by phenocrysts, plagioclase microlites in the groundmass, and streaked-out vesicles. Locally, layered structure is marked by bands of different hue.

Specific gravity, measured for 36 samples of intrusive basalt, trachybasalt, and andesite ranged from 2.54 to 2.86 and had a mean and average of 2.73. Chemical analyses were made of an andesite sill in the High Peak area. This sill has peperitic margins at top and base, is about 40 feet thick, and lies in and has moderately deformed thin-bedded water-laid andesitic rocks at the common corner of secs. 26, 27, 34, and 35, T. 8 N., R. 2 W. Parts of its peperitic margin are shown in figures 20, and 21. The chemical and normative compositions are presented in table 2 (samples 4–7).

According to Rittman's classification (1952), the noncontaminated rock from the central zone (sample 5, table 2) chemically is pigeonite-labradorite andesite. Petrographically, it is basalt. The rock is medium gray to dark gray, with a faint dusky-blue tone in many places. It is aphanitic and has small phenocrysts of plagioclase and pyroxene which make up from 20 to 30 percent of the rock. The porphyritic texture is inconspicuous except on weathered surfaces, where small plagioclase tablets about a millimeter long are seen alined in a fairly uniform flow structure. Even less conspicuous are equant phenocrysts and clusters of phenocrysts of pyroxene as much as 2.5 mm across.

In thin section, the rock is seen to have a very fine grained groundmass of plagioclase microlites, granules of pyroxene and magnetite, and aggregates of chlorite, epidote, and irresolvable matter. Plagioclase microlites are not oriented in most of the groundmass but are arranged in a flow alinement around phenocrysts. Plagioclase phenocrysts are of two distinct size groups, one about 0.2 mm long and the other about 1.0 mm. Crystals of the larger size are characterized by reverse zoning in the range An_{70} to An_{80}; the smaller crystals have normal zoning in the range An_{65} to An_{50}. Plagioclase is altered locally to clay and carbonate minerals. Pyroxene phenocrysts have an altered rind of opaque minerals, chlorite, and irresolvable dusty matter. The pyroxene is ferroaugite, pleochroic from pale green to brown, zoned, $2V_z=50°$, $r>v$, $Z\wedge c=51°$, $N\gamma=1.74$, $\gamma-\alpha=0.030$, approximately. Talc, iron oxides, and carbonate minerals occur as pseudomorphs after olivine.

The presence of iron-rich pyroxene (ferroaugite) in the rock and of magnesium-rich pyroxene in the norm can be explained by the presence of olivine in the rock but not in the norm and by the assumption that the olivine was magnesian. The combination of olivine in the rock and unusually high quartz in the norm may indicate contamination of the magma by silica.

The variations of major chemical and normative constituents from base to top of this peperitic sill are shown graphically in figure 27. The diagram shows an increase upward in SiO_2 and K_2O and normative quartz and orthoclase and a decrease upward in CaO and Al_2O_3, and normative anorthite. It also shows a higher content of H_2O and CO_2 and normative albite and magnetite and a slightly lower content of FeO and MgO and a normative enstatite in the base and top as compared with the middle.

The uncommonly high content of H_2O and CO_2 in the peperitic margins probably was derived from the moist sediment. Lower MgO and FeO in these margins may be due to dilution of the magma by assimilation of sediment and filling of vesicles; however, the differences are not far greater than the uncertainty in the reported value, and the content of MgO and FeO may really be quite uniform.

Strata above and below the sill are similar, and the upper and lower peperite margins are indistinguishable. These symmetrical relations suggest that the asymmetrical variations in SiO_2 and K_2O (also expressed in terms of normative orthoclase and quartz) are not due to contamination, but they reflect an upward enrichment, perhaps owing to rising volatiles rich in dissolved K_2O and SiO_2.

Thus, some relations suggest contamination, other suggest volatile rise of some constituents; perhaps both processes were operating simultaneously.

Upward volatile enrichment in potassium is also indicated in the large sill which lies southeast of the chemically analyzed sill, in the W½NW¼ sec. 35, T. 8 N., R. 2 W. This sill caused considerable deformation of the country rock and has peperite along its upper margin. The central part is cut by a dike and several small amygdaloidal sills. The main mass is coarse trachybasalt with about 20 percent K-feldspar and 44 percent labradorite (An_{68}), whereas the dike grades upward to porphyritic augite latite with about 35 percent K-feldspar and 30 percent andesine. K-feldspar occurs in both parts of the intrusive as poikilitic grains enclosing plagioclase and augite, but in the latite dike it also fills interstices, replaces plagioclase, and fills vesicles that are younger than the epidote linings on some vesicle walls. Potassic fluids must have invaded the country rock for a few inches to a few feet above both the sill and the dike because K-feldspar has formed there as irregular interstitial masses and, close to the sill, as irregular porphyroblasts. Epidote has heavily impregnated the country rock for several tens of feet from the contact. This occurrence strongly suggests upward enrichment in K-feldspar; it suggests further that the vesicles began to be filled in a late magmatic stage.

The andesitic and basaltic rocks are truly separate and distinct petrographic types, as is partly borne out by the composition of plagioclase crystals (fig. 28). Rocks transitional between andesite and basalt were not found in the map area, but they are common in the intrusive bodies on the east flank of the Elkhorn Moutains (fig. 28).

Approximate relative abundance of different petrographic types, based on 42 thin sections of the intrusive rocks, is presented in table 3, with other data.

TABLE 3.—*Relative abundance, grain size, and mineral content of Cretaceous intrusive rocks, based on study of 42 thin sections*

Petrographic type	Relative abundance (percent of total samples)	Number of samples	Minerals present (number of samples)			Anorthite content of cores of plagioclase crystals		Size of crystals in mm				Number of samples autobrecciated
								Mafic minerals		Plagioclase		
			Augite	Amphibole	Olivine	Range (percent An)	Average (percent An)	Range	Average	Range	Average	
Trachybasalt	47	20	19	8	7	87–56	73	0.4–25	1.5	0.7–3.4	1.6	5
Basalt	36	15	15	5	8	82–60	71	.2–8	2.0	.2–2.0	1.0	4
Andesite	17	7	7	6	3	36–30	32	.2–2.3	.8	.2–1.0	.4	2

PLAGIOCLASE

All plagioclase phenocrysts are zoned. Nearly all zoning is normal, with calcic core and more sodic rim. Subtle oscillatory zoning commonly is combined with the more conspicuous normal zoning. Only a few rocks contain reverse-zoned plagioclase, and those crystals are larger ones only. In some rocks, plagioclase phenocrysts occur in two distinct size groups.

As shown in figure 28, the compositions of the calcic cores of plagioclase crystals fall into two principal groups, with a gap between An_{38} and An_{53}. However, because the data were recalculated and plotted as moving averages, the gap shown in figure 29 is slightly less than was actually observed, An_{36}–An_{56} (table 3).

Altered inclusions are prevalent parallel to the pinacoids (010) and (100) and locally parallel to all faces of phenocrysts, resulting in a concentric pattern. These inclusions commonly are irregular spindles, plates, and blebs of devitrified glass. Primary inclusions are magnetite, ilmenite, apatite, augite, and olivine. Primary hornblende was not observed as inclusions in plagioclase. Secondary amphibole occurs locally as inclusions, but it may be pseudomorphous after pyroxene or glass.

Combined carlsbad-albite twinning is widespread and is the most common twin law. Albite and pericline twins are next more frequent but only about ⅛ or 1/10 as abundant as carlsbad-albite twins. Other twin laws are only sparsely represented.

PYROXENE

Pyroxene occurs in all but one of the rocks studied. The crystals tend to be in glomerophyric clusters, in places with plagioclase, magnetite, or olivine. Pyroxene is commonly too altered for determination of optical properties. Nevertheless, it is possible to determine not only that many crystals were pyroxene but that the pyroxene was monoclinic, because the stubby prisms are capped by prominent positive clinodomes (011).

Most of the determinable pyroxene is colorless to very pale augite, but some basalt sills contain small phenocrysts of ferroaugite. Some augite crystals are zoned and a few exhibit hourglass structure. Most crystals show (100) twinning; in many the composition plane, which is roughly through the middle of the crystal, consists of a very narrow zone of slender (100) polysynthetic twin lamellae. Augite crystals in some rocks are characterized by broad (100) twin lamellae, rather evenly spaced. These twin lamellae

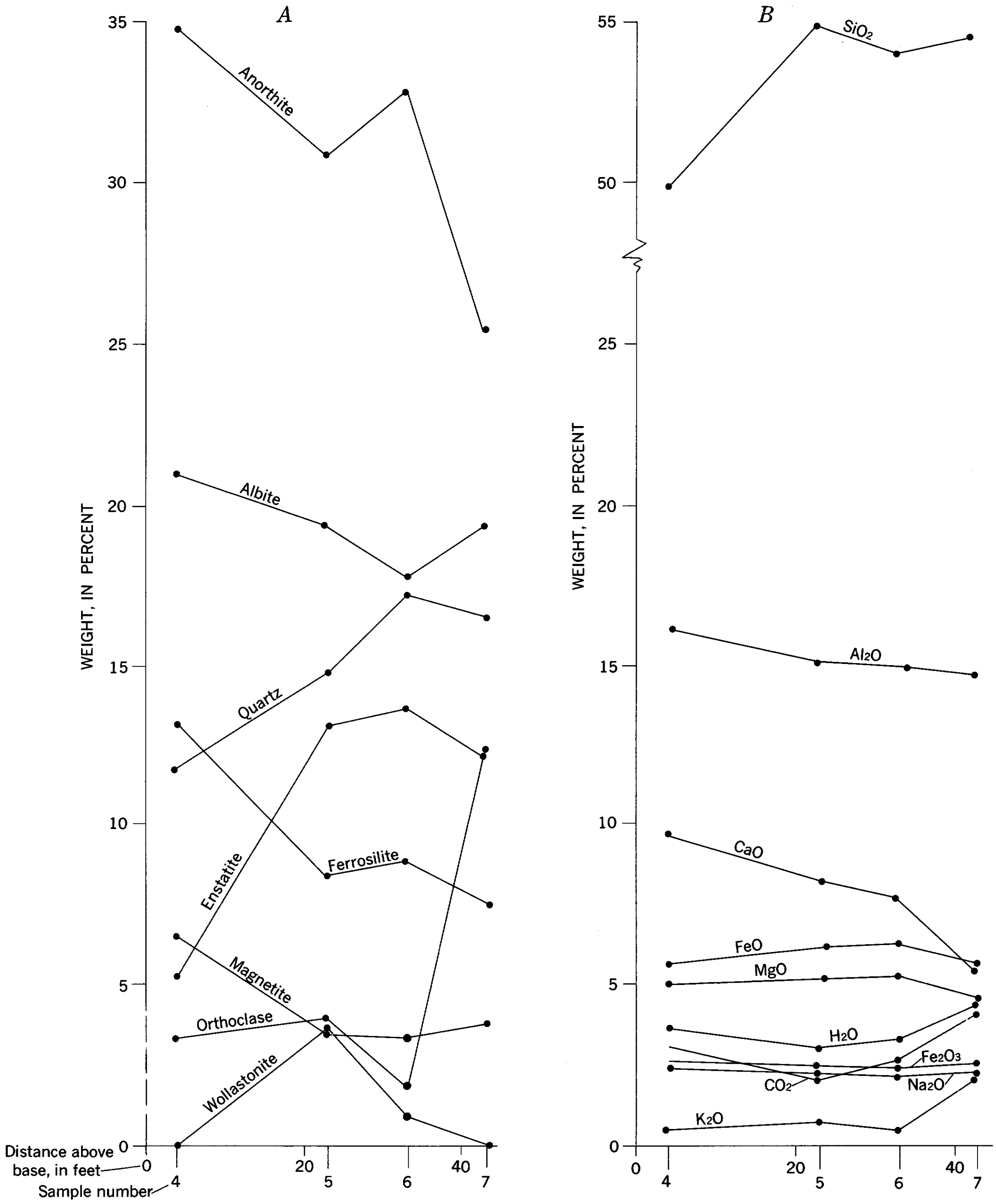


FIGURE 27.—Diagram showing variations in composition from base to top of peperitic sill. *A*, Principal normative minerals; *B*, Principal oxides. Sample number from table 2.

tend to pinch and swell abruptly by steplike offsets; each twin lamella acted apparently without regard to the shapes of adjacent lamellae, and some abruptly terminate, leaving rectangular spaces between continuous adjacent bands. No exsolution lamellae were recognized.

Inclusions in pyroxene are opaque minerals, olivine, apatite, and, locally, plagioclase. Alteration products include rutile, ilmenite, and leucoxene.

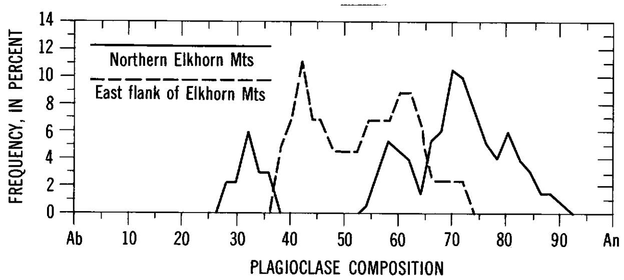


FIGURE 28.—Frequency diagrams of composition of plagioclase crystals in Cretaceous intrusive rocks. Data based on average anorthite content of the calcic cores of phenocrysts determined by extinction methods in each of 42 rocks from the northern Elkhorn Mountains (this study) and 15 rocks from the eastern flank of the mountains (R. A. Weeks, written commun., 1957). Plotted as moving averages.

AMPHIBOLE

Amphibole occurs as phenocrysts, overgrowths on pyroxene, and pseudomorphs after pyroxene. Most is pale-green to colorless tremolite-actinolite as partial pseudomorphs after dark-brown and greenish-brown hornblende and pyroxene. Hornblende locally formed as parallel overgrowths on (001) pinacoids of pyroxene. In some of these crystals, (100) lamellar twinning in the pyroxene is matched against that of (100) twinning in the hornblende, the whole appearing in certain positions of extinction as a single twinned crystal. Twinning on (100) is common in the primary hornblende and commonly is inherited by the secondary amphibole. As in the pyroxenes, the composition plane generally consists of a narrow medial zone of slender polysynthetic twin lamellae.

Hornblende crystals generally are long prisms and occur as separate phenocrysts, in contrast to the clustered equant pyroxene phenocrysts. But in trachybasalt especially, and in some andesite and basalt, hornblende occurs in large penetration twins in the form of six-rayed stars or rosettes. Diametrically opposed rays of these stellate groups are of the same optical orientation and the twins are, therefore, trillings (fig. 29). The individual rays locally exhibit polysynthetic (100) twinning as well.

Amphibole phenocrysts commonly are gradationally zoned and have dark hornblende cores and colorless to pale-green tremolite-actinolite rims. Some of the pale amphibole extends coreward along cleavages, and probably is deuteric, but it may have formed later, during thermal metamorphism induced by the batholith.

Inclusions are common and mostly are opaque minerals, pyroxene, apatite, plagioclase, and, locally, olivine and rutile.

OLIVINE

Olivine formed in some rocks of each lithologic type, though very little is preserved and the olivine now is represented mostly by pseudomorphs of talc, antigorite, chlorite, carbonate minerals, and iron oxides. In many rocks the characteristic euhedral olivine outlines are well preserved, especially where the grains are enclosed in fresh pyroxene or hornblende.

K-FELDSPAR

K-feldspar occurs with rare exception only as late interstitial granules and irregular forms in the groundmass and as secondary veinlets, networks, and irregular patches and blebs largely replacing plagioclase but also replacing mafic minerals. K-feldspar also occurs in a few amygdules.

In some rocks, K-feldspar occurs sparsely as phenocrysts, and the groundmass contains abundant interstitial K-feldspar granules. A few rocks contain xenoliths which are rich in K-feldspar in the form of large irregular poikilitic clear untwinned crystals.

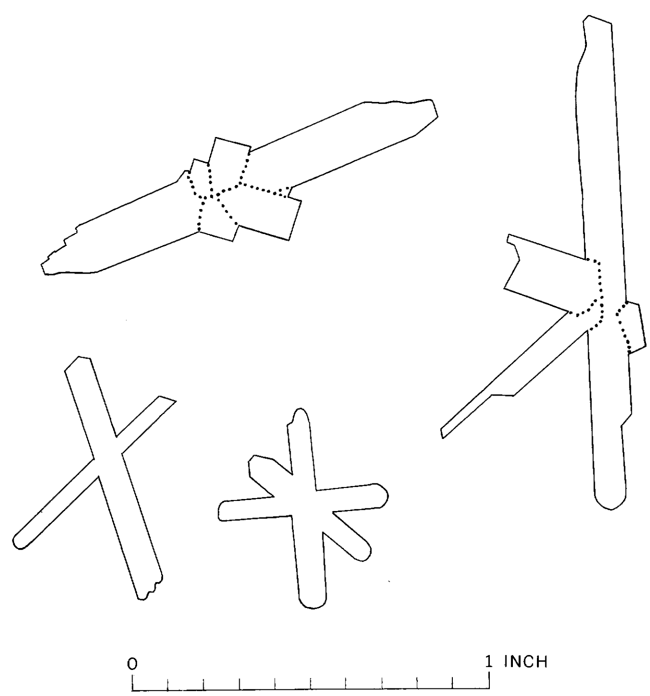


FIGURE 29.—Sketches of stellate penetration twins (trillings) of hornblende in porphyritic trachybasalt sill. Dots show contacts as revealed by cleavage planes. The simple penetration twin is preserved as a mold only. The small trilling is too altered to preserve cleavage.

QUARTZ

Quartz was not observed as phenocrysts and is present in the groundmass only in some andesites and trachybasalts. Quartz is a rather common very fine grained alteration product of hornblende. No estimate was made of the abundance of groundmass quartz because of the very fine grain size and the general masking effect of the secondary minerals.

BIOTITE

Biotite occurs sparingly in some andesites and trachybasalts. Much of the chlorite in some thin sections probably represents complete alteration of biotite, and biotite was more prevalent than its present abundance indicates. Estimates of biotite content based on chlorite are not warranted, however, because chlorite also is a common alteration product of olivine, pyroxene, and hornblende.

MAGNETITE

Magnetite is abundant in all rocks studied and occurs as minute granules and skeletal crystals scattered throughout the groundmass or concentrated in thin layers that mark contorted flow banding. In addition, in some rocks titaniferous magnetite occurs abundantly as inclusions in hornblende and as fine dust concentrated along cleavage cracks and around the rim of hornblende, where it is intimately associated with leucoxene.

VESICULAR STRUCTURE

Most intrusive rocks are microvesicular; some, mostly sills and dikes, also are macrovesicular. In nearly all, the cavities have been filled with silica, carbonate minerals, chlorite, epidote, and lesser amounts of other minerals. The microvesicles tend to be more irregular than the macrovesicles which are flattened and streaked out in flow alinement. In sills and dikes the vesicles are for the most part parallel with the contacts, except for local areas of turbulent flow streaking. Macrovesicles are sparse in the large intrusive masses, but they are common in small dikes cutting early intrusives.

CATACLASTIC STRUCTURE

Cataclasis is prevalent in the intrusive rocks. Four gradational degrees of cataclastic effects are recognized: (1) some phenocrysts broken and pulled apart; remainder of rock not affected; (2) some phenocrysts shattered but the pieces still intact; remainder of rock not affected; (3) groundmass cut by network of fractures which commonly are deflected around crystals; and (4) entire rock affected. Different parts of an intrusive mass may exhibit different types of cataclasis. Of the phenocrysts, plagioclase appears to have been the most susceptible to cataclasis.

In cataclasis of type 1, the phenocrysts are broken, and the pieces are strewn out along flow lines, at random, or clustered with fragments of other minerals. Generally, the fragments in the clusters are mismatched and apparently are not parts of the same crystal. Plagioclase shattered in this manner shows normal zoning with zones and twin lamellae discordantly truncated at the broken faces. In some rocks the individual pieces and the clusters of fragments of plagioclase are encased in shells of albite or albite-oligoclase with different optical orientation. Cataclasis of this type presumably was accomplished during forceful injection of a viscous magma which contained intratelluric phenocrysts.

In cataclasis of type 2, the phenocrysts are weakly to intensely shattered, but their parts remain intact. The shattered character is made conspicuous mostly by alteration which was guided by the fracture systems. In the near-extinction position under the microscope, this fracture pattern is discernible, even where alteration is lacking, because each fragment is rotated very slightly from the orientation of its neighbors. Crystals shattered in this manner resemble those shown in figure 7*A* and *B*. Most plagioclase crystals affected are altered, generally intensely. Albite is the chief product; but K-feldspar, minerals of the epidote group, and others also are present locally. All gradations occur, even in a single thin section, from nonshattered and unaltered to intensely shattered and pervasively altered. The plagioclase phenocrysts exhibit normal zoning, with calcic cores grading to moderately sodic mantles and then abruptly, though still continuous and gradational, to much more sodic rims of albite and albite-oligoclase. In general, the sodic rim is not shattered, but the inner shells and core are. Albite of the rim fills the cracks and has replaced laterally from there to form irregular and hazily defined networks and patches of sodic plagioclase throughout the crystal. Thus, cataclasis of this type was accomplished just before the formation of the sodic rim, late in the cooling history of the rock but before final consolidation. This is analogous to albitization in rocks of the batholith, which took place nearly contemporaneously with the late-stage growth of K-feldspar and quartz, described below.

Cataclasis of type 3 represents incipient autobrecciation, already described. Cataclasis of type 4 may represent advanced stages of autobrecciation, already described, or may be the result of other kinds of brecciation, such as produce cognate breccia, intrusion breccia, or fault breccia.

ALTERATION OF ELKHORN MOUNTAINS VOLCANICS AND INTRUSIVE ROCKS

All rocks of the Elkhorn Mountains Volcanics and the intrusive rocks related to them are altered to some degree. The alteration appears to have been produced by several processes during several stages and includes deuteric and other autometamorphic processes, hydrothermal and pneumatolytic metamorphism due to the heat of the volcanic pile and to volcanic phenomena, and thermal metamorphism due to the Cretaceous intrusive rocks and the Boulder batholith. The minerals and textures resulting from processes of different kinds and ages are mostly similar, and the rocks all look very much the same. The principal basis for distinguishing alteration of various types from each other and from mineralogically similar low-grade thermal metamorphism is the distribution and spatial relations of the alteration effects.

The most prevalent alterations are saussuritization of plagioclase, and chloritization and epidotization of mafic minerals and rock fragments; uralitization of pyroxene is less prevalent. Mafic minerals and rock fragments commonly are more thoroughly altered than are the feldspars, but because feldspar is more abundant, saussuritization is more conspicuous. The green color of the rocks generally is caused by abundant epidote and actinolitic hornblende, whereas the blue tones generally indicate a high chlorite-epidote ratio, and red hues are largely due to oxidation of magnetite which had formed from the breakdown of mafic minerals. Red colors locally are due to the presence of deuteric and hydrothermal jasper.

Alteration is highly variable in degree and extent and in the geometry of its distribution. Some slightly altered tuff and breccia contain fragments of highly altered intrusive and extrusive rocks. These alteration features may be inherited—for example, rock fragments in which the alteration minerals are discordantly truncated at the boundaries of the fragment and detrital grains of epidote, chlorite, and other alteration minerals. Or, the alteration may have been syngenetic or epigenetic, some fragments being more thoroughly altered than others because of differences in composition or texture—for example, (1) haloes of alteration products around, and gradational outward from, highly altered fragments in mudflow breccia fragments whose slightly altered cores grade outward to a highly altered rind which blends with a highly altered enclosing matrix; (2) entire beds or parts of a bed, which are selectively altered; and (3) joints, flow bands, or other structures which controlled alteration. Pipelike zones of alteration may have been fumaroles.

Some alteration veinlets cut others which, in turn, cut selectively altered fragments or detrital fragments of altered rock or crystals embedded in rocks that are only slightly altered. These crosscutting relations indicate that at least four different episodes of alteration affected some parts of the volcanic pile. Although several of these may really be only different stages of a single period of alteration, it is likely that many different episodes of alteration have affected the volcanic pile. The entire pile probably was not subjected simultaneously or continuously to the attack by vapor and hot water, but in overall aspect the entire volcanic district undoubtedly was a steaming hot pile during much of its accumulation.

Alteration of autobrecciated intrusive rock and lavas and of ash-flow tuff has been described briefly and thermal metamorphism spatially related to the batholith will be described below.

Many of the breccias and conglomerates probably are mudflow deposits. Those that have relict alteration features which appear to be syngenetic are thought to have been hot mudflows.

PLAGIOCLASE

Plagioclase has been converted to minerals of the epidote group, albite, and calcite. Zoisite is most common in the phenocrysts, and epidote most common in the groundmass where it probably also formed from mafic minerals. Sericite and muscovite are widespread; quartz is common in places; tremolite-actinolite, chlorite, siderite, and fine-grained aggregates of K-feldspar are less common; and K-chabazite, thompsonite, garnet, and clay minerals are sparse.

Minerals containing sulfur, fluorine, and boron are very minor alteration products. This implies that solfataric activity was negligible.

MAFIC MINERALS

Augite has been altered to tremolite-actinolite, chlorite, epidote, rutile, sphene, leucoxene, magnetite, ilmenite, limonite, hematite, nontronite, saponite, and carbonate minerals, and in some places to quartz and K-feldspar, but not to zoisite.

Olivine has nearly everywhere been altered, mostly to talc, antigorite, and carbonate minerals, and locally also to chlorite or iddingsite, alone or in combination.

Hornblende has been altered to the same suite of minerals as was augite, only with lesser amounts of the titanium-bearing minerals. Some relict crystals are complete pseudomorphs and can be recognized only by the typical amphibole cross sections or, in places, by preservation of prismatic cleavages by films of iron oxides. Some phenocrysts of dark hornblende are zoned and have nearly colorless rims of tremolite-actinolite which extend inward along cleavage and produce a splotchy appearance.

GROUNDMASS

Microlites of plagioclase and granules of mafic and opaque minerals were altered in the same way as the larger crystals, and all groundmass glass was devitrified. In some places, far from the batholith, the devitrification and recrystallization resulted in materials so fine grained that the characteristic vitroclastic texture is well preserved. In the field these rocks appear very dense and stony, resembling chert and porcelain. The former glass shards and lapilli of calcic quartz latite ash-flow tuff of the lower unit of the volcanics are now aggregates, fibers, mosaics, lamellar masses, and spherulitic clusters of quartz, plagioclase, and K-feldspar with lesser amounts of chlorite, nontronite, and probably saponite. The former glass shards and lapilli of rhyolite welded tuff of the middle unit of the volcanics are now dense aggregates and spherulitic masses of quartz, K-feldspar, albite-oligoclase, and lesser amounts of the epidote group, and carbonate minerals. Quartz pseudomorphs after tridymite occur in micromiarolitic cavities, some of which have been filled with secondary minerals.

The upper least compacted parts of the welded-tuff sheets were more highly altered than the dense highly compacted and intensely welded central parts. Also, the larger partly collapsed pumiceous lapilli in the welded parts of ash-flow tuff generally are more highly altered than the enclosing rock, and such lapilli have alteration haloes (fig. 14). This kind of alteration probably was produced by residual hot fluid trapped in the pumice.

Cordierite formed from the dense groundmass of some sills and larger intrusive bodies, apparently caused by thermal metamorphism from similar Cretaceous intrusives in some places and from the Boulder batholith in others. In some of the intrusive rocks, cordierite, or perhaps the cordieritelike mineral osumilite, does not seem to be spatially related to other intrusive bodies. That cordierite may be of late magmatic or deuteric origin rather than of contact-metamorphic origin.

CRETACEOUS OR TERTIARY SYSTEM

BOULDER BATHOLITH

The large mass of plutonic igneous rock that occupies the western half of the map area (pl. 1) is a small part of the Boulder batholith, which extends from the central part of the map area westward nearly to Elliston and from about 4 miles north of the latitude of Helena to the Highland Mountains south of Butte. The batholith is elongated north-northeast and has maximum dimensions of 70 by 35 miles.

Weed (1899) named the batholith. He concluded (1912, p. 29) that it was of Miocene age; Knopf (1913, p. 34), however, assigned it a Late Cretaceous age.

The youngest rocks cut by the Boulder batholith are the Elkhorn Mountains Volcanics of Late Cretaceous age. The oldest rocks known to rest on the eroded batholith are the Lowland Creek Volcanics of Eocene age, dated as about 50 million years old (Smedes and Thomas, 1965). Detritus from the batholith is a component of deposits of late Eocene age not far to the southeast (Robinson and others, 1957).

One age determination by the K-Ar method was published by Knopf (1956), who reported (p. 744) that the sample "has a most probable age of 87 million years and is almost certainly older than 65 million years." Two other published K-Ar ages are 82 and 81 million years (Baadsgaard and others, 1961; Evernden and others, 1961). Some additional potassium-argon determinations were reported informally by G. H. Curtis (in Curtis and others, 1961, p. 347) to average near 78 million years. Ten unpublished K-Ar age determinations by the U.S. Geological Survey range from 70 to 76 million and average 72.4 million years, ± 5 percent.

Age determinations by the lead-alpha activity (Larsen) method, summarized by Chapman and others (1955) and Jaffe and others (1959, p. 79–81), indicate that the mass of the batholith is about 72 million years old, and that younger alaskite is about 61 million years old.

These data collectively indicate that the Boulder batholith and its satellites were emplaced in latest Cretaceous or possibly in earliest Tertiary time, the boundary between which has been set as 70 ± 2 million years by Holmes (1959) and as 63 ± 2 million years by Kulp (1961).

In the northern Elkhorn Mountains, the batholithic rocks are divisible into four main groups: (1) early mafic rocks in plugs and dikes and in a complex body mostly of mafic rocks ranging from gabbro to quartz monzonite; (2) granodiorite which makes up the Antelope Creek stock; (3) Butte Quartz Monzonite, constituting the main bulk of the batholith; and (4) late alaskite and related felsic rocks of granitic and quartz monzonite composition, and leucogranodiorite.

The rocks of each of these four groups were mapped separately where feasible. Further map subdivisions were made in the Butte Quartz Monzonite; in the late alaskite and related rocks, only the leucogranodiorite was mapped separately.

The relations between this sequence of four main groups and the sequence determined by Knopf from the region just to the west are shown in table 4.

TABLE 4.—*Sequence of batholith rock units showing correlation between terms used in this report and those used by Adolph Knopf*

Knopf (1957, 1963)	This report	
Alaskite and aplite	Alaskite and related felsic rocks	
Muscovite-biotite granite		
Biotite adamellite		
— ? — ? — ? —		
Porphyritic granodiorite	Butte Quartz Monzonite	
— ? — ? — ? —		
Clancy Granodiorite		
Unionville Granodiorite	Early mafic rocks	Granodiorite of the Antelope Creek stock
Olivine-orthoclase gabbro		

Scattered bodies of the early mafic rocks are correlated with Knopf's gabbro. The main body of early mafic rocks consists of an undivided complex—the Kokoruda Ranch complex—of the gabbro and its correlatives irregularly cut by Unionville Granodiorite.

The Clancy Granodiorite is coextensive with the main body of the batholith in the present map area and with the Butte Quartz Monzonite of Weed (1899, p. 740; 1912, p. 31). Believing that the Clancy Granodiorite and Butte Quartz Monzonite are the same mass, I have adopted the name Butte Quartz Monzonite, because of its priority, for these rocks.

Knopf's next stage is porphyritic granodiorite of uncertain age relations. It may correlate with some medium-grained porphyritic facies of the Butte Quartz Monzonite of the present report.

The next two stages of Knopf's sequence probably correlate with the late alaskite and related felsic rocks of this report; his alaskite and aplite undoubtedly correspond with similar rocks in the present map area.

Intrusive contacts are discordant with country-rock structures except in the region between Jackson and Crystal Creeks, where the batholith is conformable with the foliation of schistose and mylonitic volcanic rocks. Evidence is presented below which implies that the foliation was imposed upon the volcanic rocks contemporaneously with, and perhaps due to, the intrusion of the batholith (p. 85).

The chemical data presented in this report (table 2) indicate that the rocks of the batholith are calc-alkaline, having a Peacock (1931) alkali-lime index of about 59. The prebatholith igneous rocks also have an index of about 59. The postbatholith igneous rocks probably have a comparable index; their plotted positions lie near the alkali and lime curves of the batholith rocks. In addition, in all rocks but the prebatholith intrusive sill (samples 4–7, table 2), K_2O and Na_2O either are nearly equal or K_2O exceeds Na_2O. Thus, all the igneous rocks are calc-alkaline; most also tend to be potassic.

The prebatholith and postbatholith volcanic fields lie within the confines of the batholith and its satellites (see the maps of Ross and others, 1955, and Smedes, 1962a).

These close chemical and spatial relations strongly suggest that all the igneous rocks are parts of one genetic system or magma series.

EARLY MAFIC ROCKS

Early mafic rocks are exposed principally along the northeastern border of the batholith in a northwest-trending heterogeneous body of about 3⅓ square miles which also extends a short distance westward. This body is referred to as the Kokoruda Ranch complex, after the George C. Kokoruda ranch which lies within it in sec. 28, T. 9 N., R. 2 W.

The Kokoruda Ranch complex includes olivine- orthoclase gabbro which Knopf (1963, p. 8) determined to be older than the partly enclosing Unionville Granodiorite. This early gabbro, and many other rocks of the Kokoruda Ranch complex which probably are of comparable age, are irregularly invaded by Unionville Granodiorite. However, because of the poor exposures and short time available for mapping, it was not possible to subdivide the complex.

The heterogeneity of this complex and the wide range in its rock types were not recognized by earlier workers. In addition to the granodiorite, granogabbro, and gabbro mentioned briefly by Knopf (1963, p. 7–8), the Kokoruda Ranch complex includes norite, gabbro, syenogabbro, syenodiorite, monzonite, calcic monzonite, augite-bearing quartz monzonite, and rare bands of peridotite in gabbro. Petrographic features of some of the rocks studied are shown in table 5. Zones of shonkinite, orthoclase rock, and scapolite- and garnet-rich rocks formed locally by assimilation along contacts with calcareous country rocks and xenoliths.

Age relations among these various rock types are not known; they all are shown on the map by the same symbol.

