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The Boulder batholith as a source for the Elkhorn Mountains volcanics southeast quarter of the Deerlodge 15' quadrangle southwestern Montana

S. Michelle Watson

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THE BOULDER BATHOLITH AS A SOURCE
FOR THE ELKHORN MOUNTAINS VOLCANICS,
SOUTHEAST QUARTER OF THE DEERLODGE 15° QUADRANGLE,
SOUTHWESTERN MONTANA

by

S. Michelle Watson

B.S., Idaho State University, Pocatello, Idaho, 1984

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1986

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

May 29, 1986
ABSTRACT

Watson, S. Michelle, M.S., Spring, 1986 Geology

The Boulder Batholith as a Source for the Elkhorn Mountains Volcanics, Southeast Quarter of the Deerlodge 15' Quadrangle, southwestern Montana.

Director: Donald W. Hyndman

The Late Cretaceous (75-80 MA) Elkhorn Mountains Volcanics are considered to be cogenetic with the Boulder batholith and provide a deep level of exposure into a batholith-caldera related suite of rocks (Greenwood, 1979). As a test of this hypothesis I mapped the southeast quarter of the Deerlodge quadrangle, Montana, which lies on the western edge of the Boulder batholith.

Rocks in the area consist of silicified tuffs, tuff breccias, ash-flow tuffs, airfall tuffs, andesitic lava flows and flow breccias, and basaltic lava flows and flow breccias. These rocks appear to correlate to the lower unit of the Elkhorn Mountains Volcanics as defined by Klepper, Weeks, and Ruppel (1957) and Smedes (1966) in the type area Elkhorn Mountains to the east. Another more silicic densely welded ash-flow tuff blankets the eastern edge of the Deerlodge Quadrangle and may correlate to the middle unit of the Elkhorn Mountains Volcanics. Quartz monzonite-granodiorite of the Boulder batholith in the area probably represents the remaining part of the magma chamber which erupted the major ash flows.

The Elkhorn Mountains Volcanics are chemically related to the main series of the Boulder batholith (Tilling, 1973) as evidenced by K2O, CaO, Na2O, Rb, and Sr contents. Continuous chemical trends indicate that the volcanic and plutonic rocks are related by evolution of a single magmatic system. The rocks in the study area originated in a caldera environment. The exact source for the volcanics was not located during mapping but the caldera was probably to the east in the area now occupied by the Butte Quartz Monzonite. An alternative explanation is that a caldera is present in the immediate vicinity of the map area and that the welded tuff unit represents an intracaldera sequence.
ACKNOWLEDGMENTS

I could not have completed this project without the help of several people. I would like to thank my committee members, Don Hyndman, Gray Thompson, and Wayne VanMeter, for their guidance and help. I would especially like to acknowledge Don Hyndman for his careful review of this manuscript, availability and ability to answer all my questions, and providing that extra push that occasionally was needed to get me going. Bob Derkey and the Montana Bureau of Mines and Geology provided the initial suggestion and funding for this project.

My field assistant, Jake the baby elk killer, was my watch dog and companion throughout the duration of my field season. He provided that extra, much needed, feeling of security that is necessary to map alone for 2 1/2 months. Leigh Beem was instrumental in the completion of this thesis. In addition to providing geological insight in the field and lab, he was my sounding board during countless hours of discussion, speculation, and frustration. He provided pressure and patience and always knew when and how much of each to administer. My friends at the University of Montana helped me keep my sanity by providing the excuses necessary to put off my work and go drinking. Karen Wogsland deserves special recognition in this category.

Finally, I would like to thank my parents for lovingly providing both moral and financial support.
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CHAPTER 1
Introduction

The Upper Cretaceous Elkhorn Mountains Volcanics are considered to be cogenetic with the Boulder batholith and provide a deep level of exposure into a batholith-caldera related suite of rocks (Greenwood and others, 1979). As a test of this hypothesis I mapped the southeast quarter of the Deerlodge 15' quadrangle, southwestern Montana, which lies on the western edge of the Boulder batholith.

The volcanic units in the area, the Elkhorn Mountains Volcanics, consist of basaltic and andesitic lava flows and breccias, airfall tuffs, tuff breccias, and ash-flow tuff sheets. Quartz monzonitic and gabbroic intrusive rocks of the Boulder batholith are also present. Other rocks include Tertiary tuffs and flows of the Lowland Creek Volcanics.

Thin section and whole-rock chemical analyses substantiate relationships of units determined by field data and were used to construct a volcanic history for the area. This report presents field, petrographic, and chemical data, and proposes a source for the volcanic rocks in a caldera environment within the Boulder batholith.

The term "caldera" refers to "large volcanic collapse depressions, more or less circular in form, the diameter of
which are many times greater than the diameter of any included vents" (Williams and Mc Birney, 1979, p. 207). The depression results from an extrusion of magma in the form of large volume ash-flow tuffs and lesser amounts of lava and other pyroclastic material.

Calderas generally exhibit eruptive cycles. These cycles help explain the relationships between lava flows and ash-flow tuffs which represent the composition of the magma chamber, and their plutonic equivalents which represent the remaining crystallized magma from which the volcanics were derived. A generalized caldera cycle is shown in figure 1. All calderas do not exhibit every stage of activity and a new cycle of activity may occur at any stage of caldera development. The stages in parentheses in the following discussion refer to the seven stages of caldera development proposed by Smith and Bailey (1968).

Figure 1a exhibits the pre-caldera stage in which intermediate volcanics are extruded onto the surface. Regional tumescence occurs due to rising plutons (Stage I). This broad doming leads to the development of ring fractures. Figure 1b shows the depression immediately after explosive pyroclastic eruptions (Stage II) and accompanying caldera collapse (Stage III). The voluminous ash-flow tuffs probably are extruded along the ring fractures. As support for the roof above the magma chamber fails, the tuffs are expelled onto the surface and the
Figure 1. A generalized ash flow caldera cycle from Lipman (1984).
chamber collapses to form the caldera depression. The intracaldera tuff may be an order of magnitude thicker than the ash-flow sheet outside the caldera. The tuffs within the caldera pond and lakes may form (Stage IV). The caldera may also contain breccias which form from the oversteepening caldera walls. The walls become unstable and collapse inward. These collapse breccias interfinger with the intracaldera ash-flow tuffs.