TABLE 5.—*Modal composition and petrographic features*

Locality	Sample	Rock Name	Specific gravity	Color index (total dark minerals)	Pyroxene	Amphibole	Biotite
Plug in Crazy Creek	1	Melasyenogabbro	2.74	41	20 percent, acmitic diopside; $2V_z$=50–65°, mostly 54°; $Z \wedge c$=41–48°, optic plane=(010); polysynthetic twins common (100), rare (010).	17 percent, groundmass aggregates of actinolite with calcite, chlorite, epidote, and magnetite.	----------
Plug north of Staubach Creek.	2	Syenogabbro (near syenodiorite).	2.74	38	17 percent, augite, pink to very pale green; zoned, with narrow rim of actinolite and an adjacent inner band of opaque dust.	6 percent, actinolite pseudomorphous after augite. Minor amounts of chlorite enclosed.	10 percent, contains inclusions of skeletal magnetite; has replaced some augite.
Probable ring dike near the Antelope Creek Stock.	3	Scapolite-bearing calcic melamonzonite.	2.84	49	43 percent, (+), $Z \wedge c$= 39–45°; $r>v$, weak. Zoned with colorless core and pale-green rim. Locally altered to chlorite.	Present locally as pseudomorphs after pyroxene. Very dark green, yellowish brown, to blue green.	Minor, as inclusions in pyroxene.
	4	Syenogabbro (No. 10, table 2).	----------	27.5	11 percent, augite, very pale to pale green and colorless.	6.5 percent, pale green to light brown, as rims and lacy networks in augite and intergrown with augite.	8 percent, late poikilitic plates as much as 8 mm across.
Kokoruda Ranch complex.	5	Quartz gabbro	3.06	37	21 percent, diopside; $Z \wedge c$=37°. Generally molded against laths of plagioclase.	5 percent, actinolite, along rims and cracks in diopside.	7 percent, late poikilitic masses.
	6	Hyperite (olivine-diallage-augite-hypersthene melagabbro).	3.03	66	31 percent, diallage, hypersthene, and augite. Augite has conspicuous (100) twinning and is netted by amphibole.	13 percent, as separate crystals and as rims and networks in augite. Zoned, with outer parts blue green.	5 percent, late poikilitic masses of pale color.
	7	Melanorite (hyperite)	3.11	73	46 percent, hypersthene: $2V_z$=60–65°, pale green to pale pink; N_z-N_x= <0.016, N_z=1.70. Augite: $2V_z$=large, $Z \wedge c$=31–41°, colorless to pale pink to brown; inclusions of diallage and olivine.	14 percent, pale green to brown uralite.	3 percent, poikilitic masses as much as 8 mm, cutting and replacing all other minerals.
	8	Melasyenogabbro (near melasyenodiorite).	3.23	51	34 percent, augite, $Z \wedge c$=41°, pink to pale green. Some is in graphic intergrowth with magnetite.	7 percent, mostly secondary after augite. Pale green; low birefringence.	7 percent, poikilitic; some replaced plagioclase and K-feldspar.
	9	Augite-bearing granodiorite (close to syenodiorite).	2.74	27	2 percent, partly resorbed, with reaction rim of hornblende.	12 percent, as reaction rims on augite, with side pinacoids in parallel position.	11 percent, very dark brown; in large poikilitic plates.
	10	Olivine syenogabbro	2.83	34	16 percent, pale pink, $2V_z$=50°; $z \wedge (001)$=29°; $Z \wedge c$=26°.	----------	4 percent, Y=Z=red brown, X=pale brown to light yellowish brown.
	11	Augite-bearing granodiorite.	2.89	24	3 percent. Replaced by amphibole, with development of skeletal and granular magnetite.	12 percent, green hornblende, as reaction rims and replacement along pyroxene cleavage. Has replaced some plagioclase and was replaced by biotite.	8 percent, dark brown, has replaced some hornblende and plagioclase; in poikilitic plates as much as 6 mm.
	12	Monzonite	2.79	33	14 percent. Replaced by actinolite and biotite; magnetite closely associated.	4 percent, actinolite, as rims and networks in pyroxene locally replaced by biotite.	10 percent, irregular poikilitic plates, with strong absorption.
	13	Augite-bearing quartz monzonite.	2.75	23	6 percent, titanaugite, pink to pale green; distinct (001) parting ("malacolite"); $Z \wedge c$=42°.	3 percent, uralite	12 percent, contains schiller and skeletal magnetite.
	14	Melanocratic augite quartz monzonite.	----------	29	10 percent, colorless to pink; $2V$=50°; $r>v$, distinct. Some fresh, others altered to carbonate minerals, actinolite, biotite, chlorite, and magnetite.	6 percent, reaction rims on pyroxene; tremolite, with outer rim of greenish-brown hornblende.	11 percent, some crystals are bent and strained. Much schiller.
	15	Augite monzonite	2.68	29	11 percent, colorless to very pale green. Commonly glomerophyric. Magnetite abundant as schiller, granules, and intergrowths.	8 percent, haloes of actinolite around pyroxene.	7 percent, euhedral plates and as irregular masses replacing pyroxene. Strong pleochroism, nearly black to light yellowish brown.

of representative early mafic rocks of the batholith

Olivine	Quartz	Opaque and accessory minerals	Plagioclase	Composition of plagioclase (anorthite percent)		K-feldspar	Plagioclase ÷ K-feldspar	Average grain size, mm	Remarks
				Range	Average of core				
------	3 percent	4 percent	47 percent, moderate argillic alteration; local K-feldspar replacement blebs along cracks and rim.	33–69	60	9 percent, cryptoperthite; $2V=45°–49°$. Occurs as late interstitial masses.	5.2	2.9	Subophitic texture. Very long slender apatite; abundant calcite and interstitial spherulitic intergrowths of epidote and penninite; magnetite abundant.
Trace. Now completely altered to talc.	------	5 percent	46 percent, crudely alined, strongly zoned. Few large phenocrysts are as much as 6 mm.	13–54	51	16 percent, late interstitial filling between and partly replacing plagioclase.	2.9	1.0	Subophitic texture. Sample is from inner part of plug; outer part is mafic rich.
------	------	6 percent	19 percent, partly converted to scapolite, K-feldspar, and epidote. Extensively albitized.	43–62	55	23 percent, formed late and replaced plagioclase and scapolite.	0.8	3.2	Contains 9 percent scapolite, which is Na-rich ($N_z-N_x=0.012$). Abundant coarse apatite and sphene.
Trace. Now completely altered to talc or antigorite.	3.5 percent, irregular interstitial grains.	2 percent	49 percent, crudely alined, complexly zoned and twinned. Narrow rind of albite.	30–70	63	20 percent, poikilitic masses of cryptoperthite and microperthite as much as 8 mm across.	2.5	3.5	Mode is closely similar to norm.
------	6 percent	4 percent	57 percent, intensely veined by network of An_{50} in host of An_{70}. Well alined.	55–70	67	------	------	1.5	Abundant sphene replacing diopside. Subophitic texture.
12 percent, rounded and fractured clear grains and clusters; partly replaced by biotite.	------	5 percent	34 percent, well-alined laths as much as 50 mm long; netted with actinolite, and partly replaced by biotite and minor amounts of K-feldspar.	56–91	74	Minor blebs in plagioclase.	------	2.6	Contains some nearly colorless green-tinted mica. Mild cataclastic structure. Cut by dikelets of peridotite.
6 percent, inclusions in augite and hypersthene.	------	4 percent	27 percent, partly replaced by actinolite and biotite. Some cores extremely calcic.	61–98	74	------	------	2.6	Hypersthene encloses olivine, diallage, and augite. Coarse schiller in diallage.
------	2 percent	3 percent	37 percent, moderately well alined. Healed cataclastic structure; sericite abundant along fractures. Abundant apatite inclusions.	44–64	52	10 percent, some microperthite. Poikilitic masses as much as 12 mm; replaced plagioclase in part.	3.8	1.8	Augite probably titaniferous.
------	9 percent	2 percent	49 percent, strongly zoned partly replaced by K-feldspar.	30–49	42	15 percent, poikilitic masses as much as 15 mm; replaced plagioclase, in part.	3.3	2.5	Augite crystals have broad mantles of dark-green hornblende.
11 percent, very faint pink tint. Partly altered to chlorite.	1 percent	3 percent	47 percent	42–61	54	18 percent	2.6	------	Contains about 2 percent apatite.
------	12 percent	1 percent	45 percent, complexly zoned. Abundant inclusions of apatite and opaque minerals.	32–57	50	19 percent, poikilitic masses as much as 5 mm. Microperthite abundant, commonly of "fingerprint" texture.	2.4	1.8	K-feldspar crystals extend across contact into xenoliths. Seriate texture.
------	1 percent	5 percent	41 percent, moderately well alined. Some large masses are clusters of crystals enveloped in a single clear sheath of plagioclase.	25–60	48	25 percent, partly interstitial; mostly poikilitic.	1.6	.8	Textural relations of K-feldspar to plagioclase analogous to ophitic texture. Minor amounts of blue apatite.
------	15 percent	2 percent	37 percent, abundant inclusions in selected zones. Oscillatory zoning superimposed on normal progressive zoning.	29–68	48	25 percent, poikilitic anhedral masses as much as 5 mm.	1.5	1.4	Mafic minerals shredlike, with abundant magnetite associated. Local recrystallized mortar structure.
------	14 percent	2 percent	34 percent, most are zoned, some are highly albitized.	28–56	37	23 percent, mostly as cryptoperthite, some as microcline. Myrmekite common at contacts with plagioclase.	1.4	2.1	Mild cataclasis. Abundant coarse sphene. Quartz formed late and locally replaced biotite along cleavages. Graphic intergrowths of augite and magnetite are common.
------	5 percent	3 percent	37 percent, moderately well alined; strong normal zoning	22–52	43	29 percent, irregular anhedral and sutured grains; myrmekite common.	1.3	1.0	Magnetite abundant but restricted to inclusions in mafic crystals.

TABLE 5.—*Modal composition and petrographic features of*

Locality	Sample	Rock Name	Specific gravity	Color index (total dark minerals)	Pyroxene	Amphibole	Biotite
Kokoruda Ranch complex—Continued	16	Quartz monzonite	2.64	11	------	2 percent, shredded aggregates of greenish brown hornblende.	8 percent, streaked out in cataclastic trails; dark colored, strongly pleochroic.
	17	Monzonite	2.76	28	7 percent, colorless augite, partly converted to clusters of tremolite rods along cleavages.	12 percent, colorless, with irregularly distributed patches of pale green. Abundant schiller and dendritic to skeletal magnetite in the colorless parts.	7 percent, replacing amphibole in shredlike clusters. Absent from deuterically altered parts.
	18	Quartz monzonite	2.67	17	------	11 percent, colorless cores enveloped by green hornblende which in turn is rimmed with blue-green amphibole. Abundant magnetite in colorless parts. Sparse euhedral brown hornblende.	5 percent, strongly pleochroic poikilitic plates. Locally has replaced plagioclase and amphibole.
	19	Calcic melamonzonite	2.85	51	42 percent, euhedral and subhedral crystals; faintly pleochroic colorless to pink to very pale green; rutile as schiller. Polysynthetic twinning and exsolution lamellae (100); $Z \wedge c = 45°$.	------	6 percent, poikilitic foils as much as 5 mm.
	20	Calcic melamonzonite (No. 9, table 2).	------	50	41 percent, hypersthene (28 percent) and ferroaugite (13 percent) as much as 2.2 mm.; schiller common in both. Ferroaugite locally forms a mantle on hypersthene.	------	5 percent, irregular poikilitic flakes as much as 10 mm.
	21	Monzonite	2.61	27	14 percent, replaced along rims and cleavage by actinolite and chlorite. Distinct pleochroism pink to colorless to very pale green. $Z \wedge c = 43°$.	1 percent, pale actinolite or tremolite, mostly rimming pyroxene; also in veinlets probably of deuteric origin.	10 percent, bent and recrystallized, locally healed with quartz.
	22	Quartz monzonite (near granodiorite) (No. 8, table 2, average of modes of 8 samples).	2.82	26	11 percent	6 percent	8 percent
Inclusion in Butte Quartz Monzonite; probably a relic of the Kokoruda Ranch complex.	23	Augite quartz monzonite.	------	23	11 percent, euhedral crystals and anhedral grains in clusters; locally replaced by biotite along cleavages; colorless to pale pink.	2 percent, actinolite rimming pyroxene.	9 percent, ragged poikilitic foils as much as 35 mm across. Strongly pleochroic dark reddish brown to light yellowish brown.
Average of all modes listed above.	------	Synthetic average rock type, lies on the syenodiorite-granodiorite boundary.	2.84	33	16 percent	6 percent	7 percent

Other bodies of early mafic rocks elsewhere are correlated with the older part of the Kokoruda Ranch complex; that is, they are believed to be older than the Unionville Granodiorite. These include three small plugs of monzonite, syenodiorite, and syenogabbro in the middle-eastern and southern parts of the map area, and a possible ring dike of monzonite and syenogabbro which lies near the western border of, and is cut by, granodiorite of the Antelope Creek stock.

These early mafic rocks have thermally metamorphosed the country rocks to produce hornfels and tactite zones which are in many places hundreds of feet thick. Thermally metamorphosed xenoliths as much as 600 feet long abound locally, especially in the northern and western parts. Many of the xenoliths clearly are of hornfelsed Elkhorn Mountains Volcanics; others are unidentifiable hornfelsed shaly and sandy rocks. In some places, xenoliths of many rock types are close together, indicating considerable churning of stoped blocks.

Outcrops of the early mafic rocks are somewhat disintegrated and decomposed, except for the gabbroic types which yield sound bouldery outcrops. Fresh samples of some rock types were collected from blasted rock exposed along new roadcuts.

KOKORUDA RANCH COMPLEX

The Kokoruda Ranch complex extends from a short distance west of the map area eastward past Little Butte to the foot of the high ridge, which is the north *representative early mafic rocks of the batholith*—Continued

Olivine	Quartz	Opaque and accessory minerals	Plagioclase	Composition of plagioclase (anorthite percent)		K-feldspar	Plagioclase÷K-feldspar	Average grain size, mm	Remarks
				Range	Average of core				
	20 percent	1 percent	39 percent, strongly zoned, localized. Myrmekite abundant; moderately sericitized. Ends rounded off by cataclasis.	10–38	32	30 precent, ruptured anhedral grains and large poikilitic crystals rounded and rimmed by mortar.	1.3	1.1	Very sparse mafic and opaque minerals. Mafics fine-grained (avg 0.12 mm) and shredlike owing to intense cataclasis, which is partly healed.
	7 percent	2 percent	35 percent, mild cataclasis. Altered to albite-zoisite-epidote-sphene-calcite-sericite masses in deuterically altered bands or zones.	35–60	47	30 percent, rodlike and vermicular masses throughout plagioclase. Anhedral grains and poikilitic and interstitial masses	1.2	.8	Seriate texture. Abundant large euhedral apatite; late interstitial quartz. Saussuritized along deuterically altered joint-controlled zones.
	13 percent	1 percent	38 percent, subtly alined; complexly twinned and zoned crystals and clusters. Calcite, clay, sericite alteration in calcic inner zones.	14–47	38	32 percent, cryptoperthite and microperthite in poikilitic masses as much as 4 mm. Ruptured grains are microcline microperthite.	1.2	1.4	Seriate texture; moderate cataclasis, mostly healed by recrystallization. Blebs of K-feldspar abundant in plagioclase. Late interstitial sphene.
2 percent, sparse clusters of small anhedral crystals netted by nontronite(?).		1 percent	26 percent, randomly oriented simple well-formed laths showing strong normal zoning.	36–71	59	23 percent, large poikilitic masses of cryptoperthite and local microperthite as much as 12 mm. enclosing pyroxene, biotite, and plagioclase.	1.1	2.6	Coarse apatite. Long parallel microprisms of rutile and slender biotite formed where K-feldspar replaced pyroxene. Biotite formed at plagioclase contacts.
2 percent, highly irregular crystals and equant grains as 1.6 mm enclosed in hypersthene.		2 percent: Apatite and zircon make up about 1 percent.	26 percent, laths as much as 3 mm long.	40–72	55	24 percent, poikilitic grains as much as 10 mm; mainly orthoclase cryptoperthite but includes some microperthite.	1.1	1.6	Hypersthene, about $en_{65}fs_{35}$. $2V_x=61°$; $N\gamma=1.702$; $\gamma-\alpha=0.015$; $r>v$, weak; simple (100) twins. Ferroaugite, near augite: $2V_z=48°$; $z\wedge c=44°$; $N\gamma=1.719$; $\gamma-\alpha=0.027$; $r>v$, weak; polysynthetic (100) twin lamellae.
	6 percent	2 percent	32 percent, partly replaced by K-feldspar and quartz.	27–56	45	35 percent, cryptoperthite with irregular microperthite of "bleb" type; partly replaced by quartz; $2V_x=51–56°$, $X\wedge a$ in (010)=14°.	0.9	1.4	Seriate texture. Veinlets of deuteric(?) amphibole.
	10 percent	1 percent	42 percent	28–57	48	22 percent	1.9		
	13 percent	1 percent	36 percent, randomly oriented, complexly twinned; strong zoning with oscillatory superimposed on normal zoning.	30–58	49	28 percent, cryptoperthite and microperthite in large anhedral poikilitic grains and irregular interstitial masses intergrown with quartz.	1.3	1.3	Seriate texture. Much late interstitial quartz, partly intergrown with K-feldspar.
2 percent	7 percent	2 percent	41 percent		52	19 percent	2.1		

end of the Elkhorn Mountains (pl. 1). Thermally metamorphosed Paleozoic and Mesozoic sedimentary rocks lie to the north, Mesozoic volcanic rocks to the east, Unionville Granodiorite to the west (Knopf, 1963), and Butte Quartz Monzonite lies to the south.

Contacts of the Kokoruda Ranch complex with the Elkhorn Mountains Volcanics are steep and clearly discordant; the intrusive appears to have been emplaced into the volcanic rocks and the middle unit of the Colorado Formation along preexisting north- or north-northeast-trending faults. Along its north boundary, the complex cuts the Kootenai and Morrison Formations. West of the map area, the contact cuts down section and is close to the top of the Mission Canyon Limestone. Although the northern contact generally is concordant with the strike of the country rocks, it probably is sharply discordant with their dip, as suggested by the following observations:

1. Aeromagnetic data indicate that the intrusive contact is steep (Davis and others, 1963);
2. The country rocks dip toward the complex and steepen toward it;
3. Just west of the map area, strata locally are overturned;
4. Small intrusive bodies scattered north of the main contact just west of the map area suggest that larger masses of igneous rock lie at shallow depth north of the exposed contact; and
5. Sheared rocks and steep strike faults occur locally in country rocks along the contact.

The conformable strike of the northern contact and the country rocks may be due to stoping of large blocks along bedding planes, or it may indicate that the upper part of the complex is a sill.

The eastern edge of Knopf's map (1963), which joins the western edge of the present map north of latitude 46°30′, shows Unionville Granodiorite to be coextensive with the Kokoruda Ranch complex. A body of gabbroic rock in the complex, in the NE¼ sec. 21, T. 9 N., R. 2 W., is called the Knapp stock by Knopf (1963, p. 8), who described it as being older than Unionville Granodiorite and granogabbro adjacent to it. Samples 5, 6, 7, 8, 10, 19, and 20 (table 5) came from an area in the Kokoruda Ranch complex tha probably lies within the Knapp stock of Knopf. Thus, the early mafic rocks in the Kokoruda Ranch complex not only correlate with, but include, the early olivine-orthoclase gabbro and the Unionville Granodiorite of Knopf.

Contact relations with other batholithic rocks generally are obscure. Large blocks of these mafic rocks occur as xenoliths in the more siliceous batholithic rocks, and plugs and dikes of quartz monzonite cut the mafic rocks, proving that the Kokoruda Ranch complex is older.

Topographic expression of the complex is that of gently rolling timbered hills and flat fields, locally timbered. The rocks readily weather to grus and soil, so that exposures are fair to poor.

Rocks of the complex commonly are foliated and jointed. Sets of joints were measured at 6 localities in the complex; 4 of these are in the map area and 2 are just to the west. Of 11 individual joint trends from these localities (fig. 30), all but 3 fall within the +2-percent maxima of the contour diagram of joints of the Butte Quartz Monzonite.

Foliation locally is pronounced, but it is hard to measure because the outcrops are crumbly. Only two foliation planes were measured, one in the map area and one just west of it; both are vertical (fig. 30). The average strike of the two is N. 50° W., which is within 2° of the average of 26 foliation planes in rocks of the Butte Quartz Monzonite.

Rocks of the complex are cut by three plugs of augite-bearing quartz monzonite and by dikes of coarse- to fine-grained quartz monzonite, all probably part of the Butte Quartz Monzonite; by dikes and sheets of felsic rocks which probably are of the late stage of the batholith; and by dikes of lamprophyre, one of which is cut by aplite.

DIKE OF MONZONITE AND SYENODIORITE

A thick dike of monzonite, grading to syenodiorite, crops out in a strip 1½ miles long in secs. 30 and 31 T. 9 N., R. 1 W. The dike, averaging 500 feet thick, strikes about north, but it is slightly concave to the east, toward the Antelope Creek stock. Its dip seems vertical, but it may be steeply westward as hinted in the offset of segments by the steep fault across the S½ sec. 30. On the north, the dike pinches out near the north boundary of sec. 30. Its southern end is covered by colluvium, beneath which the dike may pinch out or be truncated by the stock. The dike, probably a segment of a ring dike, lies between an earlier basalt sheet and the middle unit of the Elkhorn Mountains Volcanics in places; it is entirely within the basalt sheet in other places. A large segment of the dike just east of the map area also lies within the basalt sheet; a smaller segment lies between the middle unit of the volcanics and the Antelope Creek stock.

The dike contains inclusions of basalt from the sheet and inclusions of volcanic rocks; it is cut by pegmatite and syenite dikes. Just east of the map area the dike clearly is cut by granodiorite of the Antelope Creek stock. The stock is correlated with the Unionville Granodiorite, for reasons given below. The relation between the ring dike and stock are comparable with that of the early gabbro and Unionville Granodiorite, with which they are correlated.

The dike contains much garnet, scapolite, and pyroxene near its margins. Tactite and tactite minerals are developed in scattered parts and at many places along the contact; one steep platelike body of tactite at least 1,000 feet long was mapped between the dike and the earlier basalt sheet near the Buzz mine, NE¼ sec. 31, T. 9 N., R. 1 W. Many large blocks of white coarse-grained pure calcite marble and other blocks of silicated marble and tactite were found on two small mine dumps in the southern part of sec. 30; they apparently were broken from a large inclusion during mining. Because the dike is in contact with noncalcareous andesitic pyroclastic rocks and basaltic intrusive rocks, the presence of these carbonate rocks implies that the monzonite magma of the dike, or the earlier basaltic magma, carried up blocks either of Paleozoic carbonate rocks from a depth calculated as at least 4,600 feet or of carbonate rocks from local beds in the volcanics. If these xenoliths are of Paleozoic rocks, they must have been carried up by magma rising through at least seven-eighths of a mile of sandstone, shale, and other sedimentary rocks after passing the highest thick carbonate beds, and the long platelike slab near the Buzz mine must have remained intact during long transport. If, on the other hand, the carbonate rock represents material derived from limestone in the Elkhorn Mountains Volcanics, it would have to have been carried up only about 2,000 feet or less, and the

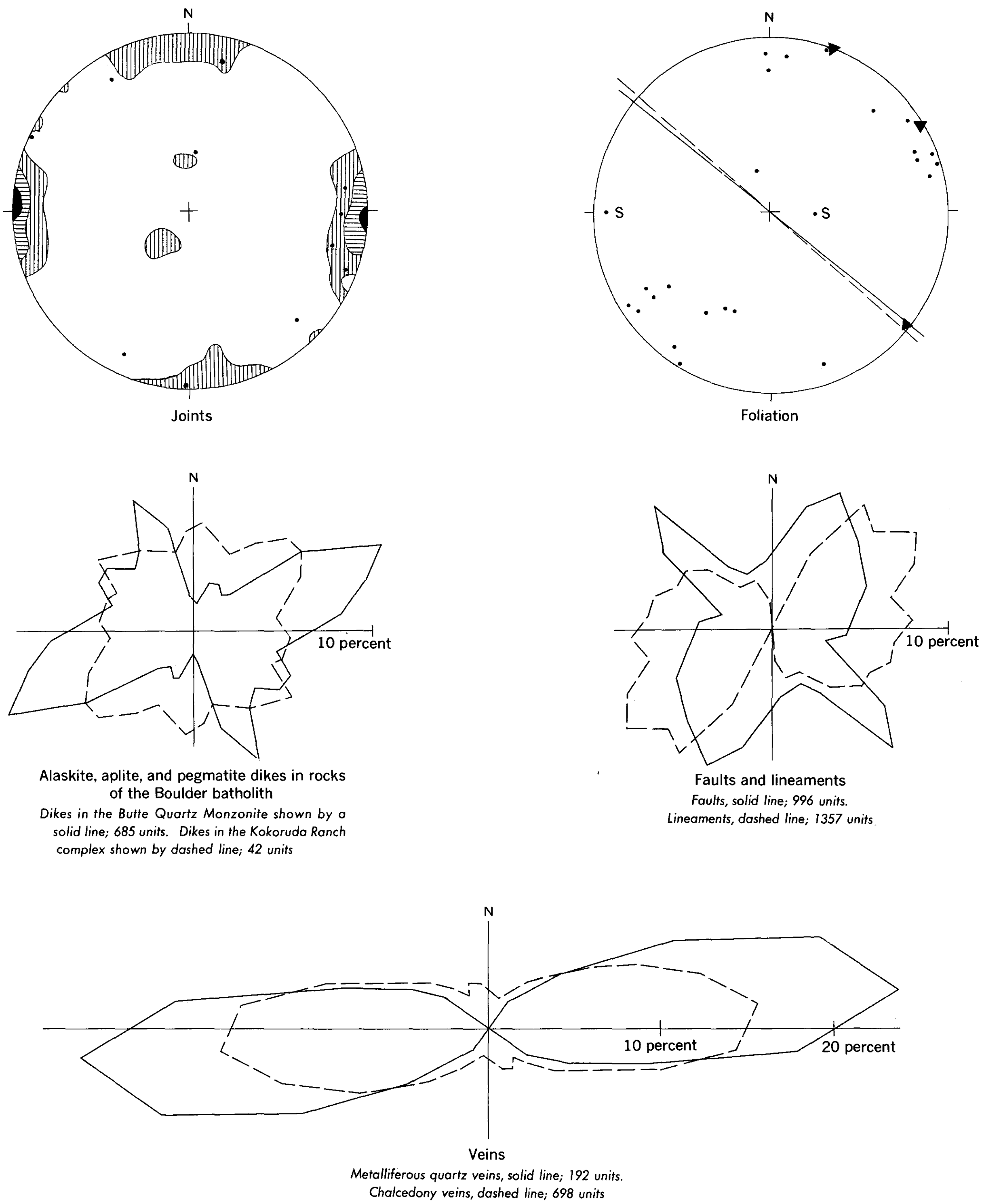


FIGURE 30.—Summary diagrams of joints, foliation, dikes, veins, faults, and lineaments.

Joint diagram.—Contour diagram of poles of 283 joints in Butte Quartz Monzonite and point diagram of poles of 11 joints in the Kokoruda Ranch complex. Contours 2–6–10 (11) percent. Equal area projection of lower hemisphere.

Foliation diagram—Point diagram of poles of 26 foliation planes in Butte Quartz Monzonite (dots) and 2 in the Kokoruda Ranch complex (triangles). Schliere marked by letter S. Average strike of foliation shown by solid line for Butte Quartz Monzonite and dashed line for the Kokoruda Ranch complex.

Rosettes.—Each rosette is a statistical summary showing relative abundance of trends of all high-angle planar structures of a given type and is weighted according to length. Construction explained on page 75.

steep plate of carbonate rock near the Buzz mine may only represent part of a bed that has been tilted upward but not dragged far by the intrusive masses.

Large lenses of marble are interstratified with volcanics in the southern Elkhorn Mountains (Knopf, 1913, p. 130). Klepper and others (1957, p. 35) thought it most likely that these lenses represent calcareous tufa deposited by thermal springs during the period of volcanism. There, as here, intense recrystallization has obliterated all primary structure and texture that might have given clues to the origin of the rock.

SMALL PLUGS

A small plug of monzonite is located below Montgomery Springs on upper Spokane Creek (pls. 1, 2). The exposed dimensions are about 700 by 200 feet; part of the plug is covered by surficial debris. Mafic monzonite is present along the northern border.

Medium-grained syenodiorite with fine-grained mafic-rich selvage occurs as a small plug on the ridge crest north of Staubach Creek. This plug is intrusive into tuff breccia and abuts against welded tuff on the west.

A small elongate body of monzonite crops out in the NE cor. sec. 34, T. 9 N., R. 2 W., southeast of Little Butte, near the Kokoruda Ranch complex. This plug lies in metamorphosed welded tuff of the middle unit of the Elkhorn Mountains Volcanics.

PETROGRAPHY AND CHEMICAL COMPOSITION

Varieties of the early mafic rocks were not mapped separately, but marked heterogeneity of the group is shown by the petrographic data for selected samples in table 5. In general, the early mafic rocks are dark to medium gray, and have a color index ranging from 11 to 73. Specific gravity of the suite ranges from 2.61 to 3.23.

Composition of the plagioclase ranges from An_{10} to An_{98}; in the 20 varieties that contain two feldspars, the ratio of plagioclase to K-feldspar ranges from 0.8 to 5.2. Pyroxene is a principal constituent in 19 samples and a minor constituent in 2 others. Amphibole is present in 20 varieties, mostly as reaction rims around and replacement veinlets in pyroxene. In most samples the pyroxene equals or exceeds in volume the sum of amphibole and biotite.

Biotite is present in 21 samples, typically in very irregular and ragged foils, half an inch or more across, which enclose many other minerals. Textural relations strongly suggest that these irregular crystals formed principally by replacement of other minerals during a late magmatic or deuteric stage. Some of the largest foils of biotite, nearly 1½ inches across, are in the mafic rocks which now occur as large inclusions in the Butte Quartz Monzonite, and it is probable that the biotite there grew partly after engulfment.

Olivine is a principal constituent in three samples, where it ranges from 6 to 12 percent; it occurs as a few percent or less in four others. Quartz occurs in 17 of the samples and ranges from 1 to 20 percent. K-feldspar, mostly as poikilitic masses of cryptoperthite and microperthite, occurs in all but two samples and ranges from 9 to 35 percent.

An attempt was made to achieve a sample representative of the bulk composition of the Kokoruda Ranch complex. This was done by collecting and mixing in equal parts eight separate samples which were estimated to be representative of roughly equal parts of the whole complex. Because the rock types were not mapped, the selection of the samples was based on overall impressions of rock distribution as judged in the field, largely by texture and color. The sample may be biased in favor of rocks whose texture, composition, structure, or some other factors made them more resistant to decomposition and disintegration. At best, the sample is an approximation of the bulk composition of the complex. Its composition is quartz monzonite, near granodiorite (sample 8, table 2).

A single sample of darker heavier rock of the complex, probably from the Knapp stock, is calcic melamonzonite near syenogabbro (sample 9, table 2), and a sample of the dike 1⅛ miles east of the map area is syenodiorite (sample 10, table 2). The modes and other petrographic data for the analyzed and other representative early mafic rocks are given in table 5. In addition, the proportions of modal quartz, K-feldspar, and plagioclase and of normative quartz, orthoclase, and plagioclase in those rocks are shown on plate 3, figure 2, along with rocks from the probable ring dike just east of the map area.

The texture of typical monzonite is illustrated in figure 31.

GRANODIORITE OF THE ANTELOPE CREEK STOCK

Rocks of the intermediate stage of the batholith are exposed in the Antelope Creek stock which lies partly in the map area and partly in the Townsend and Canyon Ferry quadrangles. The stock, about 2½ miles across, consists of medium-grained granodiorite with a fine-grained contact facies and local medium- and coarse-grained mafic-rich facies. It is cut by dikes of fine-grained quartz monozonite, granite, aplite, alaskite, and pegmatite, correlated with the batholith, and by younger dikes of porphyritic quartz latite.

Because of their close similarity in mineralogy, composition, texture, and age relations, these rocks are correlated with the Unionville Granodiorite of Knopf (1957), just west of the map area.

FIGURE 31—Poikilitic K-feldspar in monzonite, showing textural relations of included minerals. All K-feldspar shown is part of a larger single grain with carlsbad twinning. Sketched with nicols crossed. K-feldspar, clear; plagioclase, striped, showing albite twin lamellae; ferroaugite, shaded lightly, middle left part of figure; biotite, shaded heavily, lower center and lower right; olivine, stippled, lower center. Alteration along cracks shown by stippled streaks.

PETROGRAPHY AND CHEMICAL COMPOSITION

A composite sample representing 11 separate samples from all parts of the stock was analyzed chemically, as was a sample from just east of the map area (samples 11 and 12, table 2). Both are granodiorite, as shown by the modes of table 6.

TABLE 6.—*Modal composition of three representative samples of grandiorite of the Antelope Creek stock*

[Norms of the analyzed samples (samples 11 and 12, table 2) are shown for comparison]

	Mode (volume percent)			Norm (weight percent)	
	A	B	11	11	12
Quartz	16	15	10	16	19
K-feldspar	14	16	18	18	19
Plagioclase	46	47	56	50	47
Biotite	11	8	6	------	------
Amphibole	10	11	8	------	------
Pyroxene	1	2	------	------	------
Color index	22	21	14	10½	10
Opaque and accessory minerals	2	1	2	5½	5
Range in plagioclase composition ......percent An	31–57	30–55	29–45	------	------
Composition of plagioclase ......do	[1] 48	[1] 45	[1] 40	43	41
Plagioclase / K-feldspar	3.3	2.9	3.1	2.8	2.5

[1] Average composition of plagioclase cores.

The proportions of modal and normative quartz and feldspars and the range in composition of granodiorite of the Antelope Creek stock are shown on plate 3, figure 3. Norms calculated from chemical analyses of the Unionville Granodiorite of Knopf (1957) are shown for comparison.

Analyzed sample 11 (table 2) is typical of the main part of the stock. It is a medium-gray to medium-light-gray seriate granodiorite having an average grain size of about 2 mm. Small partly digested inclusions, probably of the volcanic rocks, are scattered throughout. The approximate mineral composition, in percent, is: andesine, 56; K-feldspar, 18; quartz, 10; hornblende, 9½; biotite, 6; accessory minerals, ½.

Andesine occurs in subhedral tablets of carlsbad-albite twins as much as 2 mm long. Strong progressive zoning ranges from cores of about An_{45} to rims of about An_{25}, with weak oscillatory zoning superimposed. Films and sparse networks of albite-oligoclase are present in most grains. Hornblende, pleochroic from light green, yellowish green, and medium green to light brown, is in euhedral and subhedral prisms as much as 1.5 mm long. These and the plagioclase crystals are randomly oriented in an entangled fabric and are engulfed by interlocked anhedral grains of cryptoperthite, microperthite, quartz, and myrmekite, and subhedral plates of biotite. Accessory minerals include sericite, apatite, sphene, zircon, and opaque minerals.

BUTTE QUARTZ MONZONITE

Quartz monzonite and granodiorite of many textural varieties make up the major part of the batholith. These rocks in the mapped area are coextensive with the Clancy Granodiorite, named by Knopf in 1957. Regional studies (unpub. data by M. R. Klepper, H. W. Smedes, and R. I. Tilling) indicate that the quartz monzonite and granodiorite are similar to, and also probably are coextensive with, the Butte Quartz Monzonite, named by Weed in 1899. Although it is debatable which is the more suitable name, these rocks are here called the Butte Quartz Monzonite, because it has priority and to conform with usage on recent maps and reports in adjoining areas to the south and west (Becraft and others, 1963; Becraft and Pinckney, 1961; Pinckney and Becraft, 1961; and Smedes and others, 1962).

Quartz monzonite appears to be the main rock type; granodiorite is subordinate. However, the boundary between the two rock types is artificial, based on proportions of feldspars, and many of the rocks lie on or near the boundary.

In the map area, Butte Quartz Monzonite is in contact with the Elkhorn Mountains Volcanics to the east and the Kokoruda Ranch complex to the north. Butte Quartz Monzonite is cut by felsic dikes and sheets of the late stage of the batholith and by still younger dikes of quartz latite and rhyolite. Xenoliths are scattered throughout, though only locally abundant, large, or conspicuous.

A prong of the batholith, the Jackson Creek lobe, which is connected to the main mass by a narrow link near Crystal Creek (pls. 1, 2), extends southward across the headwaters of Jackson Creek. Other bodies of quartz monzonite, probably parts of the Jackson Creek lobe, lie north of that lobe in the W½ sec. 35, T. 9 N., R. 2 W., and southwest of the lobe along the East Fork of McClellan Creek in the S½ NW¼ sec. 14, T. 8 N., R. 2 W. Large blocks of quartz monzonite in the morainal debris above Casey Meadows prove that quartz monzonite lies beneath the moraine at the head of the East Fork.

Pyroxene hornfels and metamorphosed welded tuff containing minute single and clustered prisms of pale-blue dumortierite and numerous small unmapped aplite dikes extend in a narrow belt southward from the southern edge of the map area west of Moose Creek. The presence of such rocks suggests that a dikelike plutonic mass lies at slight depth in that area. Because aplite and other felsic dikes occur abundantly only in association with the Butte Quartz Monzonite elsewhere, their abundance here suggests that the postulated shallow plutonic mass is Butte Quartz Monzonite.

Primary structures are very faint in most parts of the mass, the bulk of which is structurally homogeneous. Flow structure is marked by steep northwest-striking foliation and by lineation which plunges vertically and steeply northwest. The contact against volcanic rocks is very irregular in the northern part, but it is relatively regular and steep in the southern part where the eastern edge of the batholith is inferred to have been controlled by a major postvolcanic fault of north-northeast trend.

Thermal metamorphism is widespread in the north but not in the south. Batholith rocks commonly are fine grained at their borders in the north but not in the south.

In places, quartz monzonite is brecciated and healed by quartz monzonite of finer grain size, lighter color, and more felsic composition; in other places the relations are reverse. Some coarse-grained rocks contain slabs of fine-grained leucocratic quartz monzonite. Other rocks are crudely layered, having alternating layers blended but of different grain size and with different proportions of mafic minerals; the layers have contradictory age relations.

The subtlety and diffuseness of nearly all the contacts among different textural types of Butte Quartz Monzonite and the seemingly erratic distribution and wide textural range of rocks over short distances, coupled with the narrow range in composition, point to virtual contemporaneity and to a single stage of intrusion.

In mapping, the rocks were divided according to grain size and color, as was done in the Jefferson City quadrangle to the west (Becraft, 1955, p. 1642; Becraft and others, 1963, pl. 1). Rocks are thus divided into types, such as coarse-grained and light, medium-grained and dark. Additional subdivisions, shown by suffixes, are based on the presence of conspicuous phenocrysts of K–feldspar, or the presence of an aplitic groundmass, lacking in mafic minerals. Examples of such rocks are medium-grained, light, and porphyritic; fine-grained, light, with aplitic groundmass.

In general, rocks described as light colored have an overall value on the Rock-Color Chart of N 6 or higher, and dark-colored rocks N 5 or lower, most commonly N 4. Average grain size is as follows: fine-grained rocks, less than 1 mm; medium-grained rocks, 1–2 mm; and coarse-grained rocks more than 2 mm, though rarely more than 5.

The bulk of the Jackson Creek lobe is medium-grained light-colored quartz monzonite. The other principal areas of medium-grained rocks are along the batholith margin in the Crystal Creek and Jackson Creek area in the northeast, south of the fault which lies northeast of Lava Mountain, in the lower Dutchman Creek area in the southwestern part, and in the high wilderness area in the upper reaches of Dutchman Creek.

Fine-grained rocks occur as a narrow contact facies in many places in the northeastern part of the batholith and as irregular bodies and dikes that are especially common from south of Lava Mountain to north of Maupin Creek.

PETROGRAPHY AND CHEMICAL COMPOSITION

The bulk of the rocks of the Butte Quartz Monzonite in the map area are coarse grained. These rocks are seriate, light colored, and composed of gray to white glassy plagioclase tablets; black biotite plates and clusters; black hornblende prisms and clusters; irregular clear light-gray to colorless quartz grains; and irregular grains and interstitial masses of K–feldspar ranging from white to various shades of pink and pinkish gray (fig. 32).

Coarse-grained rocks are gradational from porphyritic to nonporphyritic. Porphyritic rocks have large phenocrysts of K-feldspar, commonly ½–1 inch long. Some phenocrysts are conspicuous euhedral to sub-

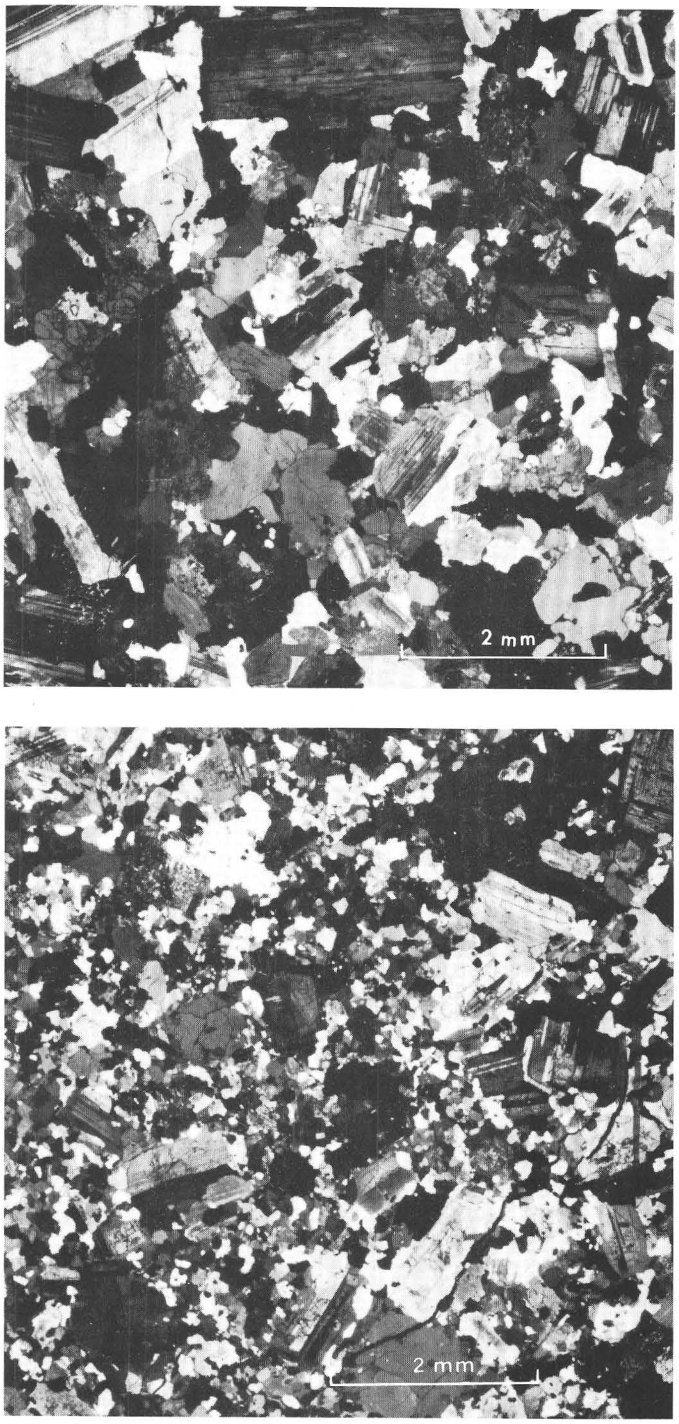


FIGURE 32.—Quartz monzonite. Upper, Coarse-grained seriate Butte Quartz Monzonite. Crossed nicols. Lower, Fine-grained Butte Quartz Monzonite with aplitic groundmass. Crossed nicols.

hedral tablets of elongate pinacoidal habit (001), with minutely crenulated edges and sparse small inclusions. Others are mostly inconspicuous anhedral highly irregular poikilitic grains in which included minerals commonly make up more than half of the total volume. These poikilitic anhedra extend through as much as 1 cubic inch, and can be recognized by reflections from their cleavage planes on fresh surfaces.

Both types of phenocrysts formed late, largely by replacement of other minerals. In many specimens, single large phenocrysts straddle the contact with xenoliths, and also are scattered throughout xenoliths as porphyroblasts. These crystals, all of which formed virtually in the same way at the same time, point out the inadequacy of current terminology, for in the batholithic rocks they are phenocrysts and in the xenoliths, porphyroblasts.

Both the poikilitic anhedral and the euhedral types of phenocrysts are present in some rocks, and a few scattered euhedral phenocrysts can be found in almost any outcrop. Those rocks with an average of at least 10 conspicuous phenocrysts per square foot of exposed rock were mapped as porphyritic. Locally, the rocks are rich in K-feldspar, and phenocrysts of K-feldspar are as abundant as 35 per square foot.

Medium-grained rocks are dominantly light colored, locally dark, and are characterized by shredlike clusters of mafic minerals.

Some rocks mapped as medium grained are even grained and of uniform texture, others are seriate. In places, both types contain conspicuous euhedral phenocrysts of K-feldspar or, less commonly, anhedral poikilitic phenocrysts. As in the coarse-grained phases, only those medium-grained rocks with an average of at least 10 conspicuous phenocrysts per square foot were mapped as porphyritic. Gradations from porphyritic to nonporphyritic are less prevalent in the medium-grained than in the coarse-grained rocks.

The dark rocks commonly have many small mafic-rich xenoliths and give the impression that they have been contaminated by xenolithic matter. The proportions of mafic minerals range widely in these rocks.

Fine-grained rocks have a more uniform grain size than the medium- and coarse-grained rocks, are equigranular to aplitic, and porphyritic. In some fine-grained rocks the phenocrysts are of euhedral K-feldspar, but more commonly they are of plagioclase, mafic minerals, quartz, or a combination of these minerals. Biotite is more abundant than hornblende.

Some bodies of fine-grained rocks are miniatures of the coarser grained rocks, whereas others have medium-grained crystals set in an aplitic groundmass (fig. 32). Many of these rocks with aplitic groundmass are associated with myriad small dikes of alaskite and related felsic rocks. The texture, composition, and field relations of these quartz monzonites strongly suggest that they are hybrid.

In places, metamorphosed rhyolite welded tuff of the Elkhorn Mountains Volcanics is in contact with fine-grained quartz monzonite of the batholith. These fine-grained rocks grade outward into coarse-grained Butte Quartz Monzonite. In these places the metamorphosed volcanics are cut by networks of aplitic veinlets, and many of the contacts are blended by recrystallization and local metasomatic alteration of the volcanics.

The chemical and normative composition of two samples of Butte Quartz Monzonite are given in table 2 (Nos. 13, 14). Modes of these and 17 other representative samples are given in table 7. The proportions of modal and normative quartz and feldspars and the range in composition of Butte Quartz Monzonite are shown on plate 3, figure 4. Most of the rocks are quartz monzonite, despite the wide variety of textures. The modes of table 7 show that the light-colored fine-grained rocks are richer in quartz plus K-feldspar but lower in plagioclase than the coarse-grained rocks; the modes further support the supposed hybrid nature of many of the fine-grained rocks. They also show that there is no essential difference in composition between the porphyritic and nonporphyritic coarse-grained rocks.

Coarse- and medium-grained Butte Quartz Monzonite has typical monzonitic texture, in which euhedral to subhedral plagioclase crystals are partly enclosed by irregular grains of K-feldspar and quartz, as shown in figure 32. K-feldspar also occurs in euhedral or anhedral poikilitic phenocrysts, described above. The texture is seriate, but plagioclase generally is not present in the smaller grain sizes. Plagioclase and the larger K-feldspar crystals tend to cluster, as do the smaller K-feldspar and quartz grains.

The proportions of biotite and hornblende vary erratically. The total amount of these minerals is rather constant over wide areas, but in distances of a few hundred feet some rocks grade from having nearly all biotite to having nearly all hornblende. These relations suggest that the changing proportions of these two minerals may be a response to local differences in water-vapor pressure during crystallization.

PLAGIOLASE

Most plagioclase is in zoned crystals. The cores of these crystals make up 60–85 percent of their total bulk, are of euhedral to subhedral tabular (010) to stout prismatic (001) habit, and are enveloped in irregular albitic rims.

The composition of the cores ranges from an average of An_{40} in the center to An_{20} near the rims. The rims range from about An_{15} to nearly pure albite. The cores show normal zoning, and some crystals also have weak oscillatory zoning. The rims generally are not conspicuously zoned. The change from core to rim is abrupt, or gradational over a very narrow zone.

Some plagioclase crystals were broken before the albitic rim grew, and the shatter zones have been penetrated and healed by rim plagioclase. In many places much of the core is replaced by albite and sodic oligoclase; crystals cut normal to the cleavages exhibit grating texture and, locally, chessboard texture, owing to this replacement.

Much myrmekite is scattered along contacts between the sodic plagioclase rims and adjoining K-feldspar crystals. The textures suggest that in some rocks the two minerals crystallized together; in other rocks K-feldspar crystallized later, veining and replacing both core and rim plagioclase; and in other rocks sodic plagioclase crystallized later, veining and replacing some of the K-feldspar (fig. 33*A*). The same relations hold between quartz and K-feldspar, between sphene and K-feldspar, and, by extension, are inferred to have existed among quartz, sphene, and sodic plagioclase.

In some fine-grained quartz monzonite the plagioclase phenocrysts have crenulated and poikilitic margins (fig. 33*B*).

Locally, calcite, epidote group minerals, sericite, clay minerals, and, rarely, rutile replace a little of the central part of plagioclase crystals. The plagioclase cores are altered more than are neighboring crystals of K-feldspar, and the sodic rim generally is unaltered.

K-FELDSPAR

K-feldspar occurs as large optically continuous masses which enclose and replace plagioclase and other minerals, as large euhedral to subhedral stocky poikilitic phenocrysts with crenulated margins, as unevenly distributed irregular granules, as micrographic intergrowths, and as deuteric veinlets. It also occurs locally in scattered blebs, with haloes of sodic plagioclase, enclosed in sodic and intermediate plagioclase; the blebs may be antiperthite.

The masses of K-feldspar appear to have crystallized late and largely in open spaces, for they mold around crystal faces of other minerals; in part they, and some of the other K-feldspar grains, may be the result of replacement.

Some feldspar occurs as clear apparently homogeneous grains having local anorthoclaselike lamellae so closely spaced that they are barely visible at high magnification. These crystals are judged to be orthoclase cryptoperthite. X-ray analyses by D. B. Stewart (written commun., 1956) confirm this identification. Other grains and parts of grains that exhibit grid

TABLE 7.—*Modes of 19 representative samples of Butte Quartz Monzonite*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Textural type [1]	cl	cl	cl	cl	cl	[2] clp	clp	clp	clp	clp	[3] ml	ml[1]	ml	mlp	mlp	mlp	fl	fl	fl
Quartz	21	22	15	35	21	27	21	17	27	25	14	16	16	16	16	16	25	27	32
K-feldspar	22	22	27	24	27	14	26	24	30	33	24	24	29	24	26	31	33	32	30
Plagioclase	44	44	41	32	33	41	45	37	35	34	52	43	38	45	46	44	35	32	27
Biotite	8	½	8	8	7	13	4	11	5	6	1	7	9	1	2	2	5	6	8
Amphibole	4½	4	6	0	11	3	0	9	2	2	7	1	6	10	7	5	2	2	2
Pyroxene	0	0	0	0	0	0	0	0	0	0	0	7	1	0	0	0	0	0	0
Color index	12½	4½	14	8	18	16	4	20	7	8	8	15	16	11	9	7	7	8	10
Opaque and accessory minerals	½	½	3	1	1	2	4	2	1	0	2	2	1	4	3	2	0	1	1
Range in anorthite composition percent	12–44	11–44	24–49	20–54	23–49	---------	12–54	21–41	21–45	14–53	37–40	19–46	23–46	21–38	20–46	28–47	24–36	20–54	31–62
Average anorthite composition of core parts. do	41	40	41	42	39	---------	45	35	38	35	40	33	42	32	38	41	29	43	50
Plagioclase / K-feldspar	2.0	2.0	1.5	1.3	1.2	2.9	1.7	1.5	1.2	1.0	2.2	1.8	1.3	1.9	1.8	1.4	1.2	1.0	0.9

[1] Described in explanation of geologic map, pl. 1.

[2] Sample 13, table 2.

[3] Sample 14, table 2.

twinning are considered to be microcline. Still other grains and parts of grains are microperthite, generally of either the vein or the patch type. In many rocks, cataclasis appears to have controlled the development and localization of microcline and of exsolved sodic plagioclase. Unpublished chemical analyses of K-feldspar from Butte Quartz Monzonite outside the map area indicate a normative composition of Or_{75} to about Or_{83} (written commun., R. W. Chapman, 1956; R. I. Tilling, 1963).

Many grains have a wavy or moiré appearance, owing to irregular extinction and to the irregular distribution of the subtle lamellae. Sodic plagioclase in microperthite makes up from 15 to 40 percent of the total volume of the grain.

Twinning is common in K-feldspar grains and is nearly universal in the phenocrysts. Carlsbad twins are the most abundant, and the crystals have a stout prismatic (001) or pinacoidal (010) habit. Manebach twins are common and locally outnumber the carlsbad twins. Manebach twins are characterized by a tabular (100) habit, elongated along the *a* axis. An estimate of the frequency of occurrence of different twinning laws is 85 percent carlsbad, 13 precent manebach, and 2 percent baveno. No other twin laws were detected.

K-feldspar forms veinlets that are crystallographically continuous with some of the larger grains of K-feldspar (fig. 34). These veinlets cut grains of K-feldspar, quartz, plagioclase, biotite, and hornblende. Epidote, albite, chlorite, actinolite, allanite, sphene, calcite, sericite, iron oxides, and sparse pyrite occur in some of these veinlets along with the K-feldspar. These veinlets formed late in the cooling history, probably during the deuteric stage.

QUARTZ

Quartz is abundant but rarely as phenocrysts. The most common forms are groundmass granules and extensive irregular interstitial masses. Quartz locally occurs as round grains, commonly with broad rims of K-feldspar in graphic intergrowth. In fine-grained rocks, graphic intergrowths with K-feldspar are common, and some of these rocks are granophyre.

The quartz exhibits evidence of strain, such as undulose extinction and hazy to sharp blocklike fracture

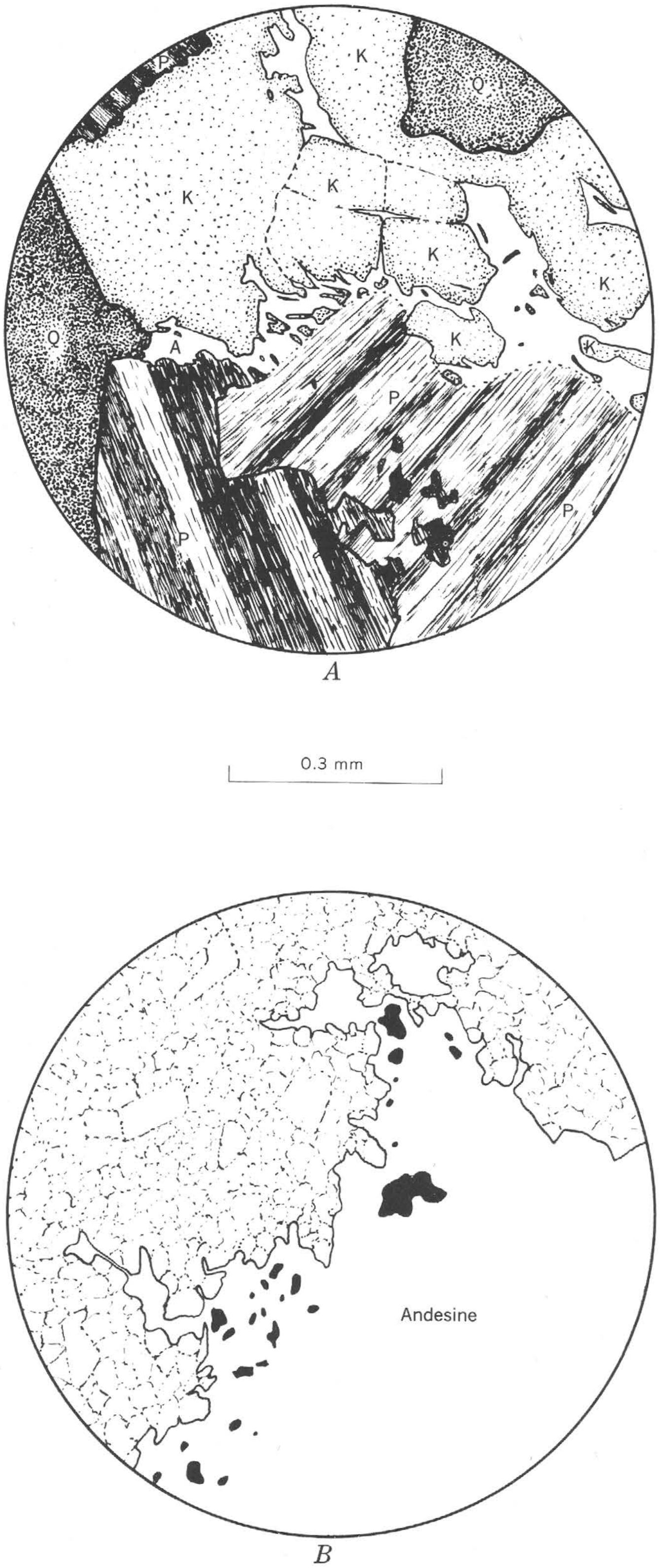


FIGURE 33.—Camera lucida drawings of feldspar crystals in quartz monzonite. Crossed nicols. *A*, Albite (about An_5) replacing andesine and K-feldspar in quartz monzonite. Albite (A) is white, andesine (P) is dark gray and shows albite twin lamellae, K-feldspar (K) is lightly stippled, and quartz (Q) is densely stippled. Fracture control of replacement is well shown in the K-feldspar. *B*, Crenulated and poikilitic margin on andesine phenocryst in fine-grained porphyritic quartz monzonite. Texture of groundmass is generalized. Inclusions of groundmass crystals in phenocryst are shown black.

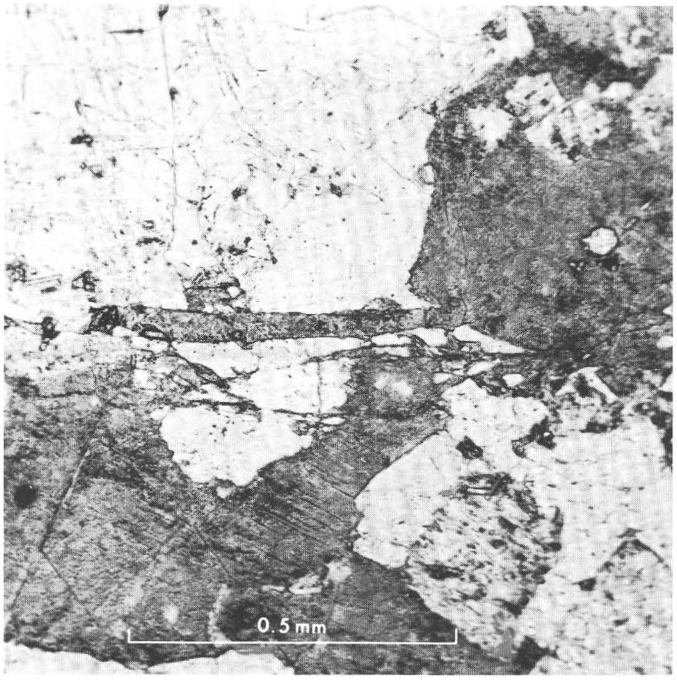


FIGURE 34.—Veinlets of K-feldspar in crystallographic continuity with phenocryst of K-feldspar, cutting K-feldspar and plagioclase. K-feldspar is dark gray, plagioclase light gray. Plane polarized light.

patterns in which each block extinguishes in a slightly different position. This blocky fracture may be due, at least in part, to grinding during preparation of the thin section. Mortar structure appears only in a few rocks that have a sheeted shear structure, which probably is due to deformation after the rock was consolidated. Extremely narrow barely visible lamellae that were observed in quartz grains in some rocks are interpreted as deformation lamellae.

Quartz occurs as inclusions in plagioclase, hornblende, and K-feldspar, and sparsely in biotite. Quartz also occurs in graphic intergrowths with K-feldspar and as myrmekite.

BIOTITE

Biotite occurs in euhedral books; euhedral to anhedral plates; irregular clusters of shreds of biotite, actinolite, and chlorite; and along cleavages of hornblende. In fine-grained rocks, biotite occurs as scattered small plates and not as phenocrysts. In coarse- and medium-grained rocks, biotite forms shiny black euhedral crystals.

Chlorite, ilmenite, magnetite, rutile, sphene, leucoxene, K-feldspar, epidote, allanite, and calcite lie along biotite cleavages and therefore are probably formed by replacement of biotite. Some biotite crystals contain fine acicular rutile crystals in geometrical patterns. Biotite is most commonly colored with $Z = Y$, moderate brown to moderate yellow; X, light shades of yellowish orange, or nearly colorless. Some biotite is green.

In many chloritized biotite crystals, leucoxene, sphene, ilmenite, and rutile have also formed as products. This implies relatively high titanium content, which is in keeping with the generally high sphene content of the rocks, and with the 3.51–4.51 percent TiO_2 in 6 chemically analyzed biotites from equivalent rocks of the batholith outside the map area (R. W. Chapman, written commun., 1956).

Some biotite formed from hornblende, appearing as mantles on hornblende crystals, along cleavage and other cracks, and as nearly complete pseudomorphs. Locally, chlorite pseudomorphs after biotite are associated with K-feldspar grains, suggesting that the feldspar was a reaction product. Although potassium must have been released during chloritization, as pointed out by Chayes (1955), apparently it migrated away from the reaction sites in most rocks.

AMPHIBOLE

Some amphibole is in euhedral to subhedral hornblende crystals, but most of it is in irregular masses of hornblende surrounded and pervaded by shredlike matted aggregates and scales of actinolite with biotite, opaque minerals, chlorite, epidote, sphene, rutile, and allanite. Actinolite is more abundant than hornblende in these aggregates; locally it is the only amphibole.

Hornblende crystals typically are poikilitic, enclosing small grains of quartz, plagioclase, opaque minerals, zircon, and apatite. Actinolite crystals and mantles on hornblende crystals commonly contain the same inclusions and also titanium minerals, epidote, allanite, calcite, and chlorite. As in biotite, titanium minerals among the breakdown products imply a relatively high titanium content. Five analyzed hornblendes from equivalent rocks of the batholith outside the map area contain from 1.05 to 1.31 percent TiO_2 and average 1.21 percent (R. W. Chapman, written commun., 1956).

Pleochroic colors of hornblende range from dark to light shades of brown and yellowish orange. Actinolite ranges from light shades of grayish and yellowish green and blue green to colorless; some is noticeably blue.

Actinolite and hornblende are completely gradational. The passage from hornblende to actinolite is marked by color changes (dark to light, brown to green, blue, or colorless), by a decrease in extinction angle $Z \wedge c$, and by a decrease of indices of refraction and of birefringence.

PYROXENE

A few granules of augite were observed in the core of a cluster of actinolite, biotite, chlorite, and other minerals in one of 90 thin sections. Pyroxene is comparably sparse in the Butte Quartz Monzonite and related rocks west of the map area (Becraft and others, 1963, p. 8).

ACCESSORY MINERALS

The more widely distributed and abundant accessory minerals are magnetite, ilmenite, apatite, zircon, and sphene. Other minerals of more local occurrence or of minor abundance are epidote, zoisite, clinozoisite, allanite, tourmaline, calcite, leucoxene, rutile, xenotime, and monazite.

Magnetite, ilmenite, apatite, and zircon apparently formed early and occur as euhedral to subhedral grains enclosed in hornblende, biotite, and feldspar. Magnetite also formed during the late magmatic or deuteric alteration of mafic minerals.

Sphene appears to have crystallized late. Locally it is in euhedral acute double wedge crystals, but more typically it fills irregular interstices between crystals of other minerals and in cleavage fractures in K-feldspar. A representative example of late sphene that has cemented fractured K-feldspar grains and probably has replaced much of the feldspar is shown in figure 35. Some sphene crystals are twinned (100); some are pleochroic in shades of pink, yellow, and brownish red.

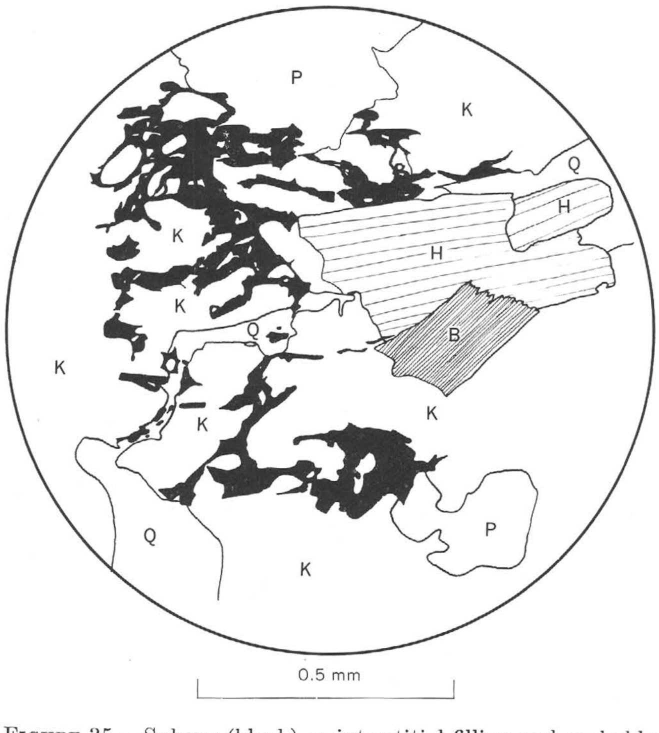


FIGURE 35.—Sphene (black) as interstitial filling and probably as replacement of K-feldspar along shattered zones. All the sphene is in optical continuity and probably is part of a single poikilitic crystal. A little perthitic albite is adjacent to some parts of the sphene. K-feldspar, K; plagioclase, P; quartz, Q; biotite, B; hornblende, H.

Pleochroic haloes occur around most zircon inclusions in biotite and around some of those in hornblende. Allanite occurs locally, generally as oriented overgrowths which mantle epidote crystals.

PRIMARY STRUCTURES

FOLIATION AND LINEATION

Foliation and lineation in the batholith are sparse, weak, and difficult to detect.

Homogeneous planar structure, as contrasted with planar structure marked by compositional layering, is developed alone or with a subtle lineation. This homogeneous planar structure and the lineation both are shown most conspicuously by alinement of mafic minerals and less well by feldspars. In a few places, K-feldspar phenocrysts are either more abundant, or they are exclusively alined along ill-defined steep straight zones. This selective distribution may have been controlled in some way by early fractures that formed during consolidation of the magma. These relations are in agreement with the conclusion that the K-feldspar phenocrysts formed late and that their faint planar structure is due principally to the inherited planar pattern of plagioclase and mafic minerals.

A point diagram (fig. 30) of the poles of 26 foliation planes measured in the Butte Quartz Monzonite in the mapped area shows that only two planes have trends outside the northwest quadrant and that the average strike direction is N. 48° W. The dip of 20 of the measured planes is 70° or steeper; 12 of these have a south or west component of dip, and 8 have a north or east component.

Lineation generally rakes 90°, but at two places lineation plunges northward at about 80° and in one place northward about 30°.

The homogeneous planar structures are believed to represent flow layers. Foliation and lineation indicate that the magma moved vertically along northwest-striking flow planes, as Grout and Balk (1934, p. 885, 888, 889) noted. However, the degree of development of foliation is proportional to the degree of late-consolidation cataclasis, indicating that the movement was of largely consolidated crystal mush. From this, it appears that the foliation records only late-consolidation movement of the batholith and does not necessarily offer any clue to primary intrusive tectonics, as Grout and Balk assumed.

JOINTS

Fractures in Butte Quartz Monzonite into which aplite, alaskite, and pegmatite were injected are interpreted as primary intrusion and cooling joints. The trends of these filled joints make a diffuse frequency diagram[3] (fig. 30) with maxima centered approximately at N. 55° E., N. 55° W., N. 80° W., and N. 5° E., listed in order of decreasing magnitude. The dip of most filled joints could not be determined.

Barren joints or joints containing only films of clay are abundant and commonly are well exposed; the strikes of most fall into one or two prominent maxima (fig. 30). These joints, as discussed below, probably are not related to the emplacement or cooling of the batholith, but they formed later as a result of regional stresses.

COMPOSITIONAL LAYERING

Locally the Butte Quartz Monzonite has highly foliated zones as much as 4 feet thick, formed by alternating thin layers rich in mafic minerals, and thick layers rich in felsic minerals. Some of the felsic layers have a heterogeneous texture similar to that of alaskite or pegmatite rather than that of typical quartz monzonite. These layered strongly foliated zones grade into apparently structureless quartz monzonite.

Near the contacts of some dikes of aplite, alaskite, and pegmatite the quartz monzonite host rock consists of felsic-rich and mafic-rich layers. The dike contacts are sharply to hazily defined, and a foot or so away from the dike the layered rock gives way to foliated and then to structureless quartz monzonite (fig. 36).

In some places where several dikes of aplite, alaskite, and pegmatite are close together, the dikes have internal layering parallel with their walls, the screens of quartz monzonite are layered and foliated, and contacts between dikes and country rock are hazy. Some zones of foliated or layered quartz monzonite contain scattered discontinuous bands or thin pods of aplite, alaskite, and pegmatite.

Most compositional layering in Butte Quartz Monzonite is interpreted as the result of mechanical differentiation in zones of flow. As some mafic layers are only two or three crystals thick, it is assumed that the mafic minerals were pulled into zones of more active flow. Layering near sharply defined dikes probably was induced by forceful intrusion of dikes into partly

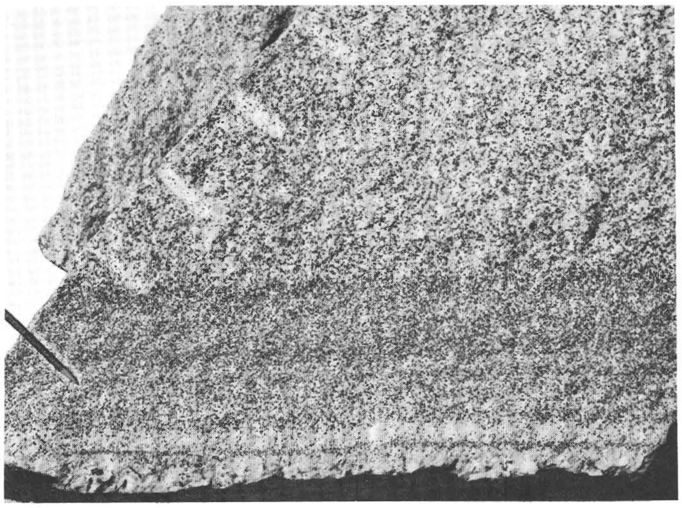


FIGURE 36.—Compositional and textural layering in Butte Quartz Monzonite along margins of pegmatite dike. Pegmatite, mostly broken away, lies along lower edge of the block. Photograph in quarry near middle south edge of sec. 35, T. 9 N., R. 3 W.

solidified quartz monzonite. The layered dikes may represent drag by multiple or mass dike injection, with subsequent reaction and blending of contacts; or they may represent the reverse, with dike location controlled by zones of more active flow. Discontinuous lenses of pegmatite or other felsic rocks in foliated layered zones may represent pegmatites formed virtually in place by late magmatic differentiation supplemented by mechanical flow differentiation. In any event, dike emplacement and layer formation were closely associated.

In the northwestern part of the map area, layers of normal coarse-grained Butte Quartz Monzonite alternate with layers of leucocratic quartz monzonite. Each layer is flat lying and 2–5 feet thick; some are uniform in thickness throughout an observed extent of more than 100 feet, others are lenses 6–20 feet long. Contacts between layers are blended over a space of less than 1 inch, and some leucocratic layers are brecciated and healed by normal Butte Quartz Monzonite; the leucocratic layers therefore solidified before the normal layers.

AUTOBRECCIATION

On a microscopic scale, all the coarse- and medium-grained Butte Quartz Monzonite exhibits evidence of at least mild cataclasis during the late stages of crystallization. Cognate and replacement breccias provide larger scale evidence of cataclasis. Locally, rock of one texture outlines and blends with rounded to angular blocks and slabs of rock of slightly different texture or

[3] The rosette frequency diagrams were constructed as follows: The map trends of each 500 ft of each structure were recorded as units. Each structure less than 500 ft long also was plotted as one unit. Curved structures were treated as polygonal arcs. Tallies were made of the number of units in each 10° of azimuth; the combined tallies were converted into percentages of measured units in each 10°-sector, in terms of the total units recorded (shown by numbers on the rosettes). Trends on the boundary between two 10°-sectors were distributed between the two sectors in the same proportion as the total units whose trends clearly were within those sectors. The diagrams were smoothed by means of moving averages; each value used in plotting the rosettes is the average of the original percentage for the 10°-sector shown and half the percentage of the two adjoining sectors.

210-690 O—66——6

composition. The contacts are blended, apparently by reaction and replacement crystallization. The resulting rock is in part replacement breccia but mainly cognate breccia (figs. 37, 38). The host rock is coarse-grained porphyritic Butte Quartz Monzonite; its matrix is medium- to fine-grained leucocratic quartz monzonite or granite.

XENOLITHS

Xenoliths are abundant in coarse- and medium-grained rocks of the Butte Quartz Monzonite. At least one can be found in almost any 100 square feet of exposure, and five or more are commonplace. In fresh outcrops some xenoliths are inconspicuous because they have been converted to rocks approaching quartz monzonite, but most stand out because of size, color, or abundance. Xenoliths 500 feet long have been seen, but most are a few inches to 1 foot long; some are slablike, but most are rounded and equant. A representative exposure is shown in figure 39.

Near the relatively straight steep eastern margin of the batholith, xenoliths are only locally abundant. Near the very irregular border north of Crystal Creek, in the stock in Casey Meadows, and in the southern part of the Jackson Creek lobe, xenoliths are more abundant and the texture of the host quartz monzonite is more varied than normal. Xenoliths of welded tuff in those areas are the most profoundly transformed; they are now granulitic quartzo-feldspathic rocks and granophyre that strikingly resemble many of the fine-grained quartz monzonites of the batholith. Similar transformed welded tuff makes up part of the prebatholith country-rock wall and roof in those areas.

Xenoliths occur in all stages of transformation to rocks approaching the host quartz monzonite (fig. 40). Nearly every fresh clean exposure of quartz monzonite reveals many nearly obliterated xenoliths.

In some places near contacts with prebatholithic rocks, xenoliths are rich in coarse hornblende crystals; around such xenoliths (fig. 41) the host quartz monzonite also is rich in coarse poikilitic hornblende and in small crystals and shredlike masses of biotite. In other places, far from the contact, sparse xenoliths are rich in coarse hornblende crystals, but the surrounding host quartz monzonite is not; these xenoliths appear to have acted as collectors of ferromagnesian materials,

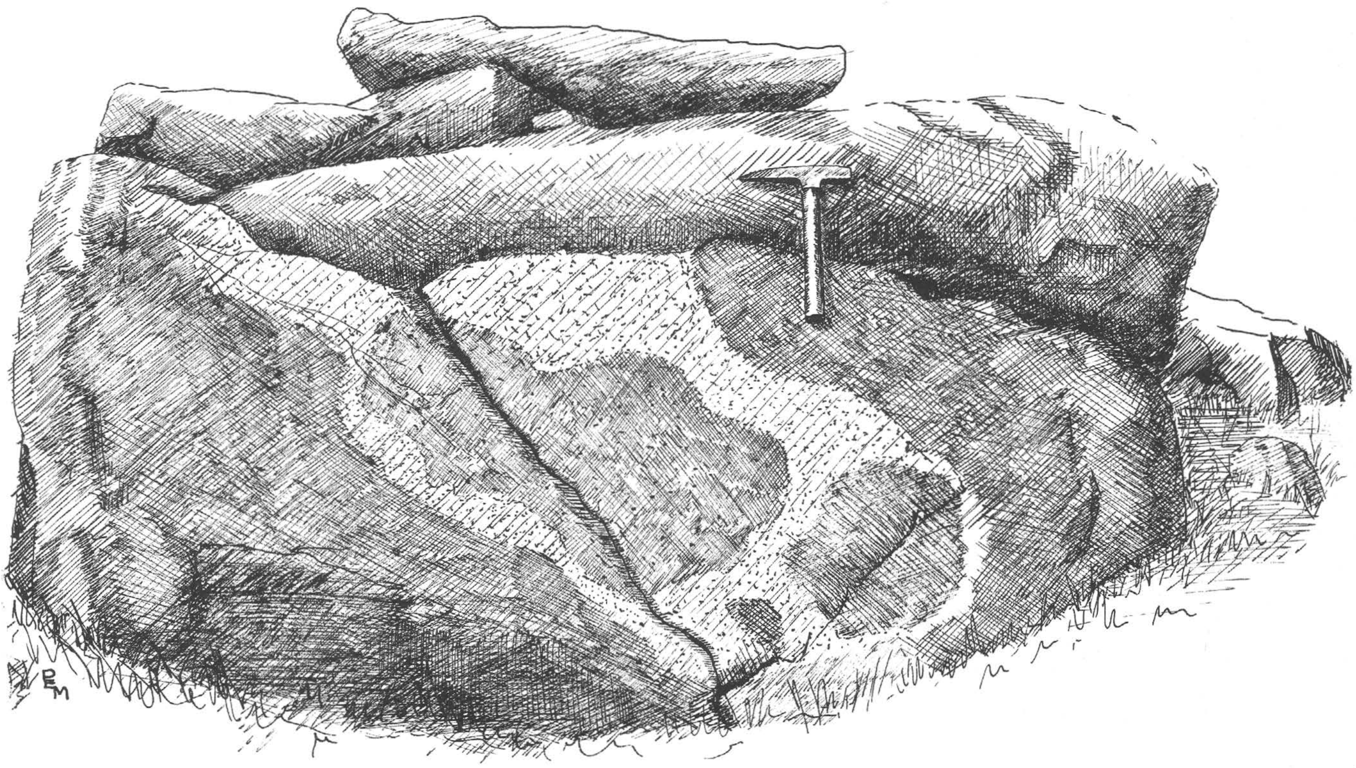


FIGURE 37.—Cognate breccia of Butte Quartz Monzonite from the southern slopes of the valley of Warm Springs Creek. Sketched by Paul Myers.

perhaps derived from other xenoliths which were being transformed into more-felsic rocks.

Xenolith swarms as much as 15 feet long crop out along the canyon of lower Strawberry Creek, in the SE¼ sec. 34, T. 9 N., R 3. W. Several swarms of densely packed dioritic xenoliths are exposed, all of rather uniform size and rounded shape. From a short distance these swarms look like conglomerate (fig. 42). The matrix of this mass is richer in K-feldspar and biotite and is finer grained than the adjoining rock that has only the normal abundance of xenoliths.

Because of the abrupt change from xenolith-rich to xenolith-poor rock, lack of flow streaking of xenoliths, the podlike form, and the presence of several similar but smaller pods all within a small area, these xenolith swarms or pods are interpreted as xenoliths of xenolith-rich rocks that formed at or near the contact at the roof of the batholith, were subsequently engulfed by processes of autobrecciation or stoping, and sank until trapped at their present sites by cooling.

Xenoliths are in places streaked out to form schlieren, but these are not common in the map area. In some places the xenoliths are distributed along zones of flow, but they are not themselves streaked out (fig. 41).

ALASKITE AND RELATED FELSIC ROCKS

Sheetlike and steep dikes and irregular bodies of felsic rock, dominantly alaskite,[4] aplite, and granitic or quartz monzonitic pegmatite are assigned to the final intrusive stage of the Boulder batholith in this

[4] The term "alaskite" is used for leucocratic quartz-feldspar rocks whose textures are heterogeneous and complex, following Roberts (1953). These rocks commonly exhibit textures ranging in a single hand specimen from aplitic through granophyric, granitic, and porphyritic, to pegmatitic and graphic.

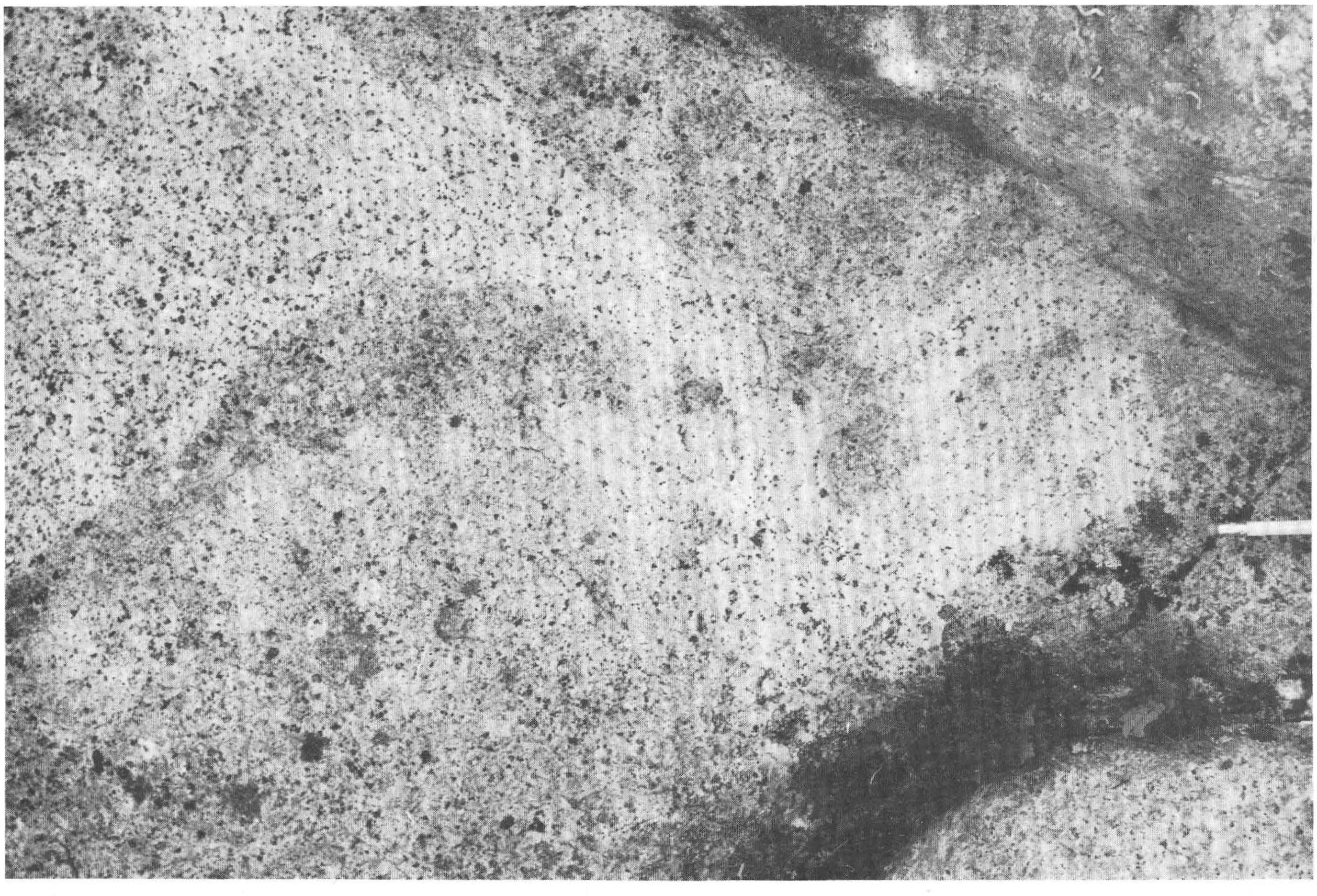


FIGURE 38.—Cognate breccia of Butte Quartz Monzonite, showing blended contacts. Photograph shows detail of same ledge as figure 37. Pencil gives scale.

area. Generally small and intimately mixed, these young felsic rocks are mapped as one unit. Less common rock types are potassic granite, syenite, quartz pegmatite, and quartz-tourmaline pegmatite. A mass of leucogranodiorite, mapped separately, occurs in the Jackson Creek lobe and grades into aplite-alaskite which has intruded and partly replaced brecciated Butte Quartz Monzonite and Elkhorn Mountains Volcanics.

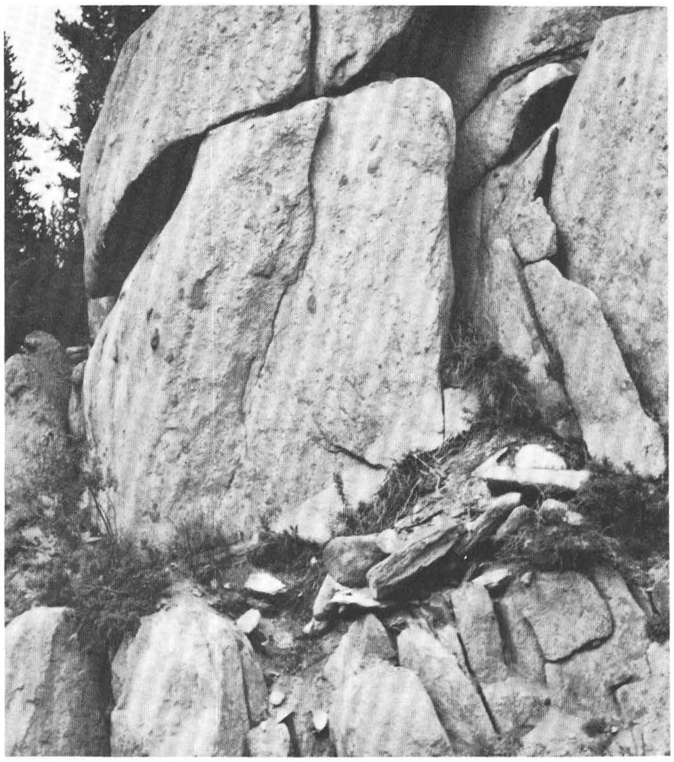


FIGURE 39.—Typical xenoliths in Butte Quartz Monzonite near Crystal Creek.

The felsic rocks are widespread, probably forming 2 or 3 percent of the batholith in the map area. They are nearly restricted to the batholith, only extending a few feet to a few hundred feet into the volcanic country rocks.

Felsic rocks of the late stage generally are of erratic texture and structure. Only a few dikes are entirely aplite or pegmatite.

Dikes and irregular bodies commonly are layered, with various combinations of alaskite, aplite, pegmatite, quartz rock, K-feldspar rock, leucocratic quartz monzonite, and granite alternating both regularly and irregularly. Because of these combinations of textures, the rocks generally must be called alaskite-aplite-pegmatite, aplite-pegmatite, alaskite-pegmatite, or aplite-alaskite. Some narrow dikes are zoned; in some of these the coarser textures are in the center, in others the coarser textures occur along the margins, and in still others they are between the center and margins. Most bodies are not regularly zoned, and textures change along as well as across the layers; thus many thin layers blend into thicker layers. Some pegmatitic layers and pods are miarolitic, with well-formed crystals of clear or smoky quartz, K-feldspar (microcline, perthite, microperthite, and orthoclase), tourmaline, and silvery green mica. Locally, molybdenite, epidote, pyrite, magnetite, and sphene are conspicuous and form in interstices, as euhedral crystals in miarolitic cavities, or as joint coatings.

The pegmatites rarely contain crystals more than 2 inches across, but 15-inch doubly terminated quartz and subhedral perthite crystals were found southwest of Strawberry Butte, north of Strawberry Creek.

Most aplite-alaskite-pegmatite cuts Butte Quartz Monzonite and is younger than the monzonite. Some aplite, however, is older, for it occurs as inclusions in quartz monzonite in several places. Some aplite dikes which cut the Kokoruda Ranch complex probably were formed as a late differentiate of the magma of the early stage, and some dikes cutting the Antelope Creek stock may be late differentiates of magma of the intermediate stage.

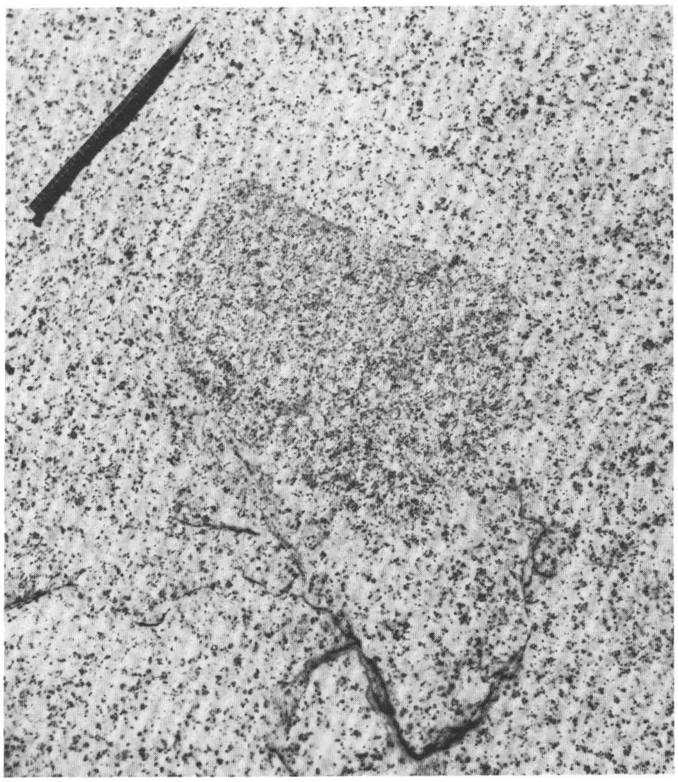


FIGURE 40.—Xenolith in Butte Quartz Monzonite showing contacts well defined on two sides and indistinct elsewhere. Photograph in the quarry near the middle south edge of sec. 35 T. 9 N., R. 3 W.

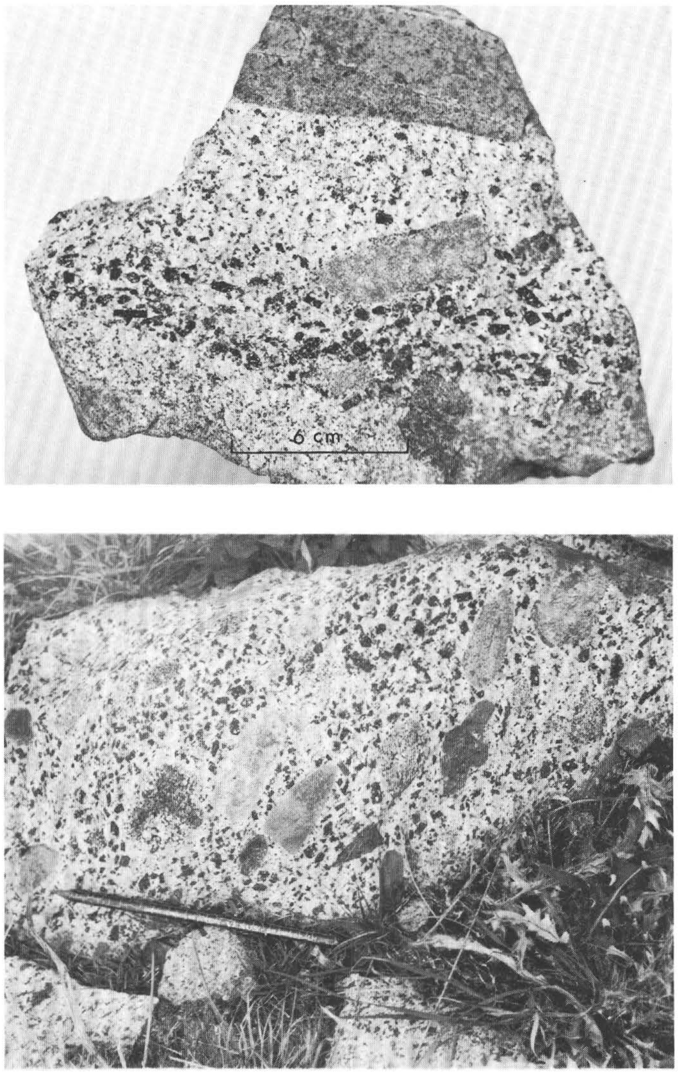


FIGURE 41.—Xenoliths of metamorphosed basalt and other volcanic rocks in hornblende-rich quartz monzonite in the southeastern part of the Jackson Creek lobe. Poikilitic hornblende phenocrysts and the xenoliths are arranged in flow layers parallel with the contact with metabasalt. Upper, Contact with metabasalt country rock. Lower, Variety of rock types and range in degree of transformation of xenoliths.

Reconnaissance petrographic studies suggest that pegmatite associated with the early mafic rocks tend to be richer in plagioclase and to have plagioclase of more calcic composition than that associated with later stages, to contain actinolitic hornblende, to contain coarse apatite, to contain aegirine locally, commonly to contain chalcopyrite, and to be associated with dikes of fine-grained quartz monzonite. Dike rocks associated with granodiorite of the Antelope Creek stock are sparse and have not been studied.

Although each major intrusive stage of the batholith may have alaskite-aplite-pegmatite associated as late magmatic phenomena, these are petrographically similar (except for the tendencies just noted) and all such rocks are mapped as a single unit.

Alaskite, aplite, and pegmatite occur in four principal types of bodies: (1) hazily defined segregations of pod or lens shape; (2) dikes whose margins blend into quartz monzonite which commonly is foliated or layered; (3) sharply defined flat or steep dikes and irregular bodies whose crosscutting relations with earlier dikes show dilation offset; and, (4) as wide and narrow bands or zones along part of the batholith contact.

Segregations occur apparently at random and without preferred orientation. They commonly are miarolitic and, being completely enclosed in quartz monzonite, seem to be residual differentiates. Segregation pods are the earliest formed members of alaskite-aplite-pegmatite associations. Dikes with blended contacts cut segregation pods, but they do not cut sharply defined dikes or sheets. Sharply defined dikes and sheets cut blended dikes and segregation pods. The dikes commonly occur in sets indicating joint control.

Most of the complex outcrop patterns and many of the undivided areas of mixed alaskite and quartz monzonite represent dike complexes, flat dikes on gently rolling ground, or dikes on dip slopes.

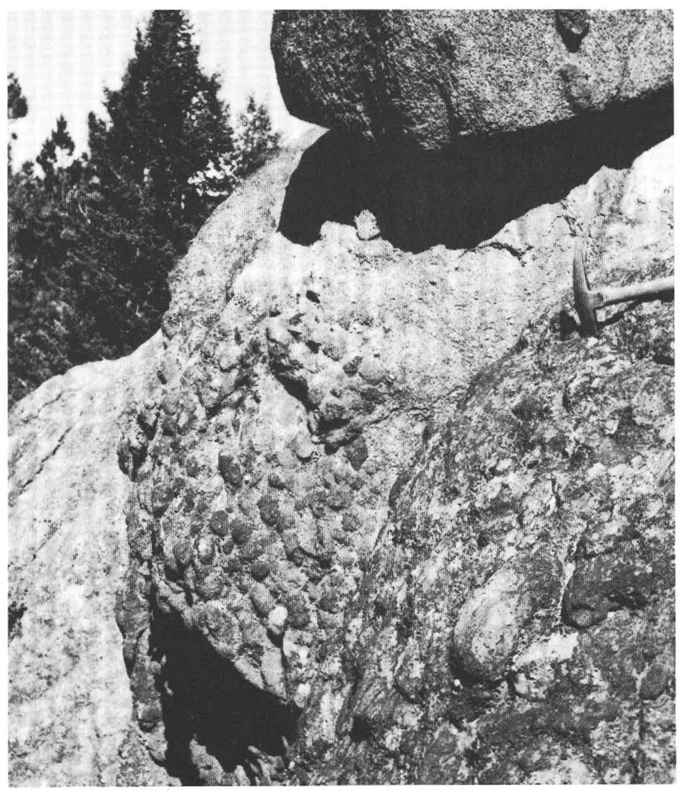


FIGURE 42.—Xenolith swarm in canyon of lower Strawberry Creek.

Dikes of alaskite, aplite, and pegmatite generally are more resistant than the host rocks; aplite is the most resistant. These dikes stand out as low rubbly rocky bands on grassy slopes and in cultivated fields. They are most abundant in the western part of the map area, where they form the northeast end of a wide belt which extends for more than 18 miles southwestward across the Jefferson City quadrangle (Becraft and others, 1963). This belt also is characterized by an abundance of Tertiary dikes and of chalcedony and quartz veins.

Only one body of these late felsic rocks, too small to map, was found in the wallrock more than 500 feet from the batholith. This body, of alaskite, is 4,000 feet from the nearest exposures of the batholith, along the north side of a small wedge-shaped fault block in Cretaceous sedimentary rocks on the ridge between Mitchell Gulch and Corral Creek, NW¼SE¼ sec. 15, T. 9 N., R. 2 W.

Alaskite, aplite, and fine-grained leucogranodiorite form a wide margin of the batholith where it bulges eastward between the East Fork of McClellan Creek and Jackson Creek (pl. 1). Similar felsic rocks lie along the western margin of the Jackson Creek lobe between Jackson and Crystal Creek. The leucogranodiorite bordering the Jackson Creek lobe contains about 48 percent sodic andesine, 27 percent quartz, 2 percent K-feldspar as orthoclase cryptoperthite, and 4 percent biotite. It grades westward into alaskite, which, in turn, grades into quartz-rich aplite. This aplite contains many xenoliths and nebulous masses which probably are skialiths, because the aplite appears to replace and grade into the sheared volcanics still farther west. The volcanic rocks exhibit all gradations in the replacement sequence. Away from the contact they look normal, but they are shown by the microscope to be impregnated with granular K-feldspar and to have a very fine grained hornfels texture. Granophyre dikes are common in the felsic rocks and in the metamorphosed volcanics; these volcanics are cut by veinlets of K-feldspar and quartz.

Alaskite-aplite-pegmatite occurs as lenses and irregular masses in schist and amphibolite of the septum of metamorphosed volcanic rocks between the Jackson Creek lobe and the main mass of the batholith. The pegmatite occurs in the "pressure shadows" of deformed fragments and in the spaces between stretched boudins. It may be related to the late stage of the batholith, or it may have formed by thermal metamorphism. Some clearly is of replacement origin.

In one place, fine-grained quartz monzonite is rhythmically interlayered with thin sheets of an unusual kind of aplite-pegmatite that contains octahedra of titaniferous magnetite as much as half an inch across, and slender prisms of aegirine.

Some hazy sheets and patches of alaskite-aplite-pegmatite appear to be the end stage of endomorphism of coarse-grained rocks, which proceeded by reducing grain size, destroying mafic minerals, reconstituting them in shredlike clusters, and finally developing granular quartz and K-feldspar at the expense of the larger crystals of plagioclase and mafic minerals.

A few exposed equant to oblong quartz masses are as much as 60 feet long. These podlike masses are of coarse anhedral quartz grains as much as 9 inches across; they are mantled by K-feldspar and vuggy quartz or by alaskite which contains silvery-green secondary mica.

Quartz pods also occur along pegmatite dikes, generally at bends in strike or dip of the bodies.

Tourmaline (schorlite) is very common in alaskite-pegmatite bodies. The tourmaline is of several different ages, to judge by its textural and structural relations, for it occurs as subhedral to enhedral grains which appear to have crystallized synchronously with quartz and K-feldspar and to have comparable texture; as interstitial fillings which mold around other crystal faces; and as fracture fillings and joint coating of several ages which cut pegmatite and many other rocks.

One alaskite-pegmatite sheet 4 inches thick forms a gentle anticline and syncline. Tourmaline occurs as interstitial fillings molded against quartz and K-feldspar in the crest and trough but not on the limbs. The limbs near the crest and trough are cut by a set of diagonal joints, which extend into quartz monzonite above and below. One member of the joint set is barren; the other is filled with tourmaline near both the crest and the trough. The interstitial crest-and-trough tourmaline probably formed in a closed system. Where the system was tapped by fractures, residual tourmaline-rich fluids migrated along the limbs into the fractures.

PETROGRAPHY AND CHEMICAL COMPOSITION

The chemical and normative compositions of one sample of quartz monzonitic alaskite are given in table 2 (No. 15).

The following description of the rock was supplied by R. W. Chapman (written commun., 1955):

The rock is medium-grained, light pinkish gray, and leucocratic. Under the microscope it is mainly a mass of granophyric intergrowth of quartz and K-feldspar together with many scattered grains of K-feldspar, albite-oligoclase, and quartz. The only accessory minerals observed are tiny grains of dark-brown biotite and magnetite. The approximate modal composition is K-feldspar, 47.5 percent; quartz, 31.5 percent; plagioclase, 19.5 percent; biotite, 1 percent; magnetite 0.5 percent.

In this and other similar rocks of the late stage, the K-feldspar commonly is highly irregular in shape and optically heterogeneous. A single large grain may have parts that are clear and optically homogeneous (probably cryptoperthite) and that grade or abruptly change to parts that exhibit typical grid twinning of microcline. Some parts are microperthite, and other parts of the same grain or of adjacent grains may have subtle narrow barely visible anorthoclaselike lamellae which may be transitional from cryptoperthite to microperthite. In some rocks and grains, microline, or at least grid-twinned K-feldspar, occurs only along zones that appear to be fractures in K-feldspar crystals. Perthite is not common.

Plagioclase occurs as subhedral to anhedral small grains, commonly enclosed in large grains of K-feldspar. Plagioclase occurs mostly as albite, An_{2-8} or oligoclase An_{12-16}. Some grains of oligoclase have rims of nearly pure albite; the more calcic part generally is partly sericitized.

Ten other samples of similar rocks outside the map area have been chemically analyzed (unpub. data, M. R. Klepper, written commun., 1962), and modes have been determined for 49 samples. Their proportions of modal and normative quartz and feldspar are shown on plate 3, figure 5. All the norms are near the middle of the quartz monzonite field, but the average of the modes is on the boundary between quartz monzonite and granite. The average of the norms recalculated for an assumed orthoclase composition of Or_{80} (from unpub. analyses, R. W. Chapman, written commun., 1956) is very close to the average of the modes, supporting the assumption that all the K-feldspar is in the range Or_{75} to Or_{83}.

The sample from the map area happened to have the least plagioclase of the analyzed samples. In spite of the varied textures of these rocks, their bulk compositions are similar. The average and range of normative compositions (in weight percent) of the analyzed samples are as follows: Quartz, 38.5, range 35–40; orthoclase, 31.5, range 28–35; plagioclase, 27.5, range 21–31; other minerals, 2.5, range 1.5–4; composition of plagioclase, An_{12}, range An_6–An_{19}. The ratio of plagioclase to orthoclase averages about 0.9 and ranges from 0.6 to 1.1.

ALTERATION EFFECTS

Alteration effects locally are closely associated with alaskite-aplite-pegmatite dikes and with quartz pods. The alteration consists of sericitization and kaolinization of feldspars, silicification, and lesser pyritization and carbonatization. Generally, only the host quartz monzonite is altered, near the contact. Between Warm Springs Creek and Burnt Mountain there are swarms of dikes around which the alteration effects are more widespread. Near lower Dutchman Creek and extending west of the map area for at least a quarter of a mile, the felsic dikes have themselves been altered. In some places the dikes are altered, whereas the host rocks are altered only slightly or not at all; in others the felsic rocks and the country rock are both intensely altered. In intensely altered host rocks the mafic minerals and feldspars have been converted to sericite and calcite; the resulting rock is very light colored and resembles the felsic rock of the dikes. Pyrite upon weathering stains these rocks red and brown; sericite gives them a silvery and sparkling appearance. Extreme silicification has converted parts of dikes to vuggy quartz-rich masses, closely resembling epithermal quartz veins. Flakes of secondary white mica in these rocks are nearly half an inch across.

The intimate association of alteration and felsic bodies, the sharp decrease of alteration away from the contact, and the local restriction of alteration to the felsic bodies combine to indicate that the alteration was produced by the felsic rocks. Similar alteration in and adjacent to aplite-pegmatites south of the area, near Boulder, Mont., has been described by Neuerberg (1958).

SPECULATION ON DEPTH RELATIONS

Depth zoning related to cooling of the batholith may account for the variety of contact relations of the late-stage felsic rocks and their observed relative ages.

The alaskite-aplite-pegmatite that occurs as the hazily defined pods or lenses probably originated at depth by differentiation in place. Bodies with blended contacts may have intruded quartz monzonite which was still mushy, at slightly higher levels. The sharply defined dikes showing crosscutting relations and dilation offset apparently intruded still higher quartz monzonite that was completely solidified.

The Butte Quartz Monzonite probably crystallized slowly from the top down and from the walls inward, so that the upper parts are older than the lower parts. Pegmatites progressively derived as late differentiates of quartz monzonite magma could also be of different ages. At a given time, differentiates could produce felsic rocks of different form—segregation bodies at one depth, dikes with blended contacts at higher levels, and sharply defined dikes at still higher levels. With time, the possible places of origin of felsic differentiates would be depressed, and succeeding depth zones would partly overlap those formed earlier. Thus, sharply defined dikes could cut other sharp dikes and segregation pods; blended dikes could cut only segregation pods; and segregation pods could not be expected to transect any dikes or other pods. These are the relations observed in the field.

METAMORPHISM

In the map area all preexisting rocks were metamorphosed to some degree by the batholith. Magma of the early stage appears to have metamorphosed its host rocks more extensively than did later magma. This relation also holds to the west, in the Elkhorn district (Klepper and others, 1957, p. 52), and in the Rader Creek and Toll Mountain area 35 miles to the southwest (M. R. Klepper, oral commun., 1960).

Barrell[5] (1902; in Weed, 1901, p. 511–549) studied the contact metamorphic effects of the batholith in the Elkhorn district 4 miles south of the map area. Knopf (1913, 1942, 1950, 1953, 1957, 1963) studied the contact metamorphism just west of the map area. The occurrence and composition of fassaite from the present map area were reported by Knopf and Lee (1957).

Speaking of the entire batholith, Billingsléy (1915, p. 47) thought that contact metamorphism was slight. Grout and Balk (1934, p. 879) described it as being in remarkably narrow zones, at some places hardly recognizable. On the other hand, Knopf (1957, p. 95) wrote of the impressive and voluminous development of calc-hornfels. A cogent factor, probably not recognized by all earlier workers, is that many of the intensely metamorphosed rocks "retain completely the innocent appearance of normal sedimentary rocks***." (Knopf, 1957, p. 95).

Why magma of the early stage effected more metamorphism is not known. It may be that the oldest magma had more latent heat than did the younger magmas. Striking differences in metamorphic effects along the contact of the Butte Quartz Monzonite, described below, suggest that the differences may reflect differences in the modes of emplacement and the configurations of the intrusive bodies.

METAMORPHISM BY EARLY MAFIC ROCKS AND GRANODIORITE OF THE ANTELOPE CREEK STOCK

Rocks of the early and intermediate stages are closely associated, and it is not known to which stage the metamorphism around some of the bodies should be attributed.

Rocks of the Elkhorn Mountains Volcanics near the Kokoruda Ranch complex were metamorphosed to granular rocks containing combinations of enstatite, diopside-hedenbergite, amphibole, muscovite, garnet, andalusite, cordierite, orthoclase, plagioclase, quartz, sphene, epidote, tourmaline, calcite, rutile, and magnetite. Porphyroblasts, as much as several inches long, are commonplace and consist of tremolite, hornblende, mica, garnet, andalusite, and orthoclase, alone or in combination. Granulitic enstatite and diopside rocks with calcic plagioclase at the contact give way to granular rock and hornfels rich in amphibole, mica, garnet, and andalusite farther away. As the distance from the contact increases, the grain size diminishes; the metamorphic plagioclase becomes more sodic and is accompanied by epidote, calcite, and locally, scapolite; relict igneous plagioclase becomes more discernible; tremolite gives way to hornblende; and orthoclase diminishes in size and abundance.

Argillaceous sedimentary rocks were converted into granular to flinty rocks composed of andalusite, cordierite, micas, feldspars, and quartz. Tourmaline is widespread though erratic, and minute prisms of dumortierite occur locally; these minerals are metasomatic as are concentrations of mica and orthoclase in structurally controlled zones.

A representative porphyroblastic hornfels developed from siltstone of the Kootenai Formation 50 feet from the Kokoruda Ranch complex is illustrated in figure 43. The irregular gray areas are all part of a single poikiloblastic orthoclase crystal. Biotite also occurs as large poikiloblastic plates, not shown in the figure.

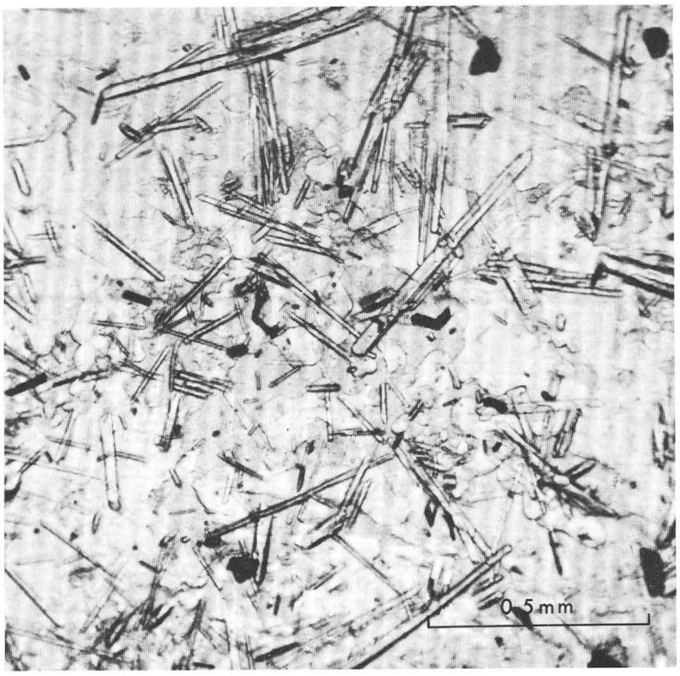


FIGURE 43.—Photomicrograph of cordierite-sillimanite hornfels with prophyroblasts of orthoclase. Irregular gray areas are all part of a single poikiloblastic orthoclase crystal; clear areas of low relief are cordierite and sparse quartz; clear needles of high relief are sillimanite; small dark prisms and geniculate twins are rutile. Plane polarized light.

[5] Barrell, Joseph, 1900, The geology of the Elkhorn mining district, Montana: Yale Univ., unpub. Ph.D. dissertation.

Sillimanite appears to have developed last, at the expense of orthoclase and cordierite.

Cherty and clean quartz sandstones were recrystallized into vitreous quartzite. Impure argillaceous rocks contain the same calc-silicate minerals as the volcanic rocks.

Bedding, delicate banding, amygdaloidal, porphyritic, flow, and other primary structures commonly are preserved (fig. 6) even in the most intensely recrystallized rocks, except as noted below. Various xenoliths in the Kokoruda Ranch intrusive complex can be identified, for example, as crossbedded siltstone, lapilli tuff, and amygdaloidal porphyritic lava. In the Three Forks Shale just west of the map area, spirifers are well preserved even though they and the host rocks are now spotted cordierite hornfels (Knopf, 1963).

Carbonate rocks were more completely transformed and, near the contact, do not retain primary textures and structures. Pure limestone was converted into coarse marble, with grains as much as 2 inches across. Impure limestone and dolomite were converted into coarse-grained calc-silicate marble, tremolite rock, and tactite. Metasomatism was effective at and near the contact. Contact minerals most commonly found are garnet, spinel, clintonite, phlogopite, vesuvianite, diopside-hedenbergite, scapolite, chondrodite, wollastonite, aegirine, calcite (commonly blue), tremolite, and minerals of the epidote group. Axinite occurs locally, with garnet and epidote.

Some contacts along beds and xenoliths of carbonate rocks are zoned. For example, the zoning from syenogabbro into the country rock or a xenolith commonly consists of some or all of the following:

Biotite-olivine-augite syenogabbro
Biotite-augite monzonite
Biotite-aegirine syenite (nepheline-bearing locally)
Orthoclase rock
Fassaite rock
Fassaite-grossularite rock
Clintonite-fassaite-spinel rock
Spinel rock

Some zones are several feet wide; the total width of the zone from syenite to spinel rock generally is not more than 30 feet. Zones of fassaite and of orthoclase rocks are each no more than 2 feet wide.

Syenite and orthoclasite dikes occur near some large xenoliths or pendants of pyroxene-garnet-spinel rock. Locally, dikes of fassaite rock occur, presumably representing syntectic magma developed from assimilated carbonate rocks. Knopf and Lee (1957) described a vertical tabular mass of clintonite-spinel-fassaite rock, from near the middle west edge of sec. 22, T. 9 N., R. 2 W., that extends S. 60° E. from creek bottom to ridge crest. According to Knopf and Lee, this rock is a septum of pyrometasomatically altered carbonate rock. In addition to the minerals they described, the mass contains iron-rich K-feldspar. A zone of contaminated batholith rock of garnet- and scapolite-bearing aegerine syenogabbro and monzonite extends from the end of the pendant northward down the ridge crest. The pendant and contaminated batholith rocks are mapped together.

Tactite along the west margin of the monzonite-syenodiorite dike west of the Antelope Creek stock grades into garnet- and scapolite-rich monzonite. In places along this contract, magnetite bodies occur as replacements of carbonate rock.

Cordierite- and actinolite-hornfelses extend from the Kokoruda Ranch complex eastward to the Antelope Creek stock in a band that lies roughly along the belt of outcrop of the Kootenai, Colorado, and Slim Sam Formations.

Cordierite hornfels and local granular diopside-hedenbergite rock and tourmaline-magnetite replacement masses occur along the ridge crest and south and west of the Chicago mine, N½ sec. 26, T. 9 N., R. 2 W.

The western part of the basalt sheet near the Buzz mine on Spokane Creek contains wollastonite-actinolite veinlets which probably are deuteric calcite-epidote-chlorite veinlets metamorphosed by the monzonite-syenodiorite dike. In this sheet, grain size and the abundance of granules of metamorphic magnetite and clear diopside increase and biotite decreases markedly toward the Antelope Creek stock, strongly suggesting that metamorphism was accomplished by the stock.

Highly sheared country rocks occur here and there along the northern margin of the Kokoruda Ranch complex. The shearing dies out away from the contact. These relations strongly suggest that the shearing was accomplished during forcible emplacement of the Kokoruda Ranch complex rather than during the prebatholith orogeny. The sheared rocks later were recrystallized to schist and amphibolite.

METAMORPHISM BY BUTTE QUARTZ MONZONITE

Magma of the Butte Quartz Monzonite had little effect on the earlier batholithic rocks but marked effect on the Elkhorn Mountains Volcanics. In the volcanics, metamorphic aureoles of two general types were produred, one north and the other south of the East Fork of McClellan Creek.

South of the East Fork, where the intrusive contact is unusually regular and steep, the zones of the high- and medium-grade metamorphism are narrow. Hornfels derived from rhyolitic welded tuff tends to be biotitic throughout, whereas that derived from andesitic and basaltic rocks is more sensitive to changes in metamorphic grade. In the inner contact zone, mineral assemblages of the pyroxene-hornfels facies formed in these basic rocks. Enstatite hornfels occurs in a zone 150–450 feet wide at the contact and grades into hornfels containing clinopyroxene. This hornfels in turn grades through garnet-bearing amphibole and andalusite-hornfels, and then into epidote-albite-quartz-chlorite hornfels of the albite-epidote-hornfels facies, distinguishable from similar rocks produced by deuteric and pneumatolytic alteration during volcanic time only by their fine grain and their even distribution around the batholith. The width of the visible metamorphic aureole attributable to the batholith generally is no more than 2,500 feet.

Although of little value as an indication of metamorphic grade, rhyolitic welded tuff was more sensitive to the metamorphism than were the more basic rocks, perhaps because the rhyolite is a lower temperature assemblage than the other rocks, and probably was partly glass. The welded tuffs were texturally transformed more conspicuously and farther from the contact than were the other rocks. Away from the contact, pyroclastic and intrusive bodies seem little changed, but the intercalated sheets of rhyolitic welded tuff are bleached aplitic- to flinty-appearing rocks whose groundmass is converted to mosaic quartz and feldspar, commonly of granophyric texture. Plagioclase pyroclasts have crenulated margins. Some of the rocks are sericitized; many contain disseminated pyrite, specularite, and, in places, dumortierite. In spite of these transformations, delicate wispy flattened lapilli and eutaxitic structure still are discernible. The bleached rocks that contain sericite, pyrite, or both, may have been formed by later hydrothermal alteration rather than thermal metamorphism, but their areal distribution strongly suggests relation to the batholith contact.

In the zone of medium-grade metamorphism, metamorphic microcline, muscovite, orthoclase, and andalusite form large irregular poikiloblasts, and cordierite forms locally as smaller complex and coalesced masses.

Potassium metasomatism during a late or retrograde stage is indicated near the contact by production of muscovite and quartz from plagioclase, with orthoclase and biotite locally along cleavages. Boron metasomatism is indicated by tourmaline which locally makes up more than 10 percent of the rock, and perhaps, by sparse local dumortierite.

North of the East Fork, where the contact is highly irregular, the aureole of thermal metamorphism is broad and the rocks are coarsely recrystallized. In the innermost contact zone all rocks except the porphyritic basalt and andesite intrusives have been completely transformed texturally. Even though the aureole is broader and the rocks coarser than to the south, the grade of the inner zone is not so high. Biotite is the most conspicuous new mineral formed in the andesitic and basaltic rocks; metamorphic pyroxene is absent; and primary volcanic pyroxene largely is replaced by amphibole and mica. Granular biotite-rich rocks prevail, andalusite-mica-feldspar hornfels and cordierite hornfels are common, and actinolite is widespread though neither as abundant nor as conspicuous as biotite.

Metamorphosed welded tuff is coarse granular rock which in many places resembles aplite and other fine-grained rocks of the batholith. Only locally is it dense bleached rock like that in the southern part of the mapped area. Many of the rocks are cut by sharp to hazily defined networks of rock rich in quartz and feldspar, and, locally, rich in tourmaline. In rocks adjacent to these networks, collapsed pumice lapilli have been selectively enriched in potassium and silica and now form hazy streaky and wispy masses of quartz and orthoclase resembling aplite (fig. 44).

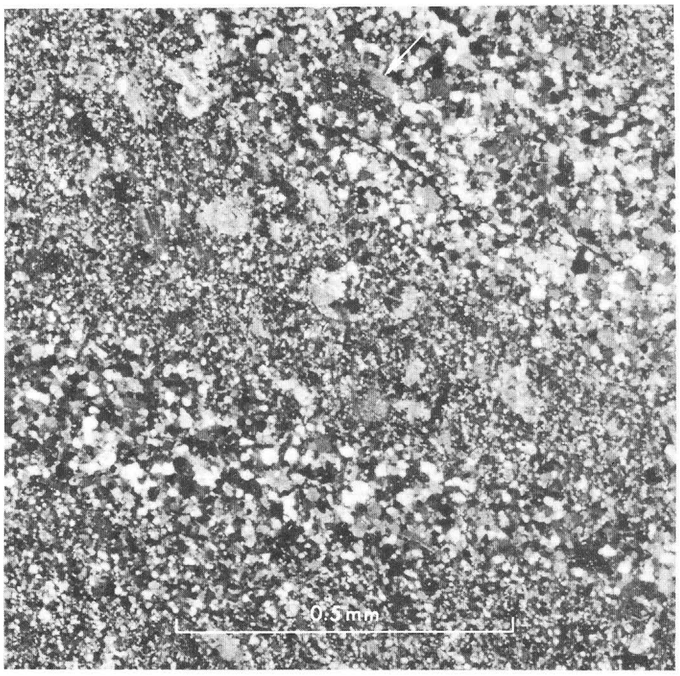


FIGURE 44.—Photomicrograph of hornfelsed welded tuff showing selective replacement of lapilli by quartz and orthoclase, producing streaks of rock resembling aplite. Hornfels in center and at bottom contains blastoporphyritic plagioclase in a very fine grained matrix of quartz and feldspars. Replacement aplitic streaks below center and at top have irregular grain sizes and blended contacts with host rock and with relict plagioclase crystal (arrow, near top). Crossed nicols.

Inclusions in Butte Quartz Monzonite throughout the batholith commonly contain K-feldspar porphyroblasts, many of which have developed astride the contact between quartz monzonite and the xenolith, as described above. Fine-grained diopside and local sphene in the cores of xenoliths give way to coarse green hornblende and then to biotite at the rims. The quartz monzonite near the contact commonly has sparse dark minerals and is rich in K-feldspar or in plagioclase.

All stages in the transformation of xenoliths to quartz monzonite may be observed in large exposures. Some xenoliths are sharply defined, others have gradational contacts (fig. 40), and still others are mere shadows on fresh exposures. Some have narrow rims of hornblende, others have wider rims of coarser hornblende, and still others are wholly converted to coarse poikiloblastic hornblende. Some small xenoliths now are single hornblende crystals as much as 2 inches long but more commonly about ½–¾ inch long. Similar hornblendization took place in country rock along the contact. Some hornblende- and biotite-rich xenoliths are rimmed with quartz and feldspar, but many are not. Enlargement of quartz and feldspar veinlets has produced replacement or injection breccias which in advanced stages cannot be distinguished from simple xenoliths swarms.

Extensive metasomatism of large xenoliths occurred locally. In one place, on the slopes of the South Fork of Warm Springs Creek (at the north end of an alaskite dike, N½SW¼ sec. 31, T. 8 N., R. 2 W.) a xenolith 100 feet across was converted into a granular plagioclase-aegirine rock with sparse calcite, cut by coarse irregular replacement veinlets of aegirine and microcline. The border of the xenolith contains very coarse euhedral sphene and poikiloblastic K-feldspar. Plagioclase has largely been converted into albite, zoisite (nonferrian), and sericite, and replaced by microperthite; aegirine is partly replaced by poikiloblastic pale-green amphibole. Quartz occurs as extensive poikiloblastic interstitial masses and partly replaces all other materials.

Volcanic rocks in the septum separating the Jackson Creek lobe from the main mass of the batholith, between Jackson and Crystal Creeks, were highly sheared into streaky mylonite conformable to the margin of the batholith. Individual blocks in volcanic breccia are now lens-shaped and discoid masses (upper fig. 45); smaller fragments were milled out to a fine paste. Subsequent thermal metamorphism by the batholith resulted in mimetic recrystallization of the mylonite to biotite schist and amphibolite. Some beds or slabs of rock were stretched and broken into boudins that have quartz, feldspar, and tourmaline in the pressure shadows between segments. In these rocks the matrix is schist.

Locally, in the eastern part of this septum, blocks of quartz monzonite are enclosed in tectonic breccia, together with blocks of tuff and volcanic breccia. The presence of quartz monzonite blocks in thermally metamorphosed cataclastic rocks requires that the shearing and crushing occurred or recurred during emplacement of the batholith. The blocks of quartz monzonite may represent an early crystallized shell of Butte Quartz Monzonite which was broken along with the volcanic rock in the septum, and the two kinds of blocks "kneaded" together by shearing during the forcible intrusion of the still-fluid mass of Butte Quartz Monzonite magma. Perhaps simultaneous intrusion of large volumes of magma on both sides of this relatively narrow septum resulted in the intense shearing which is unique to this body of country rock.

METAMORPHISM BY ALASKITE AND RELATED FELSIC ROCKS

Metamorphic effects induced by magma of the late stage are local and generally slight, except near the western margin of the Jackson Creek lobe. These effects, described previously, include silicification, sericitization, tourmalinization, pyritization, carbonatization, and feldspathization.

Metamorphic and metasomatic effects of the late stage are widespread and intense in the eastern part of the highly sheared septum of volcanic rocks between Jackson and Crystal Creeks. Following shearing and recrystallization of the rocks to schist and amphibolite during the main stage of the batholith, fracturing allowed quartz- and feldspar-bearing fluids to enter the rock during the late stage (lower fig. 45). These fluids apparently replaced the rock laterally from the fractures; they formed blended and ill-defined pegmatitic and aplitic streaks much the same as in the replacement aplite in welded tuff, described above (fig. 44). Whereas quartz and feldspar form very irregular networks, K-feldspar evenly pervades large masses of the rock as a fine groundmass mosaic and increases in abundance eastward.

The eastern side of the southern part of the sheared septum grades imperceptibly into alaskite-aplite through a zone 500–1,200 feet wide. Even well within this alaskite-aplite mass, shadowy relicts of the volcanic rocks occur.

LAMPROPHYRE AND OTHER PORPHYRY DIKE ROCKS OF UNCERTAIN AGE

A variety of rocks occur as porphyry dikes scattered sparsely throughout the batholith. Most are small, being generally less than 6 feet wide, but one in sec. 23, T. 8 N., R. 3 W., is as much as 300 feet

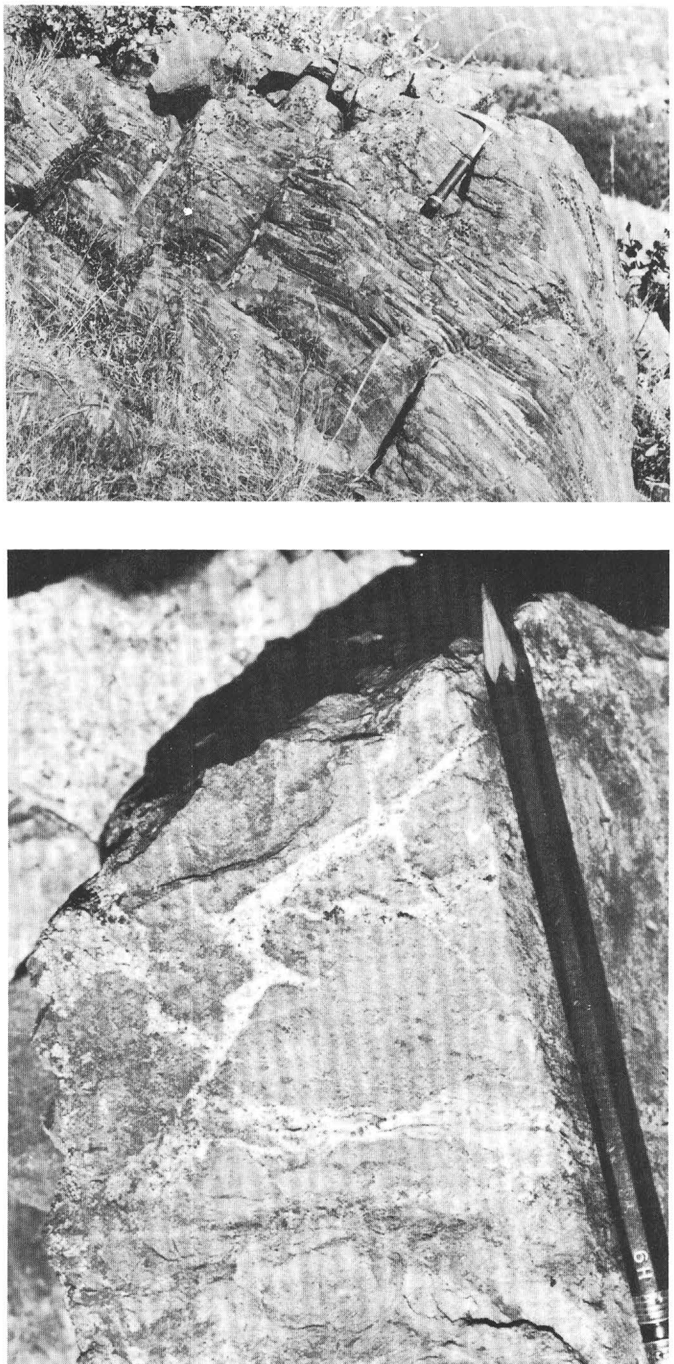


FIGURE 45.—Sheared volcanic rocks in the septum between the Jackson Creek lobe and the main mass of the batholith. Upper, Slump block of breccia in which the fragments have been sheared and streaked out into flat discs with axial ratios as large as 25:1. Lower, Veinlets and hazy replacement masses of quartz, K-feldspar, and tourmaline.

wide. Most can be traced no more than several hundred feet, but one is 3,000 and another is more than 7,800 feet long.

All the lamprophyre dikes except one are confined to the Kokoruda Ranch complex; the exception is a lamprophyre that cuts Elkhorn Mountains Volcanics in the NE¼ sec. II, T. 7 N., R. 2 W. Other porphyry dike rocks are confined to the Kokoruda Ranch complex and the Butte Quartz Monzonite.

At least one dike is known to be cut by aplite, and occurs as xenoliths in the aplite. This dike, in the Kokoruda Ranch complex, extends nearly 8,000 feet, from the SW cor. sec. 21, where it is cut by aplite, into the NW¼ sec. 22, T. 9 N., R. 3 W.

Age relations between these dikes and the Tertiary quartz latite are not known. Possibly the dikes range in age from early batholithic to postbatholithic. The category is thus a catchall for dark dike rocks of conspicuous porphyritic texture.

PETROGRAPHY

Lamprophyre and other porphyry dikes similar to those in the map area are very sparse outside the map area and have not been described. Therefore, they are described here rather fully.

In this report the name lamprophyre is used in the descriptive sense recommended by Knopf (1936) for porphyritic dike rocks having only mafic minerals as phenocrysts. In accordance with Knopf's suggestion, the rocks are named according to the phenocryst minerals; the classical lamprophyre names and rock family association are listed subordinately.

The rocks of lamprophyric texture grade toward syenodioritic and syenogabbroic rocks which have feldspar in addition to mafic phenocrysts. One dike grades along its length from lamprophyre to porphyry; that is, from a highly porphyritic rock with phenocrysts only of mafic minerals to one with phenocrysts only of plagioclase. This dike, more than 7,800 feet long, cuts the Kokoruda Ranch complex in secs. 21 and 22, T. 9 N., R. 2 W.

BIOTITE-HORNBLENDE-OLIVINE-AUGITE LAMPROPHYRE

Biotite-hornblende-olivine-augite lamprophyre occurs in a small arcuate dike in tuff of the Elkhorn Mountains Volcanics in the NE¼ sec. 11, T. 7 N., R. 2 W., just west of the small saddle along the ridge crest between Clear and Crazy Creeks. This rock belongs in the gabbro family and is an odinite.

An irregular small body of metamorphosed basalt porphyry occurs near the south end of the lamprophyre, but the relations of the two bodies could not be determined.

The rock consists of a grayish-black aphanitic groundmass studded with pseudomorphs of olivine crystals which are pitted on weathered surfaces. The rock weathers olive gray. All phenocrysts have maximum diameters of about 3–6 mm. The biotite plates are crudely alined, forming weak foliation along which the rock breaks into slabs.

Under the microscope the groundmass is seen to consist of unresolvable cryptocrystalline material (probably incipiently devitrified glass) with abundant flow-alined plagioclase microlites (An_{46-56}) and small granules of opaque material. Phenocrysts of augite, olivine pseudomorphs, hornblende, and biotite constitute about 40 percent of the rock.

Olivine.—Olivine, 10 percent, occurs as large (as much as 4 mm wide) euhedral pseudomorphs of talc, antigorite, and a carbonate mineral. Opaque granules are concentrated around rims and in networks through most pseudomorphs.

Augite.—Augite, 19 percent, occurs as euhedral crystals as much as 33 mm long, locally subhedral, owing to partial resorption. Color, neutral to yellowish gray, feebly pleochroic; common (010) exsolution lamellae; extinction angle, $Z \wedge c = 53.5°$; (+) $2V = 54°$; $r > v$, distinct. Locally exhibits hourglass structure.

Hornblende.—Hornblende, 6 percent, occurs as subhedral to anhedral rounded resorbed grains as much as 6 mm long; minute granules of opaque material concentrated in narrow zone around rim. Pleochroism: X, yellowish gray; Y, moderate yellowish brown; $Z = Y$, with green tint. $Z \wedge c = 26°$; $2V_x = 81°$.

Biotite.—Biotite, 3 percent, commonly as resorbed and bent crystal plates as much as 4 mm across. Pleochroism: X, colorless to yellowish gray: $Y = Z$, light-olive brown to moderate brown. $2V = 18.5°$; $r < v$.

Opaques.—Opaque minerals, about 1 percent, occur as magnetite and ilmenite.

QUARTZ-BEARING BIOTITE-HORNBLENDE LAMPROPHYRE

Quartz-bearing biotite-hornblende lamprophyre occurs as a narrow dike in and beside the small augite quartz monzonite plug in the Kokoruda Ranch complex near the center of sec. 21, T. 9 N., R. 2 W. This dike occurs in three slightly offset segments; the offsets may be due to small faults or to primary offsets in the fissure before the dike was emplaced. The rock belongs in the monzonite family. Johannsen (1937) gives no examples or names for lamprophyre of this family.

Megascopically the rock is olive gray to dark gray and aphanitic with small slender phenocrysts of black amphibole. Scattered sparingly throughout the rock are larger black amphibole phenocrysts as much as 4 mm long. The long phenocrysts are crudely alined parallel with the dike walls.

Lighter colored ill-defined veinlets occur in places across the dike, but they were not observed to cut completely through the dike. They are thought to represent deuterically altered seams.

In thin section the rock is seen to consist of small crudely alined phenocrysts of hornblende with sparse large hornblende set in a very fine grained groundmass of randomly oriented plagioclase laths and interstitial K-feldspar.

Hornblende.—Hornblende, about 25 percent, occurs as slender regular prisms formed around and enclosing some of the plagioclase laths; other plagioclase laths are formed around the hornblende in a peculiar texture resembling subophitic. Prisms are as much as 4 mm long, but the majority are about 0.4 mm long. Colors are X, yellowish gray; Y, grayish olive; Z, grayish-yellow core with grayish-green rims. Some crystals are decidedly blue, with Y, grayish green and Z, dusky blue green to grayish blue green. $2V_x$=large; $Z \wedge c = 20°$. All the larger phenocrysts, and a very few of the smaller ones, have dusky brown streaks. These streaks are similar in color to the pleochroic haloes which are common around zircon and other inclusions in biotite and hornblende, but they are arranged in straight parallel patterns which trend diagonally across prismatic sections; less frequently, they occur along prismatic cleavages and fractures. The streaks are very dark in the middle, but they fade out along the margins.

Biotite.—Biotite, about 8 percent, occurs as small ragged subhedral to anhedral plates. Pleochroic, $X = Y$, dusky yellow; Z, moderate olive brown.

Plagioclase.—Plagioclase, about 30 percent, occurs as very small laths confined to the groundmass, surrounded by anhedral interlocking K-feldspar in monzonitic texture. Crystals strongly zoned from An_{40} to An_{22}.

K-feldspar.—K-feldspar, about 30 percent, occurs as minute anhedral interlocking grains, producing a mosaic around the plagioclase laths. These grains are associated with anhedral quartz (5 percent), which has similar fabric.

Accessory minerals.—Magnetite and sphene, about 7 percent, are common, in some places intergrown or with sphene inclusions in magnetite. Magnetite is in part altered to hematite. Very sparse pyrite is associated with sphene-magnetite groups.

The deuterically altered seams observed in hand specimen are gradational zones in which K-feldspar becomes coarser and more abundant and acicular crystals of rutile are present. Quartz is no more abundant in these seams than elsewhere in the rock.

CALCIC TRACHYBASALT PORPHYRY

Calcic trachybasalt porphyry occurs in an east-trending dike swarm, just south of the summit of Little Butte in the NE¼ sec. 28, T. 9 N., R. 2 W. These dikes are less than 1 foot to about 6 feet wide. This rock is transitional to lamprophyre and is lamprophyric at some chilled margins.

The rock is dark gray to grayish black and is aphanitic. It has flow-alined phenocrysts of black hornblende in two distinct size groups and inconspicuous small plagioclase tablets which are about equal in size to the smaller hornblende crystals.

In many places the dike rock has penetrated narrow fissures in the host quartz monzonite. Some of the dikelets are only a few hundredths of an inch wide, but they extend into the wall 2 inches or more, indicating high fluidity. Networks of dikelets enclose stoped blocks of the wall, generally ½-2 inches long.

Many crystals of the quartz monzonite have been plucked from the wall and swept along by the dike materials, and fine flow structures of the dike rock bend around the xenoliths and xenocrysts.

In thin section the groundmass is seen to have turbulent flow structures marked by minute slender plagioclase laths. In addition to plagioclase, the groundmass consists of small granules and plates of hornblende, biotite, and magnetite. These materials are surrounded by K-feldspar which crystallized late as almost unresolvable grains and irregular interstitial poikilitic masses. The minute grains of K-feldspar aggregate probably represent devitrified glass.

Phenocrysts and clusters of augite, hornblende, and magnetite are set in the very fine grained groundmass. Magnetite euhedra are especially abundant in the clusters of augite phenocrysts.

Augite.—Augite occurs as squat euhedral prisms as much as 0.6 mm long and as clusters of euhedra. The crystals mostly are colorless; some prism sections are very pale green. Dispersion of optic axes $r>v$, distinct; $Z\wedge c=48°$; (010) exsolution lamellae are common.

Hornblende.—Slender prisms with margins rounded and corroded, as much as 5 mm long. Commonly zoned; in the core X=yellowish gray, Y=grayish olive, Z=grayish green; rims are mottled, X=olive gray and grayish olive, Y=grayish olive green and brownish black, Z=grayish yellow and dusky yellow. These crystals have dark-brown pleochroic streaks like those in the biotite-hornblende lamprophyre described above. Commonly, however, the streaks are confined to the outer zone of the crystals where irregular schiller structure also occurs. This schiller gives the outer zones their mottled appearance.

Plagioclase.—Sparse phenocrysts and groundmass microlites. Phenocrysts are euhedral tablets, less than 1 mm long, of anorthite, An_{95-92}, with more sodic rims. The phenocrysts contain abundant glass and devitrified glass inclusions except in the sodic rims, which are clear. The microlites have the composition of about An_{35-20}.

AUGITE SYENODIORITE

Two large northwest-trending dikes of fine-grained porphyritic augite syenodiorite cut across Brown's Gulch, mostly in the NE¼ sec. 23, T. 8 N., R. 3 W. The larger has a maximum width of about 300 feet and is about 3,000 feet long.

Xenoliths of the host quartz monzonite are abundant, especially near the contacts. Flow structure, moderately to well developed, bends around xenoliths and into embayments in the country rock.

Some parts of the dike are fresh, but others are so intensely chloritized and sericitized that their primary textures are nearly obliterated. The same alteration affected the enclosing country rock.

The unaltered rock is medium gray to greenish gray, fine grained, and porphyritic, with flow-alined black to dark-greenish-gray amphibole and sparse biotite phenocrysts in a matrix of yellowish-gray to grayish-orange-pink K-feldspar and plagioclase. The amphibole phenocrysts tend to form clusters and stellate twins.

The altered rock looks silvery owing to an abundance of fine sericite flakes, and commonly is darker and reddish brown owing to oxidation of disseminated pyrite. The hornblende is greener and looks micaceous because of the development of chlorite. Biotite has a golden hue.

In thin section the unaltered dike rock appears to be endomorphosed, with development of crystalloblastic textures, albitization of plagioclase, formation of actinolite and biotite from augite, and development of biotite haloes around magnetite. A few grains of euhedral augite remain.

Augite.—Augite, about 30 percent, occurs as euhedral to subhedral small equant grains and a few larger short prismatic phenocrysts. Crystals are nearly colorless, and are pleochroic, ranging from very pale pink to very pale green. They are slightly and irregularly altered along rims to actinolite and biotite.

Amphibole.—Actinolite, 1–2 percent, occurs as ragged rims on augite and also as a few small poikilitic plates in the groundmass.

Biotite and accessory minerals.—Biotite, in some places partly altered to chlorite and rutile, encloses large euhedral magnetite grains.

Plagioclase—Plagioclase, about 45 percent, occurs as phenocrysts and smaller groundmass tablets showing normal zoning with superimposed oscillatory zoning. Crenulated crystalloblastic albite-oligoclase rims extend amoebalike into the groundmass and surround the groundmass grains.

K-feldspar.—K-feldspar, about 20 per cent, occurs as a very fine groundmass mosaic. In some sections of sericitized rock K-feldspar occurs as larger poikilitic grains and clusters, enclosing or replacing other minerals.

In the altered rocks augite, actinolite, and biotite have been converted partly into chlorite, rutile, sphene, and magnetite; in some rocks completely so. In these rocks the magnetite generally is skeletal or occurs as small granules, commonly associated or intergrown with sphene, chlorite, and sparse epidote. Plagioclase is sericitized and carbonatized except, generally, for the albitic rims which tend to be clear. Small amounts of quartz are present, in some places forming late and replacing sphene. Rutile has formed in chlorite, in places producing a triangular pattern of acicular crystals.

ALLANITE-BEARING BIOTITE-HORNBLENDE TRACHYBASALT PORPHYRY

Allanite-bearing biotite-hornblende trachybasalt porphyry occurs as several dikes, a few feet to a few tens of feet wide, on the hillside just west of Grouse Creek. Sparsity of plagioclase phenocrysts suggests that the rock texturally is transitional to odinite or vogesite. The representative sample described below is from the northern of the two mapped dikes, on the line between secs. 7 and 8, T. 8 N., R. 2 W.

The rock consists of a medium-dark-gray aphanitic groundmass and 30–60 percent of euhedral phenocrysts of black hornblende and greenish-gray pyroxene (fig. 46).

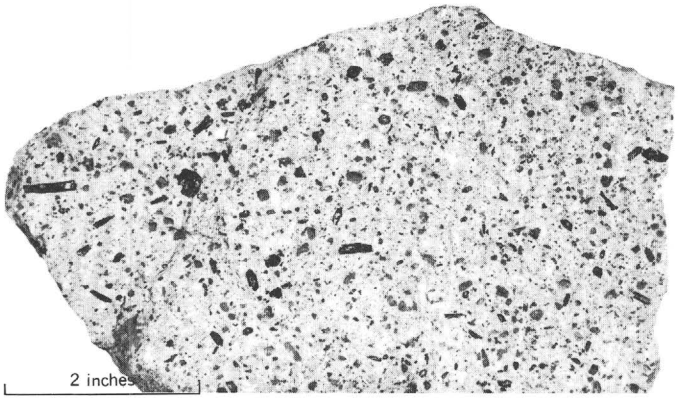


FIGURE 46.—Trachybasalt porphyry from Grouse Creek area. Black phenocrysts are hornblende, pitted equant gray phenocrysts are actinolite pseudomorphs after pyroxene, sparse white tablets are bytownite-labradorite. Scale in inches.

In some parts plagioclase is abundant; generally it is sparse or absent.

The rock weathers light olive gray; the black hornblende prisms stand out in striking contrast and the pyroxenes are etched out, leaving polygonal pits. The presence of scattered sparse plagioclase makes this rock transitional from lamprophyre to trachybasalt porphyry Local cognate inclusions of medium- to coarse-grained gabbro are composed of euhedral equant grains of black pyroxene and light-gray plagioclase. These inclusions and the dike rock enclosing them contain disseminated clusters of pyrite.

Pyroxene.—Pyroxene, about 15 percent originally, is completely altered to pseudomorphs of actinolite, epidote, a carbonate mineral, biotite, and some chlorite and sphene. Pseudomorphs are squat prisms as much as 5 mm long.

Hornblende.—Hornblende, about 15 percent, occurs as phenocrysts of slender prisms as much as 15 mm long and as subhedral grains in the groundmass. The colors are X, light olive gray to yellowish gray; Y, light olive brown to dusky yellow; and Z, moderate olive brown to grayish olive; $Z \wedge c = 28°$. The rims are slightly crenulated, owing to the breakdown of hornblende to form small magnetite granules and pale-green actinolite. Inclusions of ilmenite coated with leucoxene are common; in some places they are partly changed to sphene.

Actinolite.—Actinolite is pseudomorphic after pyroxene phenocrysts; it also occurs in fibrous clusters associated with epidote, chlorite, sphene, a carbonate mineral, and biotite. Pleochroic, with X, yellowish gray; Y, very pale green; Z, grayish yellow green to pale yellowish green; $Z \wedge c = 18°$; birefringence approximately 0.023.

Biotite.—Biotite, 3 percent, is in aggregates, pseudomorphic after pyroxene. Pleochroic, $X = Y =$ dusky yellow; $Z =$ moderate olive brown.

Plagioclase.—Plagioclase, 45–50 percent, occurs as subhedral to euhedral crystals, crystal fragments, and small clusters, commonly with crenulitic margins against feldspar granules of the groundmass, intermediate in size between the mafic phenocrysts and the groundmass. Crystals are bytownite-labradorite, An_{56-73}, average An_{70}. Oscillatory zoning is common, and albitic rims are universal. Slight albitization has proceeded from the rims along net vein systems, especially in larger crystals, which also have been partly altered to clinozoisite, calcite, and less commonly to epidote.

K-feldspar.—K-feldspar, probably about 15 percent, formed as a very fine grained late-stage mosaic and as large but inconspicuous poikilitic masses flooding the groundmass.

Accessory minerals.—Apatite and sphene are very common, and in places sphene is graphically intergrown with ilmenite; pyrite commonly is associated with sphene. Local amygdules and miarolitic cavities contain K-feldspar, quartz, pyrite (partly altered to hematite), sphene, and allanite with epidote overgrowths.

TERTIARY SYSTEM

Tertiary rocks and deposits comprise quartz latite in dikes and plugs; rhyolite in dikes, plugs, flows, and in beds of pyroclastic debris; and sedimentary deposits of poorly consolidated tuffaceous gravel, sand, silt, clay, ash, and tuff.

The oldest known Tertiary rocks in the map area are quartz latite intrusive rocks. These rocks, called dacite by Knopf (1913) and others, form the northeastern part of a broad south-southwest-trending zone of similar intrusive rocks which are contemporaneous with part of the Lowland Creek Volcanics of Eocene age (Smedes, 1965). The quartz latite in the map area is therefore considered to be of Eocene age.

Rhyolite intrusive and extrusive rocks in the map area are correlated with similar rhyolite to the southwest which is known to be younger than quartz latite of the Lowland Creek Volcanics (Ruppel, 1961; Smedes, 1962a). Weed (reported by Knopf, 1913, p. 96) regarded these rhyolites as Miocene.

The poorly consolidated tuffaceous sedimentary deposits are part of the fill of the Helena Valley. These deposits, which were called lake beds of Miocene or Pliocene age by Knopf (1913, p. 94), are coextensive with the undivided Tertiary deposits to the east which, according to Mertie and others (1951, p. 31), probably are of Oligocene age but may be Miocene. They probably are contemporaneous with the rhyolite, for several sheets of rhyolite are intercalated in them north of Helena, as indicated by well borings (Knopf, 1913, p. 94).

QUARTZ LATITE AND RELATED ROCKS

Quartz latite and related trachybasalt and latite occur rather sparsely as dikes and plugs. Dikes occur principally in poorly exposed swarms in the Antelope Creek stock, the Kokoruda Ranch complex, and in Butte Quartz Monzonite and alaskite-aplite-pegmatite near the western map edge. Only five small dikes were observed to cut prebatholithic rocks. Four cut the Elkhorn Mountains Volcanics, and one cuts the upper part of the Kootenai Formation and the lower unit of the Colorado Formation.

Two large plugs of quartz latite porphyry crop out in the Maupin Creek drainage (pl. 1). Only the larger mass has dike offshoots. The plugs are alined parallel with an arcuate belt of younger rhyolite plugs 1½ miles to the west.

The dikes appear to cut some of the metalliferous quartz veins in the Liverloop mine area, but this is uncertain owing to insufficient exposures. The dikes are in turn cut by chalcedony veins which locally silicify and kaolinize them.

PETROLOGY, PETROGRAPHY, AND CHEMICAL COMPOSITION

The most common and abundant rock type is quartz latite porphyry characterized by abundant large phenocrysts of plagioclase and quartz, sparse phenocrysts of K-feldspar and small flakes of biotite and slender prisms of hornblende set in a light-gray microcrystalline base largely of quartz and K-feldspar. Other rock types include enstatite trachybasalt and enstatite latite.

Quartz latite from the map area has not been chemically analyzed, but analyses have been made of four strikingly similar rocks from the Jefferson City quadrangle just to the west (Becraft and others, 1963, table 7, p. 28). The proportions of normative quartz, orthoclase, and plagioclase and the proportions of normative feldspars of these four samples are shown on plate 3, figure 6.

QUARTZ LATITE PORPHYRY

Rocks called quartz latite porphyry exhibit a wide range of texture and color, from black aphanitic rocks to light-gray porphyries having phenocrysts so abundant as to give the entire rock a medium-grained appearance. Alteration by deuteric and weathering processes has made them chalky to rust colored. Some dikes have margins of obsidian or pitchstone and locally are poikilitic.

The most common variety of quartz latite (fig. 47) is a porphyry which contains 20–40 percent phenocrysts of feldspars, quartz, biotite, and hornblende, in a light-gray aphanitic groundmass. K-feldspar is in white to chalky equant euhedral crystals 3–5 mm across, having random phenocrysts as much as 12 mm across. Plagioclase is abundant, but not conspicuous, as clear glassy laths as much as 10 mm long. Quartz, also inconspicuous, occurs as small white to gray or clear rounded grains generally less than 2 mm across. Biotite occurs as fresh shiny black euhedral plates usually less than 1 mm across but locally 3–4 mm across. Hornblende occurs as slender prisms, in places approaching acicular habit. Although hornblende is very conspicuous, it generally is subordinate in amount to biotite.

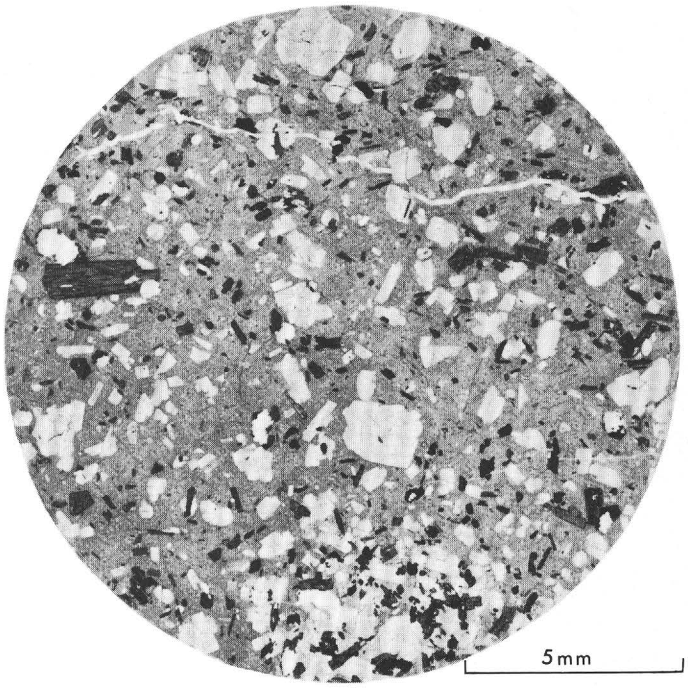


FIGURE 47.—Photomicrograph of quartz latite from dike in Liverpool mine area. Large gray prism at left and smaller ones with high relief are hornblende, small black crystals and gray crystals with lower relief are biotite. Clear crystals are quartz and feldspars. Small partly disaggregated xenolith of coarser grained quartz latite lies near lower edge of field. Plane polarized light.

Small inclusions of quartz and feldspar are common; locally larger fragments of quartz monzonite are enclosed.

Calcite and chlorite are common alteration products of the mafic minerals and locally are complete pseudomorphs. Calcite also occurs in the groundmass very extensively in places. Epidote has locally formed from both plagioclase and mafic minerals.

Plagioclase is everywhere zoned, in places strongly zoned. Both oscillatory and progressive zoning occur. In many rocks the most calcic parts of the crystals are the core and a zone in the outer portion. These calcic parts are mostly replaced by calcite, making striking patterns under the microscope. Plagioclase ranges from An_{60} to about An_{25}, with local very sharply defined sodic rims of about An_{10-15}. Glass inclusions were abundant, as indicated by devitrified and altered masses in a lineage structure.

A few dikes exhibit hornfelslike texture that suggests autometamorphism as in some sills of the prebatholith basalt and andesite. These rocks are characterized by widespread development of granules, plates, and laths of green biotite; by flamboyant oligoclase-albite crystals which surround and replace other minerals; and by interstitial quartz, in places graphically intergrown with plagioclase.

ENSTATITE TRACHYBASALT-QUARTZ LATITE PORPHYRY

A dike north of Crystal Creek (in the NE¼ sec. 3, T. 8 N., R. 2 W.,) changes along the strike from enstatite trachybasalt to quartz latite porphyry. Near the southwestern end the dike is sparsely porphyritic enstatite trachybasalt which is light olive-gray, is aphanitic with scattered phenocrysts of olive-gray to dark-greenish-gray prismatic orthopyroxene, and contains many small irregular vesicles, some of which are coated with opal.

This rock consists of a brown glassy partly devitrified base having minute granules (about 0.008 mm across) of biotite, K-feldspar, and colorless orthopyroxene; microlites and larger crystals of labradorite-andesine as much as 0.15 mm long; very sparse larger plagioclase crystals about 0.4 mm long; and scattered slender prisms of colorless enstatite as much as 3 mm long. The microlites indicate turbulent flow structure around the enstatite prisms. Opaque minerals are very sparse.

Northeastward, the dike grades into coarser grayer typical quartz latite porphyry, without pyroxene. Phenocrysts, as much as 5 mm long, are of plagioclase, K-feldspar, quartz, biotite, and hornblende. The plagioclase phenocrysts are of two types: one is clear mildly zoned calcic oligoclase to medium andesine; the other probably was more calcic, but nothing of it remains except a narrow albite-oligoclase rim around rectangular calcite pseudomorphs. The latter may correspond to the labradorite-andesine crystals of the trachybasalt end of the dike.

Quartz xenocrysts and quartzite xenoliths are scattered throughout the dike.

The striking changes in texture could have been produced by differences in cooling rates, but may not suffice to explain the change in mineralogy. Without additional data, it can only be said that two types appear to be gradational, and therefore related. For this reason, similar trachybasaltic rocks are grouped with the quartz latite.

RHYOLITE

Rhyolite occurs as plugs and dikes and as tuff, welded tuff, and rhyolitic sandstone. All rhyolite in the map area is confined to the batholithic rocks: intrusive rhyolite cuts batholithic rocks, and extrusive rhyolite rests on eroded batholithic rocks. About 2¼ miles north of the western part of the map area, however, along U.S. Highway 91, rhyolite has broken through Cambrian metasedimentary rocks (Knopf, 1963).

Flow-banded rhyolite is the prevalent type. Large masses occur at Shingle and Strawberry Buttes; whether they are intrusive or extrusive is uncertain. Similar rocks just north of the map area are known to be funnel-shaped plugs.[6] They are in line with those of the map area, and the positions of all probably are related to a single structure; therefore the large masses in the map area also are regarded as plugs.

On Lava Mountain, in the west-central part of the area (pl. 1) a poorly exposed sequence of tuff, rhyolitic sandstone, breccia, and agglomerate appears to be overlain by highly contorted, spherulitic, vesicular, and platy rhyolite lava which locally is lithophysal. These extrusive rocks have been faulted, tilted, and cut at the east and west flanks of the mountain by wide rhyolite dikes. A little galena, sphalerite, and fluorite occur in lithophysal facies of the rhyolite lavas on the south flank of Lava Mountain, as fracture fillings and coatings.

Burnt Mountain is underlain by a thick sequence of slightly to moderately welded ash-flow tuff.

PETROLOGY, PETROGRAPHY, AND CHEMICAL COMPOSITION

The rhyolite ranges from glassy to aphanitic and from even-textured to porphyritic, with phenocrysts of quartz and sanidine. The groundmass is glassy to stony and generally in thin highly contorted flow layers. The layers are alternately light gray and shades of reddish brown and alternately porous or nonporous. Some flow layers are brecciated, and the fragments are cemented by structureless rhyolite. Vesicles, miarolitic cavities, and the more porous layers commonly contain topaz in singly and doubly terminated crystals as much as 30 mm long. Lithophysal, spherulitic, and perlitic facies abound locally. Structureless rhyolite porphyry typically has a light-gray chalklike groundmass studded with large bipyramidal smoky quartz phenocrysts.

Rhyolite from the map area has not been analyzed chemically; but identical intrusive rhyolite from just west and north has been, and the composition of four samples is presented in table 2 (Nos. 16–19).

The proportions of normative quartz, orthoclase, and plagioclase of these samples are shown on plate 3, figure 7, along with two other samples of probably equivalent rhyolite from areas farther west. (Ruppel, 1963, table 4, page 49).

[6] Crowley, F. R., 1954, Geology of an area near Montana City, Montana: Montana School of Mines, unpub. B.S. thesis.

Although the norms of quartz latite partly overlap those of rhyolite (pl. 3), the average composition of the normative plagioclase is about An_{40} for the quartz latite but only about An_6 for the rhyolite. In addition, the values of SiO_2 are as follows: Quartz latite, 71–72.1, average 71.4 percent; rhyolite, 75.2 to 78.4, average 76.8 percent. That these two groups of igneous rocks truly are distinct chemically as well as mineralogically and texturally, also is shown by figure 48, which indicates the positions of the analyzed samples plotted according to Rittman's (1952) K and *an* parameters. On this diagram, in contrast to that of plate 3, the fields of composition of the two rock groups do not overlap. The discrepancy between the two diagrams has no real significance, but it illustrates the difficulties of igneous-rock nomenclature.

In rhyolite from the map area, the most abundant phenocrysts are quartz, K-feldspar, and sodic plagioclase, in that order. The groundmass consists of glass, or glass which has devitrified to chalcedony, spherulites of cristobalite, and cristobalite-K-feldspar aggregates. Tridymite occurs largely as tablets with wedge-shaped twin sections, and locally as spherulites. Most of the original tridymite has been converted to cristobalite, which in turn commonly has been converted to chalcedony. Crystallites occur profusely throughout the glassy rocks and persist as relicts into the rather coarsely crystallized rocks derived from the glassy ones by devitrification and grain growth. Dark biotite occurs as sparse small euhedral plates, commonly with many minute granules of opaque matter.

Quartz phenocrysts typically are high-temperature (β) bipyramids and short prisms. Most quartz phenocrysts are somewhat resorbed, all are ringed by spherulitic aggregates of cristobalite and feldspar. Some quartz phenocrysts exhibit complex and irregular patchy twinning; other crystals are aggregates resembling Japanese twins; still other twins are side-by-side with c axes parallel.

Curved cracks and shattered crystals invaded by the groundmass may indicate change of volume due to inversion from β- to α-quartz, or the change may be due to explosive phenomena associated with emplacement.

K-feldspar occurs as stout tabular to equant euhedral phenocrysts generally 1–2 mm long but locally as large as 10 mm. Only 1 in 20–30 crystals exhibits

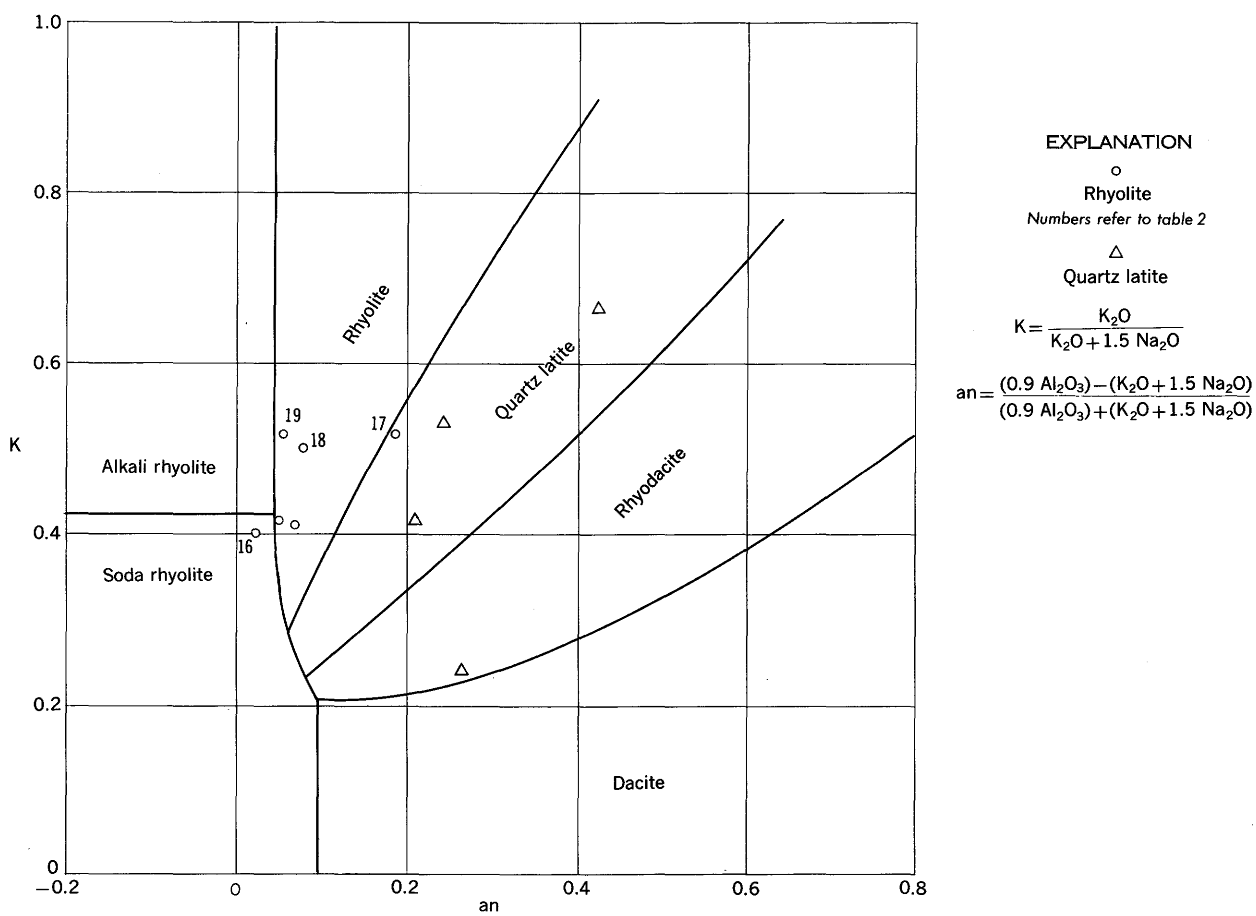


FIGURE 48.—Rhyolite and quartz latite plotted on Rittman's (1952) diagram of silica-rich volcanic rocks.

twinning. Microperthite is common in a breccia dike and plug cutting the rhyolite of Lava Mountain; elsewhere, the K-feldspar is believed to be cryptoperthite, although some extremely fine indistinct lamellae may be microperthite. Optic axial angles about X range from 5° to about 40°, suggesting that some grains are sanidine.

Plagioclase is rather sparse as phenocrysts; it occurs as squarish untwinned sodic plagioclase and as lath-shaped twinned crystals as calcic as An_{40} but mostly about An_{10-12}. The occurrence and distribution of included small blebs and streaks of K-feldspar suggests that the plagioclase was potassic, but that most of the potassic phase has exsolved. The occurrence of twinned phenocrysts increases with the degree of devitrification and crystal growth in the groundmass.

Fine sericite and clay occur as alteration products of quartz and feldspar; iron oxide chlorite, and nontronite(?) are altered from sparse biotite.

FLOW-LAYERED TOPAZ-BEARING RHYOLITE

Flow-layered rhyolite is the most abundant type of rhyolite in the map area. The layering defines an overall planar structure on which crenulations are superimposed. These crenulations range from delicate flutings with amplitudes as little as one-tenth inch to larger crumplings, folds, and convoluted structures with amplitudes of several feet or more. Crumpled layers commonly are confined between planar layers whose attitudes are consistent over wide areas.

Some exposures on Lava Mountain have open spaces several feet across, where the contorted lava has billowing and ropy structures. These openings, which are confined between planar layers, strongly suggest that the zone between planar layers was widened by piling up of a more viscous layer. In places, layers are folded over themselves four or five times. Some of the ropy structures have a diameter of 8–10 inches. They commonly are studded with small nodes produced by weathering of spherulites. Locally, lava stalactites hang from some of the open spaces, and raised elongate structures appear, probably formed by molten matter dripping or running down the sides of some of the ropy or hollow structures.

The ropy and hollow structures are interpreted as clearly indicating lava flows. The porous layered highly contorted rhyolite is similar to rhyolite exposed in dikes in the map area, in plugs just north and west of the area, and in lava flows southwest of the area.

Thin-sections reveal that the rock once was glass, but that it devitrified by spherulitic crystallization. The planar structure is marked by layers of quartz, commonly of comb-structure, separately by densely microspherulitic layers and layers with fine aggregate texture.

Topaz, although not previously reported from these rocks, is a common and widespread mineral deposited in cavities, apparently during the late vapor stage of crystallization. Topaz is especially abundant about 100 feet below the summit of Strawberry Butte, on the north slope along the road, and also on Lava Mountain in the NW¼ sec. 30, T. 8 N., R. 2 W.

Many cavities are coated with drusy quartz and topaz upon which larger topaz crystals commonly lie. The topaz crystals range from colorless to very light tints of grayish yellow, very pale blue, and purple, and are transparent to slightly clouded. The largest found measures 27 mm along the c axis and 5 mm along the b axis. The crystals are slender prisms with highly modified commonly double terminations. In the larger topaz crystals, macroprisms are dominant, giving rise to long flat sharp-edged blades; whereas in small crystals both macroprisms and brachyprisms are about equally developed, resulting in rounded needles. The macrobipyramid is the most conspicuous terminal form. A few chisel-shaped crystals were observed; their form is due to greater development of the macrodome.

RHYOLITE PORPHYRY

Several dikes are stony to resinous light-gray yellowish-gray and pale-greenish-yellow rocks abundantly studded with bipyramidal quartz phenocrysts. The largest mass of this porphyritic rock occurs in the east end of Lava Mountain. Phenocrysts range from clear to dark gray and are as much as 5 mm long. The rock is structureless except near the mines where ground water(?) alteration has affected it. The groundmass consists of a dense aggregate of quartz and feldspars without spherulites.

RHYOLITE BRECCIA

Rhyolite breccia is fairly common, but the only mappable body is a plug at the west end of the summit of Lava Mountain (pl. 1). It has a dike offshoot extendning northwestward to the north fork of Warm Springs Creek.

Blocks as much as 4 feet across of quartz monzonite, flow-banded rhyolite, rhyolite porphyry, and rhyolite breccia are abundant. Locally, the fragments outline contorted structure resembling eddies in a river. Many zones are characterized by shattered fragments in a thoroughly kaolinized matrix. A set of steep fractures commonly cuts these shattered rocks, and the fragments have a pronounced vertical elongation.

The fragments are irregularly opalized, kaolinized, and sericitized. Intensely opalized parts crop out as rubbly pinnacles and crags. Weakly opalized, and kaolinized parts have a crumbly ashlike matrix and are cut by a precipitous castellated gorge.

The exposure of the plug appears to be apical, for it dips outward under the flow-branded summit rocks. These are progressively less shattered and less opalized outward from the plug as far as 50–60 feet.

These features were seen only in the plug and are interpreted as manifestations of intermittent steam-blast explosions which did not affect the breccia dike.

The breccia is varicolored, ranging from white and shades of gray, blue, and brown, to reddish purple. Most if it is stony but some is glassy.

All phenocrysts in the breccia are shattered, and the groundmass is that of a tuff. Devitrified groundmass material embays and surrounds fragments of the shattered crystals. Opal is common to abundant as irregular masses in the groundmass, as cavity fillings, and as partial replacements of shattered feldspar.

Microperthite is common, but twinned plagioclase is rare. Glass inclusions, devitrified and commonly replaced by opal, are especially abundant in the feldspar and impart to it a peculiar "moth-eaten" texture.

Many of the inclusions in the breccia are of rhyolite porphyry similar to the rocks at the east end of Lava Mountain. Thus the breccia is younger than the flow-branded rhyolite and also appears to be younger than the rhyolite porphyry.

RHYOLITE OBSIDIAN, RHYOLITE PITCHSTONE, AND RHYOLITE PERLITE

The margins of the dikes remain glassy even though the central parts are devitrified and altered. The glassy rocks range from black to light green and include many textural varieties. All the glassy margins seen have linear flutings or striations resembling slickensides; commonly they plunge 25° or less, indicating oblique movement of the magma.

ASH-FLOW TUFF, TUFF, AND RHYOLITIC SANDSTONE

Pyroclastic and epiclastic rocks of the Tertiary rhyolite sequence are exposed only on Burnt and Lava Mountains, where they rest upon eroded Butte Quartz Monzonite. On Lava Mountain, clastic rocks and overlying rhyolite lavas are older than the intrusive rhyolite and have partly foundered into the intrusive rhyolite. On Burnt Mountain the extrusive rocks are cut by thin dikes of obsidian and pitchstone. About 2¼ miles north of the map area, along U.S. Highway 91, rhyolite has intruded rhyolite tuff and breccia. Thus, in three places where age relations are clear, extrusive rhyolite is older than intrusive.

The deposits of Burnt Mountain, poorly exposed, are largely ash-flow tuff and welded ash-flow tuff. Beds of other varieties of tuff and breccia are sparse. The few exposures of rock clearly in place are in a large landslide scar near the head of Badger Creek. There the rocks are welded ash-flow tuff with a rather uniform northwest strike and moderate southeast dip. The degree of flattening of pumice fragments ranges from about 3:1 to more than 20:1. All the rocks have been devitrified and silicified and now are dense, compact, and thoroughly indurated.

Three representative samples were studied in thin-section. All contain abundant very small plates of dark-brown biotite, are spherulitic, and contain opal in vugs. The K-feldspar is sanidine, $2Vx = 0°–5°$. Plagioclase does not occur as pyroclasts, but it is present in the groundmass.

The deposits of Lava Mountain are tuff and volcanic sandstone and conglomerate. Some beds contain fragments of charred wood. The sandstone and conglomerate beds commonly include fragments from the batholith.

SEDIMENTARY DEPOSITS

Tertiary sedimentary deposits of light-colored poorly consolidated to unconsolidated gravel, sand, silt, clay, and ash underlie the northeast edge of the map area. They lie unconformably on granodiorite of the Antelope Creek stock and on older rocks (pls. 1, 2). The relative ages of these deposits and the Tertiary rhyolite are not known. These deposits are part of the sedimentary fill of the Helena Valley to the north and are continuous with similar deposits in the Townsend Valley to the southeast. The deposits in those areas are folded, faulted, tilted, and unconformably overlain by younger sediment (Pardee, 1925,; Mertie and others, 1951; Freeman and others, 1958; and Becraft, 1958). Detailed study of these deposits in the map area was not attempted because they are largely mantled with surficial debris.

TERTIARY OR QUATERNARY SYSTEM

In the northern part of the map area (pl. 1) Tertiary sedimentary rocks and deposits are covered by weathered gravel that probably is in part of late Tertiary and in part of early Quaternary age. Some of the gravel is in fans of various age that skirt the foot of the mountains west of and near the Antelope Creek stock. Some thin patches of coarse angular monolithologic gravel probably are of mudflow origin. Other gravel may be lag gravel from the erosion of the Tertiary sedimentary and tuffaceous deposits. Weathered bouldery deposits several hundred feet thick mark an extensive landslide between the heads of Corral Creek and Mitchell Gulch. A smaller landslide is about a mile northeast of the large one.

QUATERNARY SYSTEM

GLACIAL FEATURES

Landforms and deposits clearly attributable to glaciation are widespread in the southeastern quarter of the map area (pl. 1). These include outwash, now exposed as terraces along major valleys; terminal, lateral, medial, and ground moraine; cirques; oversteepened valley walls; glacial grooves and striations on bedrock; and roches moutonnées. These features seem very young because the boulders are fresh and the landforms are well preserved. Older glacial deposits may be represented by some of the gravel mapped as Tertiary or Quaternary.

Cirques are well developed and sharply preserved at the heads of all streams draining northward from the High Peak-Casey Peak area. The largest are at the heads of the East Fork of McClellan Creek and the main branch of McClellan Creek.

The valley walls along most of the course of Beaver Creek and the South Fork of Beaver Creek have been oversteepened and scoured by glaciers. The position of the oversteepened wall is marked by cliffs, talus, and consequent gaps in vegetation. Flat tops of rock buttresses along glaciated canyon walls probably mark level strath terraces, adjusted to the height of ice in the canyons. These probable strand lines of glaciers are at elevations comparable with the rims of cirques in the headwater regions, and at decreasing elevations downstream. They indicate that the glacier in Beaver Creek was 850–900 feet thick along the margins. It would have been even thicker away from the margins, in an axial position.

Roches moutonnées and rock terraces are well developed at the head of Beaver Creek and exhibit glacial polishing, striations, and fluting.

Moraines abound in the upper parts of McClellan, Moose, Clear, Crazy, Beaver, and Jackson Creeks, and in the South Fork of Beaver Creek and the East Fork of McClellan Creek (pl. 1). Smaller moraines lie in Antelope Creek, Spokane Creek, and the South Fork of Warm Springs Creek. The most extensive deposit is that which fills the large basin east of Crazy Peak and passes over the divide into the South Fork of Beaver Creek. Erratics more than 15 feet long lie along the divide, which otherwise is smooth and devoid of bedrock.

A terminal moraine lies in Beaver Creek just east of its junction with the South Fork, about a quarter of a mile east of the map area. Fresh lateral and medial moraines lie at the mouth of Tepee Creek. Lateral moraine along the west side of Clear Creek dammed a tributary valley. A small lake, shown as alluvium on the map, now occupies a depression behind the moraine, in the W½NE¼ sec. 10, T. 7 N., R. 2 W.

Although the glacier in McClellan Creek Valley probably extended northward and merged with the glacier in the valley of the East Fork of McClellan Creek, indisputable moraine along McClellan Creek extends downstream only about to the mouth of Tepee Creek.

Numerous rounded stones from the Elkhorn Mountains Volcanics are scattered over the surface and in the stream beds in the drainage basins of Maupin and Grouse Creeks, although the volcanic rocks are not exposed in those basins. This suggests that the glacier in McClellan Creek, or outwash from it, spilled over the low divide into Maupin and Grouse Creeks. The probable spillways are saddles along the divide in the SW¼ sec. 9, and the N½ sec. 20, T. 8 N., R. 2 W.

Several levels of terrace are present along Beaver Creek. The highest of these, nearly 200 feet above the river, has slumped but appears to be a fill terrace, whereas some of the lower levels represent both fill terraces and terraces cut in fill.

Thin veneers of gravel cover many of the flat-topped high rock ledges which probably are remnants of strath terraces. These gravels probably are remnants of kame terraces deposited by melt-water streams draining the margins of the glaciers.

Outwash gravels, in general, merge upstream with moraine and downstream with gravel terraces of uncertain age but which probably are closely related to the outwash gravel. The most extensive deposit is an outwash plain 1,000 feet wide that lies along McClellan Creek from near the mouth of Tepee Creek to the mouth of the East Fork.

ALLUVIUM, COLLUVIUM, AND RELATED DEPOSITS

Unconsolidated and poorly consolidated deposits of blocks, gravel, sand, silt, and clay occur throughout the map area. Most of them are alluvial or colluvial, but some may be glacial. These deposits were not studied and are generalized on the geologic map (pl. 1).

Alluvium fills the bottoms of all larger valleys. Several alluvial terraces locally are present and can be seen especially well in the valley of Prickley Pear Creek. The older higher terraces may be outwash of the Pleistocene glaciers.

Quaternary landslides were mapped only on Lava Mountain and on the steep northern flank of the range, mainly in the NW¼ sec. 24, T. 9 N., R. 2 W., where they rest partly on older gravel. These landslides look disturbingly like glacial deposits. They form hummocky masses which resemble moraine-kettle complexes and lobate masses which resemble lateral moraine; their upturned toes somewhat resemble terminal moraines.

Well-formed perfectly preserved active rock streams occupy the headwall cirques on the East Fork of McClellan Creek. Large boulder trains at the heads of Dutchman and Warm Springs Creeks probably also are rock streams; they may be glacial debris reactivated by solifluction.

STRUCTURAL GEOLOGY

The structural framework of the area is viewed as consisting of Late Cretaceous orogenic, or prebatholith, elements; structures related to emplacement of the batholith; and younger postbatholith, elements. Many of the structures are inferred to have been influenced by ancient basement structure and to have been regenerated in Late Cretaceous and Tertiary time and perhaps in Quaternary time.

PREBATHOLITH STRUCTURES

FOLDS

The oldest structures known in the area are two small fairly sharp northeast-trending anticlines and two synclines in the Slim Sam Formation and probably in the Colorado Formation, in sec. 19, T. 9 N., R. 1 W. They plunge 20°–30° SSW. They probably started to form early in Slim Sam time, were intensified at the close of Slim Sam time, and ceased to develop before deposition of the unconformably overlying Elkhorn Mountains Volcanics.

A broad open north-northeast trending syncline crosses the volcanics in the map area. It is the northern continuation of one of a group of large folds that were formed during the Late Cretaceous orogeny (Klepper and others, 1957, pl. 1, 2). The Casey Peak and Moose Creek intrusive masses, the Antelope Creek stock, the bulk of the upper unit of the volcanics, a zone of subsided blocks of the volcanics, and the main ridge crest lie along the axis of this syncline (pl. 1). Because of the intrusive bodies and block faults, the syncline can only be approximately located. Its northern end is concealed by unconformable Tertiary and Quaternary deposits northeast of the map area.

Part of a southeast-plunging asymmetrical anticline is preserved in Paleozoic and Mesozoic strata (Lodgepole Limestone to lower part of the Kootenai Formation) in the northeastern part of the map area, near the Jefferson and Broadwater County line. This anticline lies at or beyond the eastern end of a west-trending zone of echelon folds. Like the anticline in the map area, these echelon folds all plunge southeast and are asymmetrical, with anticlines having steep east limbs and gentler west limbs.

This southeast-plunging anticline is sharply discordant with the northeast trend of the broad regional syncline and the four local prevolcanic folds just described, and is separated from them by the concealed extension of an east-west zone of faults.

FAULTS

The prebatholith faults consist of a complicated array of large faults in the region of the complex intrusive masses in the southeastern quarter of the area (pls. 1, 2) and an east-west tear fault zone and associated northerly and northeasterly cross faults in the northern part of the area (pl. 1).

Faults near the intrusive masses form complicated conjugate sets principally of northwesterly, northeasterly, and northerly trend. They bound 30 or more large blocks of the Elkhorn Mountains Volcanics. As described above, these faults clearly are related to the intrusive masses. Some of the blocks subsided into shallow magma chambers. Some intrusive masses were emplaced against the faults which bound these subsided blocks and which cut other intrusive masses. Numerous smaller blocks and plates of the volcanics also were engulfed and now are exposed within the intrusive masses (pls. 1, 2). The structural relations of the faults and intrusives, described above, indicate that the older (Casey Peak) mass is the shallow part and the younger masses (principally the Moose Creek mass) the deeper parts of a complex active magma chamber. Many of these fault blocks in a zone trending north from Moose Creek and in a zone heading northeastward toward the Antelope Creek stock subsided as much as 5,000 feet relative to the blocks outside these zones.

EAST-WEST TEAR FAULT ZONE

An east-west fault in the northern part of the area cuts the Swift and Morrison Formations and the basal part of the Kootenai. It is part of the tear-fault zone separating the southeast-plunging anticline to the north from the southwest-plunging folds to the south. Exposures in an east-west belt through that area are very poor, and additional faults may be concealed.

The Morrison Formation is nowhere completely preserved in the map area; it appears mostly to have been thinned by faulting. The formation is completely cut out by the east-west fault just north of the center of sec. 13, and is nearly cut out near the center of sec. 14, T. 9 N., R. 2 W. The dip of the east-west fault or zone of faults could not be determined, but associated small-scale faults suggest that the major ones dip steeply south.

Rocks in and marginal to this east-west zone are extensively shattered. Cataclasis is strikingly apparent on a field (pl. 1), megascopic, and microscopic (fig.

7) scale. Scarcely a piece of rock seems to have escaped the effects of this shattering for brecciated rock, feather joints, and gash fractures with quartz fillings abound, and quartz deformation lamellae were encountered in every quartz-bearing rock from this zone studied in thin section. The field and megascopic effects of cataclasis diminish rapidly south of the mapped east-west fault; only minor faults occur, and feather joints, gash fractures, and quartz fillings are lacking. Quartz deformation lamellae persist south of the zone for an unknown distance. This cataclasis probably is related to the east-west fault zone.

A fault slice of quartzite of the Quadrant Formation lies in the midst of the Phosphoria Formation on the barren rock knob east of Corral Creek in the north-middle part of sec. 14, T. 9 N., R. 2 W. The fault, dipping 30°–45° S., is interpreted as a near-bedding thrust.

FAULTS RELATED TO INTRUSIVE MASSES

A steep fault extends from the divide at the head of Moose Creek southward to Wilson Creek, south of the map area, for a total distance of at least 2¼ miles. The middle unit of the volcanics lies to the east and the lower unit to the west; the vertical displacement is of the order of 1,000–1,200 feet, east side down. For a little more than a mile, this fault was intruded by part of the Moose Creek intrusive mass and obliterated (pls. 1, 2). In a narrow belt extending south of the map area, the Moose Creek mass and the volcanic rocks were metamorphosed by an inferred dike, probably a satellite of the Butte Quartz Monzonite which was intruded along the fault, as described above.

Rocks of the lower unit of the volcanic sequence that lie in a block between the batholith and the Moose Creek mass are cut by at least five steep minor faults trending northwest. The northernmost two faults, and probably all five, are cut by the north-south fault that lies near the head of Moose Creek. One of the five faults was partly invaded by the Moose Creek mass, two others were intruded by dikes of basalt which probably is part of the Moose Creek mass. The offset along four of the faults could have resulted either from right-lateral slip or from relative subsidence to the north.

Another steep fault extends from the divide at the head of Moose Creek northwestward into the head of the South Fork of Warm Springs Creek, where it is truncated by the batholith (pls. 1, 2). The southeastern end of the fault has been invaded by the Moose Creek mass and probably controlled the northeast boundary of that mass. Along its northwestern part, this fault has brought rocks of the lower part of the lower unit of the volcanic rocks on the south against the upper part of the middle unit on the north —a vertical displacement of at least 4,000 feet, with north side down. This fault cuts a sill offshoot of the Casey Peak mass, cuts other faults in that area, and is cut by the Moose Creek mass.

A north-south fault whose position is now occupied by intrusive rock lay east of Clear Creek and cut rock of the middle and upper units of the volcanic sequence. The eastern boundary of the Moose Creek mass was controlled by this fault, and a long, slender basalt dike offshoot was emplaced along the northern part of the fault. The displacement of the base of the upper unit of the volcanic rocks could have been produced either by about 1,400 feet of vertical movement with west side down, by about 4,000 feet of left-lateral movement, or by some combination; the main component probably was vertical. Three subparallel smaller faults were mapped to the east; two had the same direction of displacement, but the easternmost moved in an opposite direction.

A north-northeast trending zone of faults lies about half a mile east of Crazy Creek (pl. 1). Two fault strands, 300–500 feet apart, were mapped. The net vertical displacement across the zone is more than 1,500 feet, with rocks of the lower unit of the volcanic rocks on the east lying against rocks of the middle unit on the west. Left-lateral slip of at least 6,000 feet would be required to produce the same stratigraphic displacement. To the north the fault zone ends against the South Fork fault. Physiographic features suggest that the fault zone continues south-southwest of the map area for about 3 miles, making a total length of about 5 miles. Relations between this fault zone and the syenogabbro plug at the southern edge of the area are not known. The syenogabbro is not sheared or brecciated and may be younger than the fault.

To judge by the mutual crosscutting relations, the faults in the north-northeast-trending zone are virtually contemporaneous with the zone of the northwest-trending faults just north of Crazy Peak. The faults at Crazy Peak do not cut the Crazy Peak intrusive mass, but they do cut slightly older sills east and southeast of Crazy Peak.

South Fork fault.—A northwest-trending steep fault of large displacement crosses the South Fork of Beaver Creek and continues to the main branch of Beaver Creek, where it meets the Beaver Creek fault (pls. 1, 2). The South Fork fault extends about 1¾ miles southeast of the map area, where it is cut off by the large north-northeast-trending Weasel Creek fault (R. A. Weeks, oral commun., 1956).

Although the South Fork fault seems rather certainly to be cut by the Beaver Creek fault, aerial photographs show a distinct lineament extending from the South Fork fault northwestward across the Beaver Creek fault. The lineament indicates that the South Fork fault probably is a broad fault zone; the lineament is 1,800 feet wide at the southeast, and tapers to about 1,200 feet where it meets the Beaver Creek fault. Just across the Beaver Creek fault the lineament abruptly narrows to only 400 feet and tapers northwestward to less than 100 feet in the saddle between Casey and High Peaks. The lineament is covered by glacial debris at the head of Tepee Creek. These features suggest that the South Fork fault was cut by the Beaver Creek fault, but that there may have been some renewed movement along the South Fork fault, cutting the Beaver Creek fault.

The South Fork fault is the north boundary of a large block of the lower unit of the volcanic rocks in the southeast corner of the map, bounded on the north and west by blocks of the middle unit (pls. 1, 2). In that area the relative displacement across the fault zone is about 3,000 feet, north side down. Farther northwest, the South Fork fault separates two blocks of the middle unit of the volcanic rocks and has relative displacement on the order of 1,500 feet, north side down.

Ghastly Canyon fault.—Another northwest-trending steep fault zone, the Ghastly Canyon fault, lies about 1¼ miles north of the South Fork fault (pl. 1). The fault is cut off by the batholith at the northwest end; it was not mapped beyond the map area at the southeast. In the southeast, rocks of the middle unit of the volcanic sequence lie on both sides of the fault. In the northwest, rocks near the boundary of the middle and upper units of the volcanic sequence on the south dip toward rocks of the middle unit on the north. In both areas the direction of relative vertical displacement is south side down. The amount of displacement is not known; in both areas it could be as little as 500–600 feet, but may be many times that.

Although the critical region is covered by glacial debris, the east margin of the Casey Peak intrusive mass appears to be offset by the fault at least 800 feet in a left-lateral sense. The eastern margin of the batholith makes a conspicuous bend at the northwest end of the fault, as though due to shouldering aside or large-scale stoping controlled by the Ghastly Canyon fault. The two small bodies of quartz monzonite near the valley floor in Casey Meadows may be cupolas of the Jackson Creek lobe or the main body of the batholith, controlled by this fault. A small area of high-grade thermal metamorphism and closely spaced zones of intense hydrothermal alteration, which lie along and parallel with the fault in Sheep Park, suggest that at least one other cupola lies at shallow depth along the fault.

The photographic lineament indicates that the Ghastly Canyon fault zone is as much as 800 feet wide in its central part, tapering to 100 feet or less at both ends.

Beaver Creek fault.—A fault zone of northeast trend in and near the saddle on the ridge between Crazy and High Peaks is inferred to extend beneath the upper valley of Beaver Creek because of the straight course of the valley, abrupt southward termination of the Casey Peak intrusive mass, and northward termination of the South Fork fault (pl. 1). The northern of the two mapped fault strands appears to continue west-southwest beneath glacial debris at the head of Clear Creek, to the headwall of the McClellan Creek cirque, where it terminates against a salient of the Moose Creek mass and apparently against a fault of northwest trend. The Staubach Creek fault may be a northeastern segment of the Beaver Creek fault, offset in a left-lateral sense by the Ghastly Canyon fault. The block northwest of the Beaver Creek fault moved relatively down, on the order of 1,000 feet.

Staubach Creek fault.—A fault of north-northeast trend extends from the southeast fork of Antelope Creek to the headwaters of Staubach Creek (pl. 1). Perhaps it is an offset segment of the Beaver Creek fault. The northeastern part of the Casey Peak intrusive mass lies against or was cut by the fault—exposures are too poor to tell which. The displacement of the base of the upper unit of the volcanic rocks can be explained by the block west of the fault having moved relatively either 8,000 feet or more southward, or about 2,500 feet down. Lateral motion is favored because it can more reasonably account for the conspicuous differences in thickness and proportion of welded tuff on opposite sides of the fault (p. 33).

STRUCTURES RELATED TO EMPLACEMENT OF THE BATHOLITH

In the southern half of the area the contact of the Butte Quartz Monzonite with the Elkhorn Mountains Volcanics is relatively straight, trends about N. 25° E., and is virtually vertical (pls. 1, 2). This straight steep contact continues southwest for at least 60 miles (Klepper and others, 1957, pls. 1, 2; Klepper, oral commun., 1960). The batholith rocks are not faulted near the contact. In detail the contact is irregular, and the batholith locally extends eastward as dikes and blunt embayments into prebatholithic rocks. These relations suggest that the eastern margin of the batholith was controlled by a major fault just west of the present contact. Irregularities of the contact probably are due to block stoping of country rock along earlier zones of weakness or along anastomosing splits of the main fault.

The sedimentary rocks between Corral Creek and Mitchell Gulch have been step-faulted along north-trending faults, the steps rising progressively westward and perhaps having some left-lateral shift, also. The net relative displacement across this zone of faults is at least 3,000 feet, west side up. The prebatholith faults that bound these stepped blocks probably are related to the main fault that controlled emplacement of the Butte Quartz Monzonite. If the batholith was emplaced along a fault on the eastern margin, it most likely advanced by lifting its roof, west of the main fault. The step faults are in harmony with such a mechanism, because they too were lifted on the west.

One of these step-faulted blocks is wedge shaped and contains a twisted southward-plunging anticline. This fold is asymmetrical to the south: it has a steep west limb near the Kokoruda Ranch complex and a gently dipping east limb. To the north, both limbs are of lower dip, and the axis locally plunges northward at low angles. The axial trace is sigmoid; at each end the axis is bent toward the bounding fault, suggesting a left-lateral component along each fault (pl. 1). There was also probably a large vertical component, west side up, to effect the large stratigraphic offset. The fault along the west side of this wedge-shaped block controlled the eastern margin of the Kokoruda Ranch complex. The anticline may be due to compression during faulting, or it may have been produced by forceful intrusion of the batholith. A conspicuous lineament lies along this fault and continues southward along the western margin of the Jackson Creek lobe, through Casey Meadows, to a point just west of Casey Peak.

A gentle broad south-plunging syncline lies near the head of Corral Creek. Its axis could not be located closely and is not shown on the map. Smaller unmapped south-plunging folds and north-south step faults lie in a zone about ¼–½ mile wide east of the margin of the Kokoruda Ranch complex. The trend and the limited extent of these structures suggest that they also were induced by drag along the main fault which controlled intrusion of the batholith.

Schist and amphibolite in the screen of volcanic rocks between the Jackson Creek lobe and the main mass of the batholith, and in local zones just north of the Kokoruda Ranch complex, described above, are interpreted as mylonite formed by intense shearing, owing to the force of emplacement and subsequent mimetic recrystallization by the heat from the batholith.

Foliation, compositional layering, schlieren, and lineation in batholith rocks, described above probably record only cataclasis late in the period of consolidation of the batholith and do not necessarily afford any clue to primary directions of intrusion of the magma.

POSTBATHOLITH STRUCTURES

Postbatholith structures include faults principally of northeast and northwest trends but also of east-west and, rarely, north-south trend, and steep joints with prominent north-south and east-west maxima. Many east-west faults and fractures are filled with quartz or chalcedony veins. Dikes of quartz latite and of rhyolite fill fractures of each of the main trends listed above.

FAULTS

A few faults were mapped within the batholith, as well as some which clearly offset its borders. These faults are parallel with major drainage, roughly of east-west, northeast, and northwest trend, and suggest that other drainage of the same trends is fault controlled. Alinement of Tertiary quartz latite and rhyolite intrusive bodies suggest an additional north-northwest fault or joint set, but no postbatholith faults of that trend were observed.

North Spokane Creek fault.—A large steep northeast-trending fault follows the north fork of Spokane Creek in the northeastern part of the map area (pl. 1). To the east it cuts the Antelope Creek stock; westward it passes into volcanic rocks and is lost near the ridge crest. The fault near the northern tip of the Jackson Creek lobe of the batholith may be a continuation; it has the same motion sense of north side down. The fault clearly cuts the Antelope Creek stock; its relation to the Butte Quartz Monzonite is uncertain. The main movement probably was vertical. The offset of the volcanic rocks requires about 2,000 feet of movement, north side down.

Sheep Creek fault.—Parallel with the North Spokane Creek fault is a steep northeast-trending fault which follows Sheep Creek for about a mile and continues another 1¼ miles into the range (pls. 1, 2). The displacement appears to increase northeastward from the western end, with relative motion of north side up. At the base of the middle unit of the volcanic rocks the throw is no more than 200 feet, but it is considerably greater to the northeast. Highly metamorphosed and coarsely recrystallized volcanic rocks to the south are brought against incipiently metamorphosed volcanic and sedimentary rocks to the north, indicating that the fault is younger than the thermal metamorphism, and, therefore, younger than the intrusive rocks which produced the metamorphism.

An east-west fault lies along the upper reaches of the north fork of Jackson Creek and, judging by the straight trend of Jackson Creek, probably extends westward to the creek mouth. Assuming that the intrusive contacts are for the most part vertical, the displacement across this fault is left lateral; it appears to increase in magnitude eastward, for the west edge of the Jackson Creek lobe is offset only about 200 feet, whereas the eastern contact is offset about 800 feet.

Tepee Creek fault.—A fault of about east-west trend was traced for 2½ miles from the canyon wall of Tepee Creek, south of the center of the map area, to within half a mile of the north fork of Warm Springs Creek (pl. 1). A single fault in the west, it bifurcates just west of McClellan Creek. The fault displaces Elkhorn Mountains Volcanics and the Boulder batholith. The batholith contact is offset across this fault by about two-thirds of a mile in a left-lateral sense, assuming that the batholith contact is nearly vertical. A large slab of rock of the middle unit of the volcanic sequence engulfed in the Casey Peak intrusive mass lies to the north, and rocks of the basal part of the upper unit lie to the south, suggesting vertical displacement, south side down.

A strong lineament extends along and beyond the mapped west end of the Tepee Creek fault, to the North Fork of Warm Springs Creek, suggesting that the fault probably extends that far. A narrow Tertiary rhyolite dike that cuts across the lineament without offset requires that the inferred extension of the Tepee Creek fault is older than the dike.

A fault of similar trend lies about 1,000 feet north of the Tepee Creek fault. This fault does not appear to offset the batholith. A lineament follows this fault and extends beyond it to the west, passing through the same rhyolite dike as does the inferred extension of the Tepee Creek fault. This northern fault is no doubt also of prerhyolite and postbatholith age.

Another fault lies about a mile north of the mouth of Tepee Creek. This fault extends southeast from McClellan Creek for about half a mile, but it could not be traced west of the creek. The assumed steep batholith contact is offset in a left-lateral sense by this fault for at least 600 feet and perhaps as much as 1,500 feet.

Burnt Mountain fault.—The fault near the southeast end of the rhyolite tuff of Burnt Mountain apparently is a hinge fault. Relative to the block southeast of the fault, the northeastern part went down at least 120 feet and the southwestern part went up at least 200 feet.

Faults in Lava Mountain.—The rhyolitic sandstone, tuff, and lava on Lava Mountain have been cut by steep northwesterly and northeasterly faults, tilted or dropped down against quartz veins in Butte Quartz Monzonite and invaded by rhyolite intrusive masses. These relations suggest partial collapse of the extrusive rhyolite into the shallow chamber of magma from which it was derived.

Faults in the Dutchman Creek area.—Several steep faults were mapped in the Dutchman Creek drainage in the southwest corner of the area. Displacement of some is shown by offsets of dikes, sheets, and zones of intense hydrothermal alteration; in others the direction of motion is not known with certainty. The position and extent of some are marked by lines of seeps, offset aplite and quartz latite dikes, and sharp topographic depressions.

Alhambra fault.—A slightly sinuous roughly north-south fault crosses Warm Springs Creek near its mouth, at the area of hot springs near Alhambra. The hot springs and their ancient and modern deposits occur on both sides of the valley along the trace of the fault. The fault cuts several aplite bodies and chalcedony veins. North of the creek the fault also cuts a large aplite-alaskite sheet, dropping the west side and perhaps also moving it southward. The vertical motion was hingelike, with the hinge a little north of the aplite sheet, because the base of the aplite on the west side of the fault is 40 feet lower on the north and 200 feet lower at the south than on the east side.

VEINS

East-west veins cut the batholith and, locally, older rocks. Chalcedony veins are younger, and some quartz veins probably are older than the Tertiary quartz latite intrusives. Some veins were repeatedly sheared and then healed by more silica.

Metalliferous quartz veins.—The frequency diagram for quartz veins (fig. 42) shows a strong maximum centered at N. 85° E.; 80 percent of all units (192) lie within the 50° zone N. 70° E.–S. 60° E., and 58 percent of all units lie within the 30° zone N. 80° E.–S. 70° E.

Chalcedony veins.—The frequency diagram for chalcedony veins (fig. 30) shows a strong maximum centered at N. 85° E., and 42 percent of all units (698) lie within 30° zone N. 70° E.–S. 80° E.

The chalcedony veins are confined to the western part of the mapped area. This area of abundant veins is also characterized by abundant dikes of alaskite and intrusive bodies of rhyolite and quartz latite (pl. 1).

The dominantly east-west trend of the chalcedony veins changes abruptly to a strong southwest trend just west of the map area. This southwest trend is nearly parallel with the batholith contact and coincides approximately with a belt of Tertiary quartz latite dikes and alaskite dikes. The southwestern part of this belt of dikes and veins dies out in an east-west splay similar to that at the northeast end (the western part of the map area). Thus, the western part of the map area is at the northeast end of a fracture system whose shape is a long narrow sigmoid. Because the fractures are represented by fissure fillings, the implied motion that operated was a right-lateral couple acting on a north-northeast zone of weakness.

JOINTS

The 283 joints measured in the Butte Quartz Monzonite give two pronounced maxima, east-west vertical, and north-south vertical (fig. 30). The north-south set is more pronounced (an 11-percent maximum) and is almost universally represented by sheeted joints. The spacing of these sheeted joints in outcrop ranges from about an inch to a foot or more.

The measurements represent localities scattered unevenly over much of the batholith; they include joints from the parts near the straight steep probably fault-controlled eastern contact in the south, near the Kokoruda Ranch complex in the north, near the highly irregular contact in the Crystal Creek-Jackson Creek area, in the Jackson Creek lobe, and far from the contact in the central and western parts of the batholith in the map area. Because the joint pattern is so simple, yet the shape and contacts of the batholith so irregular, it appears that the joints of the two major sets are not related to emplacement and cooling of the batholith but are younger features.

Joints in prebatholith rocks are more variable in short distances, probably because of the great range in competence of the rocks. Joints in the volcanic rocks locally could not be accurately measured because of strong magnetic variation. Joints within the prebatholith intrusive bodies are related to those bodies rather than to regional structures.

LINEAMENTS

Linear features on aerial photographs were transferred onto a topographic base map and the trends were incorporated in the frequency diagram shown in fig. 30. The frequency diagram shows a wide dispersion of northeast trends, accentuated by maxima at about N. 35° E. and N. 60° E. Northerly trends are insignificant. Although the northeast maxima do not coincide with the northeast fault maximum, it is clear that many lineaments are the direct expression of faults. However, many lineaments cut squarely across geologic boundaries without offset. No brecciation, alteration, or other clues to the origin of many of these lineaments could be found in the field; their origin is not known. Some may reflect local zones of sheeted joints.

Many of the faults are marked by strong lineaments, but in some places there is incomplete coincidence of faults and related lineaments. Some of those divergences may be unrecognized splits of the faults.

The lineaments generally are less than 50 feet wide. Those along the South Fork fault and the central part of the Ghastly Canyon fault are as much as 1,800 feet wide. This may indicate that those faults actually are broad fault zones.

MINERAL DEPOSITS

Mineral deposits in the area include (1) metalliferous quartz and chalcedony veins, largely confined to batholith rocks; (2) an oxidized replacement gold deposit along a gouge zone of a bedding-plane fault in the Quadrant Formation; (3) disseminated silver-lead-zinc deposits irregularly distributed in Tertiary rhyolite of Lava Mountain; (4) a replacement magnetite deposit in the monzonite dike west of the Antelope Creek stock; and (5) several gold placers.

The mines, with few exceptions, have been idle for years, and many apparently are mined out. As a result of inactivity, at the time of my examination most mines were caved, flooded, or inaccessible because of bad air, most pits and trenches were slumped or filled with trash, and surface exposures of the veins were poor. The mine dumps generally had been thoroughly picked and, in some cases, mixed, so that they were and still are poor—and even misleading—guides to the nature of the deposit. Thus, little new information was obtained regarding the size, structure, mineralogy, grade, or extent of development of the veins.

The total value of mineral production from all lode and placer deposits in the map area is estimated as more than $3,500,000, based on the data of Stone (1910), Knopf (1913), Pardee and Schrader (1933), and Roby and others (1960). More than half of this value was in silver, the remainder chiefly in gold, lead, and a little copper.

VEINS

The veins can be classed into two main groups: (1) quartz veins containing varying amounts of pyrite, sphalerite, galena, arsenopyrite, chalcopyrite, tetrahedrite, gold, ruby silver, native silver, and pitchblende(?), and in the gangue, carbonate minerals, quartz, chalcedony, and a little barite; and (2) chalcedony veins, stringers, and zones mostly devoid of metallic minerals but locally containing sparse silver or uranium minerals, pyrite, galena, chalcopyrite, sphalerite, carbonate minerals, barite, and opal.

Nearly all veins are in batholith rocks. Wherever age relations are known or can reasonably be inferred, the quartz veins are the same age as the chalcedony veins, or are older. The metalliferous quartz veins cut rocks of all stages of the batholith and are cut, locally, by Tertiary quartz latite and rhyolite dikes. Chalcedony veins cut quartz veins and Tertiary quartz latite dikes; their age relations with Tertiary rhyolite are not clear.

The quartz veins may further be subdivided into four groups based on the proportions of contained base and precious metals, and type of gangue: (1) epithermal high-grade silver; (2) mesothermal lead-zinc-silver-gold; (3) mesothermal gold and silver; and (4) hypothermal gold. Veins of type (1) may be contemporaneous with the chalcedony veins. Some of these epithermal veins are now exposed at lower altitudes than some of the mesothermal veins, suggesting that they are younger and are not a shallower facies of the mesothermal veins. Veins of types (2) and (3) probably are variants of a single type. Deposits of type (4), because of their high-temperature minerals (hedenbergite-diopside and magnetite) and the conspicuous presence of tourmaline, probably are the oldest deposits and are considered as correlative with Knopf's "tourmalinic lodes" of the "older ore deposits" (1913, p. 43–54), which he considers as closely related to late-stage consolidation of the batholith.

The majority of veins of all types strike about N. 80° E. and stand vertical or dip steeply. All veins are filled fissures; many quartz veins also were enlarged by replacing the wallwork. Chalcedony veins and high-grade silver quartz veins exhibit considerable brecciation and cementation, whereas other types of quartz veins have thinly banded structure in many parts and associated anastomosing clay gouge seams. In the Mammoth and White Pine mines sparse uranium mineralization was found in seams of pulverized and milled-out quartz and sulfides.

EPITHERMAL HIGH-GRADE SILVER QUARTZ VEINS

The epithermal high-grade silver quartz veins are partly oxidized deposits containing small amounts of gold and varying amounts of lead, zinc, copper, and antimony. Ore minerals recognized are native silver, ruby silver, argentiferous galena, sphalerite, argentite, tetrahedrite, cerussite, azurite, malachite, and sparse pyrite and arsenopyrite. Ore minerals are associated with vuggy comb quartz. Barite occurs as local druses and as coarse euhedral crystals that are younger than the young chalcedony gangue.

The veins commonly are brecciated and enclose blocks of quartz monzonite and aplite. Gray, blue, brown, red, and varicolored chalcedony and ankerite, which have firmly cemented these breccias, occur also as stringers and veinlets cutting milky quartz and sulfides. Several episodes of brecciation and cementation are recorded in the structures of many of the veins. The veins commonly are near aplite-alaskite-pegmatite dikes.

Argillic and sericitic alteration is weak to intense in the quartz monzonite along the veins but mostly lacking in aplite host rock.

Veins of this type locally are very high grade at or near the surface. Many of the veins reportedly did not wedge, but the silver content diminished with depth. Most of the mines were small and short lived; a noteworthy exception was the Liverpool.

Veins of this type were exploited in the Legal Tender, Mammoth, Liverpool-Washington, and Meadow mines. Total value of production from these and related smaller mines and prospects is estimated to have exceeded $1,500,000, chiefly in silver and lead.

LEGAL TENDER VEIN

The Legal Tender mine is on the crest of a low ridge just east of Prickly Pear Creek, near the town of Clancy. Individual claims are the First National, Second National, Legal Tender, and May Lode. The vein system consists of one main lode and several parallel stringers and splits. The main lode—locally called the Silver Vein—lies in the Legal Tender claim and is developed by a 500-foot shaft with at least 6 levels of drifts, and extensive stopes. All but the numerous surface workings are inaccessible.

The main lode consists of several narrow vertical veins of quartz and sulfides considerably brecciated and cemented by chalcedony. A large composite brecciated vertical chalcedony vein meets the lode at a low angle about 400 feet west of the shaft and either merges with the lode or, more likely, cuts it off. The lode is not known just south of this chalcedony vein, but east of the shaft several small low-grade veins occur south of the chalcedony vein and trend parallel with the main lode. If these small veins represent offset parts of the main vein system to the north of the chalcedony vein, a right-lateral horizontal displacement of at least 1,500 feet is indicated along a fault presumably occupied by the chalcedony vein.

The quartz veins and the chalcedony vein are cut by steep cross faults. East of the shaft the veins are offset to the left by amounts increasing eastward from about 5 feet near the shaft to about 150 feet near the eastern end of the vein. West of the shaft the veins are offset to the right 5 and 10 feet by two faults.

The veins are considerably oxidized. Ore minerals occur in bands and lenses, commonly overlapping or in echelon, and consist of highly argentiferous galena, sphalerite, argentite, native silver (wire, sheet, and flake), ruby silver, and cerussite. Copper and antimony have been reported (Raymond, 1873, p. 230). Abundant oxides of iron and manganese color the vein dark. Carbonates of copper occur in the gangue.

At the surface the lode is 4–6 feet wide, stands vertical, and strikes N. 80° E. At depth the lode is reported to be of the same strike but of steep southerly dip and to be locally as much as 35 feet wide. The individual veins in the lode rarely are more than 18 inches wide; stringers of valuable sulfides rarely are more than 12 inches wide. Three to six veins generally make up the lode.

The ore reportedly averaged more than 100 ounces of silver per ton, but, locally, pyrargyrite raised the grade to 200 ounces. In the first year of operation nearly $92,000 worth of ore was shipped (Raymond, 1873, p. 230). The grade is reported to have diminished in depth and development work to have ceased at the 400-foot level.

A short crosscut adit was driven north-northeast toward the juncture of quartz and chalcedony veins from the bottom of the deep ravine that lies south of the vein. This adit was open in 1954, and the rock was well exposed. The chalcedony vein was cut about 175 feet from the portal, and the adit extended about 45 feet beyond; but the vein was not met, as it should have been if the quartz and chalcedony veins remained vertical at depth. The crosscut shows the chalcedony vein to be vertical. Therefore, the quartz vein changes dip or pinches with depth.

MEADOW MINE

The Meadow mine is in the midst of the dredge tailings in Prickly Pear Valley, between the mouths of Lump Gulch and Strawberry Creek. The prospect was discovered in 1936 when the Winston Bros. gold dredge dug up rich fragments of the vein from the bedrock. In 1949 and 1950, A. E. Nugent and H. Norgaard sank a 92-foot shaft and began to develop the mine by drifts and raises. During this period about 130 tons of ore, averaging about 136 ounces of silver per ton and a little less than 2 percent lead and 8 percent zinc, were shipped to the smelter at East Helena. Net smelter returns averaged about $129 per ton. The smelter did not pay for zinc, which averaged more than 150 pounds per ton.

The vein has an average strike of N. 83° E., with minor gentle deviations and several small splits that diverge eastward. The dip ranges from 70° S. to vertical. The width ranges from 2 inches to 2 feet, but it is mostly 4–6 inches.

Vein minerals include an early assemblage of quartz, sphalerite, galena, tetrahedrite, argentite, pyrargyrite, and minor pyrite and arsenopyrite, commonly brecciated and cemented by a later assemblage of quartz, chalcedony, and ankerite. Minute amounts of radioactive material are reported to be associated with the chalcedony. Barite, which appears to be the youngest mineral in the vein, occurs as scattered euhedral crystals lining cavities in brecciated chalcedony.

LIVERPOOL-WASHINGTON VEIN

The Liverpool-Washington vein is near the northwest corner of the area, north of Lump Gulch and about a mile west of the Meadow mine. The vein ranges in strike from east-west to about N. 75° E., has an overall strike of N. 85° E., stands nearly vertical, and at the surface is as much as 4 feet wide. Surface mapping suggests that the east-west parts are splits from a main north-northeast-trending vein whose projected strike, across Lump Gulch, meets a similar vein just west of the map area—the Little Nell (or Little Nellie).

The vein is known as the Liverpool where it is stoped below the 400 level and as the Washington where stoped above the 400 level. It is developed by a shaft that is at least 750 feet deep and by several levels and stopes.

The vein consists of quartz, galena, sphalerite, pyrite, ruby silver, tetrahedrite, and sparse chalcopyrite, all of which commonly are brecciated and cemented by chalcedony and ankerite. One small sample of pitchblende was found on the dump; however, the notable lack of radioactivity in the area and elsewhere on the dump makes it unlikely that the sample originally came from this mine.

Splits from the veins are reported to be few. Some are of chalcedony only, others are of chalcedony and ankerite, and others consist of quartz and sulfides.

Several parallel and subparallel veins (including the Tycoon on the east and the Little Dotte on the north) make up a general vein system, the eastern and western extensions of which are considered to be the Meadow and Little Nell veins, respectively. This vein system makes an arcuate bend in the map area, convex northward. The intersection of this arc with northwest-trending veins may have been of importance in localizing the ore.

MAMMOTH MINE

The Mammoth mine is just above valley bottom on the east side of Prickly Pear Creek about midway between Alhambra and Clancy. By 1897 a 400-foot adit had been driven and connected to the surface through stopes (Walsh, 1906). Much of the original dump was mined because of its high ore content (Mining World, 1905b).

Minor radioactivity was detected, and the mine reopened in 1954, at which time the adit level and a 100-foot winze with levels at 35 and 60 feet were opened. Weak radioactivity was detected in two highly sheared quartz-sulfide bands on the adit level.

The vein is a highly sheared fissure deposit, as much as 5 feet wide, consisting of quartz with braided stringers of pyrite, galena, and sphalerite. Much quartz monzonite is milled into the vein. Chalcedony heals the broken vein and is itself locally brecciated, sheared, and recemented with still younger chalcedony. The ore occurs in shoots irregularly along the vein. The vein trends about N. 55° E. and dips 85° SE. in the upper workings and about 75° in the lower. Several minor splits diverge eastward from the south side.

The host quartz monzonite is kaolinized and sericitized for several tens of feet from the vein. The altered rock on both sides is cut by many chalcedony stringers; these, and the intensity of alteration, decrease away from the main vein. Pyrite is disseminated irregularly through the altered zone.

MESOTHERMAL LEAD-ZINC-SILVER-GOLD QUARTZ VEINS

The quartz veins classed here as mesothermal lead-zinc-silver-gold were mined principally for lead, but nearly all contain gold, silver, and zinc, and some contain copper. The mesothermal gold and silver veins probably are variants low in base-metal sulfides or devoid of them.

WARM SPRINGS CREEK AREA

The principal mines are near the head of the middle fork of Warm Springs Creek and in the Maupin Creek area; many other veins in the Maupin Creek area are of the mesothermal gold and silver type. Only the White Pine mine on Warm Springs Creek, which had been in operation in 1952, was open in 1953 and 1954. In 1953 the owner, Mr. George M. Hoffman of Helena, discovered anomalous radioactivity in material on the dump. The radioactivity of the vein is discussed below.

The White Pine vein is judged—on the basis of structure, age relations, mineralogy, and production—to be representative of veins of this type. The vein is part of a persistent east-west system that includes the Guess, Bell (Fleming and Steinbrenner), Carbonate Chief, War Eagle, Eagles Nest, B & G, Hummingbird, Little Emma, Middlesex, and others. The system is continuous for at least a mile and has a known vertical extent of more than 500 feet. Mineralization is reported to be persistent, but known ore bodies have been small scattered pods or lenses.

Older workings on the White Pine vein were two adits high up the slopes of a ravine on the south side of Warm Springs Creek. These adits totaled more than 1,200 feet in length (Walsh, 1912). Development was by winzes to several levels and by stopes. The main Bell adit, the only level accessible in 1954, consists of an 800-foot crosscut to the White Pine vein and a 600-foot eastward drift along the vein. This drift is west of the westernmost ore reached by the old upper workings.

Scanty reports indicate that the vein in the older workings was as much as 5 feet wide, and ore bodies were as much as 30 inches wide (Mining World, 1903, 1909).

The White Pine vein in the Bell adit is a sheared fissure filling of quartz and sulfides from 1 to 7 feet wide striking N. 85°–90° W. and dipping 80°–90° S. The average width is 3–4 feet. In 1954 the vein was mostly concealed by lagging. Where exposed, it is composed of bleached, sericitized, and kaolinized quartz monzonite laced with stringers and lenses of pyrite and sphalerite, lesser amounts of galena and arsenopyrite, and sparse chalcopyrite and quartz. Pyrite is disseminated in the wallrock, and strands of gouge cut the vein zone. Pyrite and other sulfides are in places sufficiently concentrated to form small ore shoots.

The largest concentration is reported to have been 30–40 feet long and 1½–2 feet wide. In 1954 the footwall part of this lens was exposed along the south wall of the drift, where it consists of 4–8 inches of massive sphalerite and pyrite and subordinate galena; the massive sulfides are in sharp contact with bleached pyritic quartz monzonite in the footwall and are separated by a 4-inch gouge band from the rest of the vein. A 4-ton shipment, presumably from this body, contained 0.1 ounce of gold and 15.1 ounces of silver per ton, 7.65 percent lead, 5.65 percent zinc, and 0.22 percent copper (George Hoffman, oral commun., 1954).

At the east face the vein consists of about 3 feet of soft and bleached pyritic quartz monzonite cut by a 4-inch lens and several thin stringers of pyrite and by 4–5 thin seams of black, locally radioactive, gouge. The pyrite lens contains sparse sphalerite and quartz. Slickensides range from horizontal to vertical.

According to Stone (1910), the mines of the Warm Springs Creek area had produced ore valued at more than $1,000,000 by 1907. Incomplete records indicate subsequent shipments from the White Pine and Bell mines aggregating 5,700 tons of ore containing an average of about 1.14 ounces of gold and 5.85 ounces of silver per ton, 2.9 percent lead, 2.0 percent zinc, and 0.3 percent copper. Net proceeds as listed by these records were about $166,000.

The Bell (Fleming-Steinbrenner) is reported to have produced lead, silver, and gold worth more than $250,000 (Mining World, 1907). The Carbonate Chief and Bell together are reported by Stone (1910, p. 88) to have yielded ore worth $800,000, and the Mocking Bird to have produced ore sold for $10,000–$12,000.

The Carbonate Chief vein is reported to have been as much as 6 feet wide and to have contained 1½–3 ounces of gold per ton (Mining World, 1905a). Work was done by means of a shaft and from an adit through the Bell mine.

MAUPIN CREEK AREA

In the Maupin and Grouse Creek area most of the veins are of the mesothermal gold and silver type, but a few contain silver, lead, zinc, and copper in significant amounts. These are described briefly by Stone (1910, p. 87–88) and include the Good Cheer, Willard group, Fritz Invay's claims (west of the Willard group), and the Skookum lode (near the Euclid).

The Good Cheer mine is on a 4½-foot vertical quartz vein of east-west trend and is developed by a shaft at least 165 feet deep and by 400 feet of levels. A $30-per-ton ore zone, 3–5 feet wide, has been reported (Mining World, 1904). Ore minerals are pyrite, chalcopyrite, and galena (Stone, 1910, p. 87).

The Willard group, which includes the Dover, Relief, Osage, Alpha, and Union claims, is located on two steep east-west quartz veins about 20 feet wide (Stone, 1910, p. 88). More than 400 tons of ore, valued at about $40 per ton, purportedly had been shipped before 1910. Fritz Invay's claim yielded sphalerite, galena, chalcopyrite, and siderite, according to Stone (1910, p. 88), and thus was similar to the carbonate-bearing veins of the Pilot-Euclid system on Maupin Creek.

MESOTHERMAL GOLD AND SILVER QUARTZ VEINS

Most of the mesothermal gold and silver quartz veins are in the Maupin Creek area. The meager information on the area has been taken mainly from published reports, especially that of Stone (1910, p. 86–88).

The veins contain abundant ankerite, pyrite, and arsenopyrite in addition to quartz. Other sulfides are sparse, and the ore yielded mainly only gold, silver, or both. The principal vein system has been developed for nearly a mile and consists of two principal veins, the Pilot (or Pilot-Katy) and the Euclid (or Golden Gate, or Pilot-Golden Gate) veins. The Pilot is an east-west structure, and the Euclid is of northeast trend. They join between the Pilot and Katy adits. The Pilot mine is said to have a 330-foot shaft and a 1,200-foot adit. There are 9 shafts and a crosscut at the Euclid, whose main shaft is 200 feet or more deep. Some ore from the Euclid contained more than 4 ounces of gold per ton (Stone, 1910, p. 87).

The Golden Gate has a shaft at least 200 feet deep and 500 feet of levels on a vein system 70 feet wide bearing N. 88° W. The bulk of the ore averaged about $23 per ton, and the mine is reported to have grossed about $31,000, mostly in gold (Stone, 1910, p. 87).

The Black Bear claim, on the divide between Warm Springs and McClellan Creeks, is on an east-west vein and is reported (Stone, 1910, p. 87) to have contained 12 ounces of silver and about 0.08 ounce of gold per ton. The vein was worked by several shallow shafts. It was one of the few veins that was mainly silver bearing.

The Bosphorous lode, at the junction of Crystal and McClellan Creeks, is a highly oxidized quartz-limonite deposit containing gold.

The Buzz mine, on the south fork of Spokane Creek, was a rich, though small, producer. The ore was in a narrow sheeted zone in porphyritic basalt. The vein is highly oxidized and consists of auriferous pyrite, limonite, and milky quartz. The main adit portal is at the contact between the monzonite dike and the basalt. The ore shoots were small pods of quartz irregularly distributed along the sheeted structure for at least 1,000 feet horizontally and at least 150 feet vertically. The sheeted zone strikes about N. 87° E., dips 45° S., and ranges in width from 4 inches to 2 feet (Reed, 1951, p. 37). Development was by five adits and two shafts. Production after 1891 probably amounted to $60,000 from ore that was reported to range in value from $20 to $400 per ton in gold (Reed, 1951, p. 37).

The Strawberry mine, at the divide between Strawberry and Grouse Creeks, yielded gold ore worth about $100 per ton (Mining World, 1906), but no record of production is available.

Several adits low on the west slopes of Moose Creek are reported to have entered low grade gold-silver-lead carbonate ore in highly oxidized volcanic rocks.

HYPOTHERMAL GOLD QUARTZ VEINS

Hypothermal gold lodes in the Mitchell Gulch area were extensively worked in the past and were the source of the placer deposits in Mitchell Gulch. Veins of this type contain much quartz, carbonate mineral, pyrite, and arsenopyrite, and a little sphalerite and chalcopyrite. They are considered to be hypothermal because the gangue contains diopside hedenbergite, garnet, tourmaline, and magnetite.

The Economy and Chicago-Last Hope vein systems include the main hypothermal deposits. These vein systems were worked principally from shafts; the Last Hope also was developed by an adit.

The ores were mined chiefly for their gold content, but they also contained some silver and, locally, small amounts of lead, copper, and zinc. The upper parts of all deposits are highly oxidized and yielded high-grade gold ore. The Last Hope-Chicago lode tends to follow the base of the middle unit of the Elkhorn Mountains Volcanics, and thus appears to be a bedding replacement deposit. The host rocks have been extensively epidotized and replaced by magnetite, tourmaline, diopside-hedenbergite, carbonate minerals, and sulfides. Some blocks of ore on the dump are 15 inches across and consist of massive pyrite and arsenopyrite with sparse sphalerite.

The paucity of quartz, abundance of tourmaline, and evidence of replacement origin suggest that the Last Hope-Chicago lode belongs to the tourmalinic class of deposits described by Knopf (1913), which he considered as being older than the silver-lead-zinc quartz veins.

Coarsely crystalline arsenopyrite and quartz are the most abundant vein minerals on the dumps of the Economy mine shaft and shafts to the south. The Economy and nearby lodes appear to have been fissure veins, but considerable replacement also is suggested by the abundance of sulfides in the wallrocks.

CHALCEDONY VEINS

Chalcedony veins are abundant in quartz monzonite in the western part of the map area. In addition to chalcedony, significant amounts of microcrystalline quartz and opal are present. The veins range in width from a fraction of an inch to a few feet; most are in the ¼- to 1-inch range. They occur alone or in linear zones, locally called reefs. The zones are nearly vertical and are continuous laterally and vertically for several hundred feet. The host rocks have been fractured, brecciated, silicified, and locally sericitized along these zones. Veins and veinlets within these zones mostly are subparallel with the trend of the zone but are discontinuous and lenticular. Veinlets of at least four ages commonly are present. In many places silica of earlier generations is brecciated and cemented by silica of later generations. Some reef zones are offset by cross faults, some of which also are silicified. In general, the zones are wider and contain more veinlets of silica at and near intersections of two zones.

In many places where chalcedony veinlets and silicified quartz monzonite are abundant at the surface, silica is much sparser in underground workings; the veins are fewer, narrower, and less conspicuous, and the country rock is not so intensely silicified. These relations strongly suggest that much of the silica is concentrated near the surface and that it may be supergene, related to Quaternary weathering.

The trends of all mapped chalcedony veins are summarized in the frequency diagram in figure 30.

Chalcedony veins cut metalliferous quartz veins and Tertiary quartz latite dikes (for example, the north-south dike just west of Alhambra).

The chalcedony veins are of various shades of red, yellow, brown, and gray to almost black. The black color probably is due to the presence of dispersed very fine grained pyrite, chalcopyrite, and possibly arsenopyrite (on the basis of X-ray determinations by D. Y. Meschter, written commun., 1953). Most of the chalcedony veins are devoid of ore minerals, or virtually so; a few contain uranium minerals or sparse amounts of tetrahedrite or ruby silver, galena, sphalerite, pyrite, chalcopyrite, and arsenopyrite. Near the W. Wilson mine, many dark-gray to black chalcedony veins are radioactive and probably contain dispersed very finely divided primary pitchblende; one grab sample of dark-gray chalcedony assayed 0.20 percent uranium and another, 0.15 percent uranium (Roberts and Gude, 1953). In the W. Wilson mine, commercial quantities of uranium occur in pockets in veins of this type and in altered wallrock adjacent to the veins. Some veins contain barite that formed late, possibly during the period of uranium mineralization.

Exposures in the Alhambra (Sullivan) lead-silver-gold mine illustrate the abundance, spacing, and trend of chalcedony veins and veinlets (fig. 49).

OXIDIZED GOLD DEPOSIT

The Dobler mine, in the S½S½ sec. 7, T. 9 N., R. 1 W., is an inclined shaft with drifts at several levels. It explores an oxidized gold deposit along a gouge zone of a bedding-plane fault in dolomite between thick beds of quartzite of the Quadrant Formation.

The deposit appears to be a sheetlike replacement body, but this is uncertain because of intensive oxidation and silicification, and poor exposures. The ore was mined for its content of gold, silver, and lead; the richest gold was near the surface. Limonite boxworks after galena and pyrite are abundant and well developed. Cerussite and quartz commonly encrust the boxwork. Large masses of jasperoid occur irregularly throughout. Pyromorphite occurs locally as well-developed hollow hexagonal prisms (cylinders). According to Mr. Rudolph Dobler, the mine owner (oral commun., 1954), much of the gold was in coarse flakes.

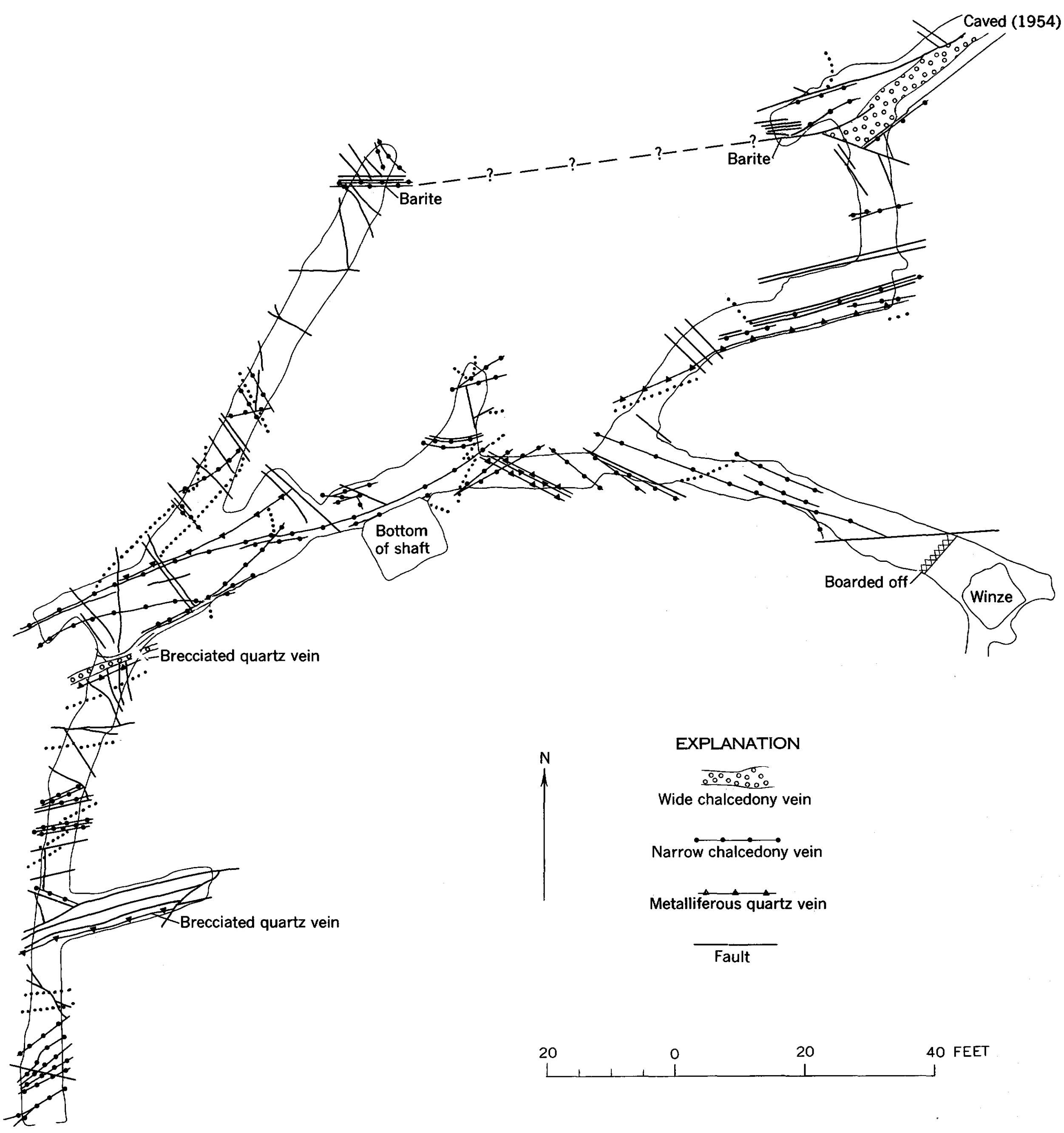


FIGURE 49.—Map showing chalcedony veins in the Alhambra (Sullivan) mine.

A very heavy flow of water, encountered at about the 100-foot level, hindered mining operations and eventually forced the mine to shut down after a depth of about 230 feet was attained and more than 1,000 tons of ore had been shipped. According to assay data furnished by Mr. Dobler, the shipments ranged from 0.30 to 4.32 ounces of gold and 1.0 to 9.1 ounces of silver per ton and averaged about 0.9 ounce of gold and 4.1 ounces of silver per ton. Lead ranged from 0.5 to 27.0 percent, with an average of about 8.8 percent.

DISSEMINATED SILVER-LEAD-ZINC DEPOSITS

Adits on Lava Mountain explore small deposits of silver-lead-zinc ore in tuff, rhyolite breccia, and lithophysal rhyolite. Meager reports in old mining journals refer to silver ore that apparently was taken from these deposits. The deposits are judged, on the basis of sparse

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dump samples, to have consisted of galena, sphalerite, pale-green and purple fluorite, and quartz in anastomosing veinlets cementing brecciated rhyolite, as fillings in lithophysal cavities, and as local small replacement masses. Radioactivity several times above background was recorded from the waters draining one of these caved adits.

Deposits of this type are restricted, so far as is known, to the Tertiary rhyolite of Lava Mountain and probably are genetically related to the rhyolite.

Quartz veins of the base- and precious-metal type, similar to those of the White Pine vein system, occur in quartz monzonite on the lower slopes of Lava Mountain and clearly are older than—and overlain by—the rhyolite.

REPLACEMENT MAGNETITE DEPOSIT

Several short shafts and prospect pits have been dug in magnetite deposits in the monzonite dike west of the Antelope Creek stock. The deposits are not exposed, but large blocks on the dumps show the magnetite to be heavily stained with limonite and to occur as irregular masses and discontinuous layers associated with contaminated monzonite which is coarse grained and contains abundant scapolite, calcite, epidote, poikilitic biotite, and coarse pale-green amphibole. These deposits are interpreted as magnetite replacement of calcareous xenoliths.

URANIUM DEPOSITS AND RADIOACTIVITY

From 1949 to 1956 the area was intensively prospected for uranium, but the only ore mined was from the W. Wilson group of claims near the middle western edge. This small production, in spite of intensive prospecting, leaves little optimism about the uranium potential of the area.

Uranium-bearing carbonaceous shale and lignite occur in the Helena Valley and the northern part of the Townsend Valley (Becraft, 1958) in Tertiary sedimentary deposits which are continuous with those in the northern part of the map area. However, no anomalous radioactivity was detected in these deposits in the map area by a reconnaissance radiation survey made with a carborne scintillation counter.

The radioactivity of all large dumps, most small dumps, and all accessible underground workings was tested with a scintillation counter during 1954. All anomalous radioactivity detected is plotted on plate 1 and is summarized in table 8. Observations include both metalliferous quartz veins and chalcedony veins. The anomalies fall into two distinct groups. The smaller eastern group of anomalies is associated with metalliferous quartz veins. The larger group, to the west, includes anomalies associated with both metalliferous quartz veins and with chalcedony veins, and is the eastern part of a large group of anomalies that extends westward about 2½ miles (Becraft and others, 1954; Roberts and Gude, 1953). This belt of anomalies roughly coincides with a zone of abundant chalcedony veins; sheets, dikes, and irregular bodies of alaskite and related felsic rocks; and quartz latite dikes. The greatest radioactivity detected within the map area is at and near the W. Wilson claims, which include the President and the A. Lincoln-G. Washington chalcedony vein system, from which some uranium ore has been shipped.

Uranium occurs as primary grains of pitchblende and as secondary minerals, of which the following have been identified (Wright and Emerson, 1957, p. 40; Emerson and Wright, 1957, p. 222): meta-autunite, meta-uranocircite, meta-zeunerite, phosphuranylite, uranophane, beta-uranophane, and gummite. In addition, rutherfordine and voglite were reported (Roberts and Gude, 1953). Minute grains of galena and pyrite, which appear to have been introduced with the silica and uranium, occur sporadically in the silica of the reefs in or near the uraniferous deposits. Other sulfides present include minute grains of sphalerite, tetrahedrite, argentite, chalcopyrite, and covellite (Bieler and Wright, 1960).

Roberts and Gude (1953) pointed out that the close spatial association of primary and secondary uranium minerals indicates that little or no migration of uranium has occurred. They concluded that the primary uranium probably was deposited in tectonic cavities by ascending epithermal fluids during one of the periods of silicification.

The main silica reef at the W. Wilson trends about N. 60° E., and small spurs on the south side trend eastward. Silica deposits are lenticular fissure fillings and impregnations in altered quartz monzonite. Dark-gray uraniferous chalcedony is present in four of the five uranium-bearing lenses studied by Roberts and Gude (1953). Known ore bodies are lenticular in plan and are irregularly dispersed throughout the silicified reef zones. A grab sample of high-grade ore assayed 9.58 percent uranium, other grab samples of mineralized rock assayed as high as 1.27 percent U, and a channel sample assayed 3.18 percent U (Roberts and Gude, 1953). Uranium ore was mined sporadically from small ore bodies at the W. Wilson mine from 1951 to 1956.

TABLE 8.—*Localities with anomalous radioactivity*

Locality	Type of vein	Type of sample	Radioactivity in mr per hr		Ratio of total radioactivity to background	Percent		Remarks
			Background	Anomaly, above background		eU[1]	U[2]	
W. Wilson and vicinity.	Chalcedony		1.7	8.3	4.9		>1.0	Mines contain pitchblende and secondary uranium minerals.
Alhambra (Sullivan).	do	Select, vein and silicified quartz monzonite.				0.03		Several inches of vein and country rock.
White Pine	Quartz	6-in. channel				0.016–.003		
Cave-in near face.	do	Select high grade.					.645 .014	2 samples.
Vein at face	do	do				.125		Very spotty distribution.
Dump	do	Select				.47 .15	 1.37	 3 samples.
B & G; dump	do	Select high grade.				.26		On strike of White Pine vein.
Carbonate Chief; dump 15 ft south of shaft.	do	do	.012	.062	6.2			Lower readings elsewhere.
Legal Tender:								
Dump of east shaft.	do	do	.001	.004	5.0			
Trend along vein.	do	do	.010	.021	3.1			
Dump of west shaft.	do	do	.007	.019	3.7			
Liverpool:								
Dump of main shaft.	do	do	.011 .011	.035 .013	4.2 2.2			 Pitchblende reported.
Dump of shaft 1,200 ft north of main shaft.	do	do	.008	.018	3.3			
War Eagle	do	4 ft altered and gouge zone.	.018	.065	4.6	.07	Trace	Radioactivity probably associated with limonite. Many zones of lower radioactivity.
Black Bear; dump	do	Select high grade	.010	.013	2.3			
Meadow; dump	do	do	.011	.012	2.1			
Mammoth:								
Dump 100 ft from portal.	do	do	.008	.008	2.0			
Southwest corner of main level.	do	do	.008	.007	1.9			Radioactivity is lower on dump of discovery shaft and underground.
Willard Group	do	do	.009	.008	1.9			Iron-stained quartz monzonite at shaft edge. Radioactivity of ore samples on dump is lower
N½NW¼, sec. 3, T. 8 N., R. 3 W.; dump.	do	do	.010	.017	2.7			Radioactivity is lower on east side of Strawberry Creek.
SE¼NW¼, sec. 30, T. 8 N., R. 2 W.; adit.	Disseminated Ag-Pb-Zn.	Water draining caved adit.	x	1.5x	2.5			Radioactivity of dump area is lower.

[1] Equivalent uranium, determined by H. W. Smedes.

[2] Uranium; chemical determination reported by L. D. Jarrard (written commun. 1953).

Detailed mineralogical and chemical studies of the W. Wilson mine were made by Bieler and Wright (1960), Emerson and Wright (1957), Meschter (1953), Roberts and Gude (1953), Wright and Bieler (1960), Wright and Emerson (1957), and Wright and others (1956).

Radioactivity has been recorded from a number of metalliferous quartz veins. The most radioactive of these form a system of parallel veins in the batholith along the middle fork of Warm Springs Creek. The veins strike east-west and include the War Eagle, Bell, Carbonate Chief, B & G, White Pine, and other veins.

The White Pine vein is exposed in places along 600 feet of recent workings, but radioactivity was detected in only a few places underground. The most radioactive of these was in highly sheared vein matter at the face of the drift, where a small select sample analyzed 0.125 percent equivalent uranium (eU). One 6-inch zone of altered country rock and sheared vein matter had high radioactivity underground, but the maximum eU of any part of this zone was only 0.016 percent. Perhaps the radioactivity was concentrated in the clay and limonite parts, some of which fell away from the sample and were not collected. Radioactivity was detected in a rockfall near the face. Samples from this rock pile are reported to contain 0.76 percent eU_3O_8 (L. D. Jarrard, written commun., 1953). No uranium minerals have been detected. Several radioactive samples were found on the dump. A diamond-drill hole from the White Pine vein 150 feet into the south wall had a heavy flow of water which had higher uranium content than water draining the White Pine vein (Philip Fix, written commun., 1954).

Greater radioactivity was detected underground in the War Eagle vein than in the White Pine vein, and water draining the caved Bell workings has a higher uranium content than does water from the White Pine workings (Philip Fix, written commun., 1954).

The most radioactive of several zones in the War Eagle adit gave a reading of 0.065 mr per hr above the background count of 0.018 mr per hr. This zone comprises 4 feet of altered quartz monzonite and gouge with several thin stringers of sheared sulfide minerals.

The B & G mine lies approximately on a westward projection of the White Pine vein. A dump sample was reported to contain 0.31 percent eU (L. D. Jarrard, written commun., 1953).

Pitchblende has been reported from the dump of the Liverpool mine, but I found no uranium minerals there. Selected samples from the dump have radioactivity of 0.035 mr per hr above background radiation of 0.011 mr per hr.

GOLD PLACER DEPOSITS

Placer deposits in Quaternary gravel were extensively worked along Prickly Pear Creek and less extensively along the upper part of Mitchell Gulch. Local placer operations have been carried out in McClellan Creek near the junction with Maupin Creek, in the lower parts of the East Fork of McClellan Creek, along Jackson Creek, and in Warm Springs Creek.

A summary of the available data, through 1947, on placer mining history and production in the area is given by Lyden (1948, p. 42–47). The following information is largely summarized from Lyden's report.

Prickly Pear Creek.—Placer gold was discovered near Clancy in 1865, but no figures are available on the apparently small production from then until 1933. The Winston Bros. Co., in 1933, placed a dragline dredge in operation near East Helena and moved steadily upstream treating gravel that yielded more than 25 cents per cubic yard in gold. Subsequently, several other dredges were put in operation farther upstream. Lyden reported (1948, p. 42) that in less than 4½ months in 1938, one electric connected-bucket dredge south of Clancy produced more than 3,000 fine ounces of gold from gravel that averaged about 18 cents per cubic yard. This one dredge also is reported to have recovered nearly $1,500,000 in placer gold in less than 5 years of operation, which accounts for nearly half of the total placer gold production of Jefferson County during the entire period from 1904 to 1945.

Mitchell Gulch. — Placer operations in Mitchell Gulch apparently commenced in 1909 and continued intermittently until 1941. The work was practically confined to the narrow valley and some of the low benchland along the west bank for about a mile of the creek downstream (north) from the Economy Mine area. Lyden (1948, p. 47) estimated gross production to have been greater than $500,000. Most of the recovery was by sluicing; some was by a stationary washing plant.

McClellan Creek.—Work has been done intermittently along McClellan Creek since 1904. Production was reported for only 7 years, but the amount of gold recovered was not stated. Lyden concluded (1948, p. 47) that the total product undoubtedly was small, and that a production of $122 in gold during 1931 probably was an average recovery for one season.

Warm Springs Creek.—The production of placer gold from Warm Springs Creek is not known. The placers were discovered in 1865, but they have not been worked since 1904, the year that the first detailed production reports were published. Apparently the deposits were small and not very rich.

Jackson Creek.—No published dates or production data are known for the operations in Jackson Creek—only the scars and slumped gravel piles overgrown with small bushes and grass attest to the former placering activity.

MINERALS

ORE MINERALS AND THEIR GANGUE

The following minerals occur in the various veins and lodes described above:

Ore minerals	*Gangue*
Argentite	Amphibole
Arsenopyrite	Ankerite
Azurite	Barite
Beta-uranophane	Biotite
Cerussite	Calcite
Chalcopyrite	Chalcedony
Covellite	Diopside-hedenbergite
Galena and argentiferous galena	Epidote
	Fluorite
Gold	Garnet
Gummite	Iron oxides
Magnetite	Jasper
Malachite	Magnetite
Meta-autunite	Manganese oxides
Meta-uranocircite	Opal
Meta-zeunerite	Quartz
Phosphuranylite	Scapolite
Pitchblende	Siderite
Pyrargyrite (ruby silver)	Tourmaline
Pyromorphite	
Rutherfordine	
Silver	
Sphalerite	
Tetrahedrite	
Voglite	

MINERALS COATING JOINT SURFACES

The following minerals were observed partly or completely coating some joint surfaces in prevolcanic sedimentary rocks, away from the batholith and stocks:

Quartz	Manganese oxides
Calcite	Iron oxides
Clay minerals	Aragonite

In addition, the following were observed on joint surfaces near the batholith and stocks:

Specularite	Tourmaline
Magnetite	Garnet
Epidote	Aragonite
Zoisite	Calcite
Wollastonite	Pyrite
Thompsonite	

Rocks of the Elkhorn Mountains Volcanics have the following minerals as joint coatings:

Thompsonite	Magnetite
Phillipsite	Quartz
Chabazite	Actinolite
Clay minerals	Calcite
Epidote	Specularite
Garnet	Iron oxides
Thulite	Manganese oxides
Penninite	

Rocks of the Boulder batholith have the following minerals as joint coatings; some of these are of deuteric origin, some were introduced during emplacement of aplite-alaskite-pegmatite of the late stage, and some are related to younger episodes of hydrothermal alteration or weathering:

Tourmaline	Actinolite
Epidote	Calcite
Zoisite	Opal
Molybdenite	Chalcedony
Pyrite	Barite
Chalcopyrite	Clay minerals
Sphene	Manganese oxides
Apatite	Uranium-bearing minerals

GEOLOGIC HISTORY

The following discussion is an attempt to place in proper chronologic order all the main known and inferred geologic events and deposits in the northern Elkhorn Mountains. The inferences, based on uncertainties which have already been discussed and evaluated, are arbitrarily stated as facts here, for brevity and continuity.

Although a fairly complete history, beginning in Precambrian time, is recorded in rocks nearby, the known geologic record in the map area begins in the Carboniferous. During Carboniferous and Permian time, the site of the map area was part of a stable shelf. Through most of this time the area was covered by shallow seas whose shifting shorelines gave rise to bedded marine clastic carbonate and noncarbonate rocks of the Madison Group and to the Amsden, Quadrant, and Phosphoria Formations.

Before the start of Triassic time, the sea had receded southward from the area and the earlier strata emerged in a low landmass. In Late Jurassic time, the sea advanced again from the east and covered the area with a blanket of calcareous cherty sandstone of the Swift Formation, derived largely from the emergent landmass of the Big Belt uplift a short distance to the east.

The Swift sea retreated eastward, and in latest Jurassic time the region was blanketed by continental deposits of the Morrison Formation, derived by erosion of lowlands which were rising to the west. The landmasses to the west continued to rise and shed erosional debris into the area during Early Cretaceous time to form alternating coarse- and fine-grained fluvial deposits of the Kootenai Formation.

In Late Cretaceous time the sea advanced and retreated several times, and alternating marine and nonmarine deposits of siltstone, sandstone, and shale of the Colorado Formation were deposited. Small rock and crystal fragments and fine ash from some distant volcanic eruptions were blown and washed into the area and deposited along with the sand, silt, and mud.

During Niobrara time, volcanic activity commenced closer to the area, and more and coarser tuff became admixed with the shallow marine deposits of the lower part of the Slim Sam Formation. General uplift, at least locally accompanied by folding, forced the early Slim Sam sea to retreat. Tuff continued to accumulate, but it was admixed with continental clastic detritus in late Slim Sam time.

During deposition of the upper Slim Sam beds, local folding was intensified. Cessation of this local folding probably coincided with the end of Slim Sam deposition; this was followed by vast outpourings of fragmental volcanic detritus, lava, and ash flows of the Elkhorn Mountains Volcanics in Late Cretaceous time. This volcanism resulted in the building up of a pile of calc-alkaline volcanic rocks more than 10,000 feet thick.

At first the volcanism largely gave rise to pyroclastic and epiclastic deposits and autobrecciated lava, ranging in composition from rhyodacite to basalt, and a few thin quartz latite ash flows. These deposits filled in the irregularities of the topography and built up a surface of low relief upon which numerous extensive thick ash flows of the middle unit were erupted and welded into sheets of rhyolite, interbedded with rhyodacitic to basaltic fragmental rocks similar to those below. This accumulation resulted in a broad flat shieldlike dome or plateau.

Broad gentle folding or tilting, known south of the area, may have occurred after deposition of the lower unit of the volcanics. Intermittent subsidence probably accompanied deposition of the middle unit. During this time the volcanism was cyclic, probably through fractionation in shallow magma chambers. Ash flows were erupted when fractures tapped the chamber after the magma had built up a high-level differentiate of rhyolite to quartz latite composition and high volatile content. Following expulsion of this differentiate, fractures opening the chamber at various times allowed the escape of basaltic, andesitic, or rhyodacitic magma having low to intermediate concentration of volatiles and produced lava and pyroclastic rocks and shallow intrusive bodies some of which were intruded into only partly consolidated moist sediment.

After the middle unit of the volcanics was deposited, active volcanism in the area sharply diminished, faulting probably occurred, and deposits of the upper unit began to accumulate in fault-bounded depressions and in streams. Preexisting volcanics were eroded from high places, reworked, and deposited in low places, together with some juvenile ash.

Following deposition of the upper unit, faulting became more intense, and that part of the volcanic plateau in the map area broke up into large blocks. Many of these blocks foundered in shallow magma reservoirs which had been rising ever higher into the volcanics throughout their period of accumulation, and which formed large complex intrusive masses with related dikes and sills.

Folding and faulting reached a climax after volcanism. During this main orogeny, steep faults in an east-west tear-fault zone cut the northern part of the area. To the north the beds were bent into a southeast-plunging anticline, whereas to the south they were bent into a broad south-southwest-plunging syncline which is part of a set of major folds south of the area.

When the main folding ceased, the area was bisected by a steep fault which extended some 60 miles to the south-southwest. Shortly after this faulting—but still during the Late Cretaceous and perhaps continuing into the Paleocene—the Boulder batholith was emplaced, in at least four major stages.

Magma of the early stage was forcibly emplaced in the northern part of the area, where it deformed and thermally metamorphosed its walls, and cooled to form the early mafic rocks of the Kokoruda Ranch complex. A ring dike was injected east of the complex, and plugs were injected into volcanic rocks in the middle-eastern and southern parts of the area.

Granodiorite of the next stage of batholith formation was emplaced as the Antelope Creek stock, which is partly contained within the earlier ring dike and partly cut out the ring dike, and as a younger component of the Kokoruda Ranch complex, where it is coextensive with the Unionville Granodiorite.

Magma of the Butte Quartz Monzonite, which constitutes the main volume of the batholith, was controlled along the east side by the steep fault which earlier bisected the area. This magma was emplaced by lifting the preexisting rock west of the fault; the magma did not deform its walls or metamorphose them as intensely as did the earlier magmas. Simultaneous intrusion of magma on both sides effected intense shearing in a narrow septum of volcanic rocks between Jackson and Crystal Creeks. Butte Quartz Monzonite in a selvage was broken and tectonically mixed with brecciated volcanic rocks on the western side of that septum. Subsequently, the sheared rocks were recrystallized and metasomatically metamorphosed.

Alaskite and related felsic rocks of the last stage of the batholith formed as late differentiates of the cooling Butte Quartz Monzonite magma. Where pockets or chambers of these differentiates were trapped, they remained to form ill-defined segregation bodies; where tapped by fractures, they moved upward to form dikes with blended contacts and, at still higher levels, dikes with sharply defined contacts. As cooling and crystallization of the Butte Quartz Monzonite continued, newly formed felsic differentiates produced alaskite and related rocks which cut similar but earlier formed rocks.

Some dikes of lamprophyre and other porphyritic rocks were injected into the Elkhorn Mountains Volcanics, the Kokoruda Ranch complex, and the Butte Quartz Monzonite, probably at several times during emplacement of the batholith, and perhaps also later.

After the batholith had formed, perhaps in the Paleocene, the area was faulted, cut by metalliferous quartz veins containing base and precious metals, uplifted, and eroded. Then, in Eocene time, dikes and plugs of quartz latite were injected contemporaneously with the extrusion, southwest of the area, of lavas which rest on eroded quartz veins in the batholith and older rocks.

The region was again faulted, cut by veins, uplifted, eroded and, probably in Miocene time, partly covered by rhyolitic sand, ash flows, and other detritus. Rhyolite lava then poured out from several vents and, together with the fragmental rhyolite, locally foundered in the shallow subterranean magma chambers. These and older rocks were then intruded by dikes and plugs of massive rhyolite and, lastly, by rhyolite breccia.

Stream, lake, delta, and mudflow deposits, and tuff —perhaps in part contemporaneous with the rhyolite tuff and lava—filled the tectonically subsiding Helena Valley with ash, gravel, sand, silt, clay, and tuff and extended into the northern part of the map area.

These basin deposits and older rocks were faulted and tilted and then eroded to a mature surface during late Tertiary or early Quaternary time. Several large landslides formed, and thick alluvial gravel aprons skirted the range.

During the Pleistocene, alpine glaciers occupied all valleys in the higher parts of the range, and an icecap may have encompassed Crazy Peak. Marginal melt-water streams cut terraces along the sides of the glaciers and left flat-topped massive rock ledges thinly veneered with gravel.

A glacier formed at the summit and east slopes of Crazy Peak and, moving eastward, filled the large depression at the head of Ghastly Canyon and spilled over into the head of the glacier that occupied the South Fork of Beaver Creek. Late in the period of glaciation, Ghastly Canyon pirated the melt-water drainage from the Crazy Peak ice mass. This drainage cut the present chasm of Ghastly Canyon in which an underfit stream now flows intermittently.

The glacier in McClellan Creek extended northward and merged with the glacier in the valley of the East Fork. Part of the glacier, or melt water along its side, spilled westward over the low divides into Maupin and Grouse Creeks, where it left a veneer of gravel of volcanic rock spread over batholith terrain.

As the glaciers melted, moraine and outwash plains were deposited and locally merged. Later melt water eroded and destroyed many of the morainal features, cut into the earlier outwash plains, and left several terrace levels of younger outwash gravel. Modern streams partly reworked some of the moraine and outwash gravel and modified slightly the ground surface previously modeled by glaciation.

Hot springs near Alhambra deposited reefs and terraces of travertine. Processes of solifluction and mass wasting continue to form rock streams, landslides, talus, and hillwash which merge locally with recent valley-fill and flood-plain deposits. The hot springs, which formerly precipitated travertine, now deposit thin crusts of silica.

Severe earthquakes, from epicenters not far away, occurred in the area in 1925, 1935, and 1959. Weaker ones are much more frequent; they all point to continuing tectonic unrest in this part of the Rocky Mountains.

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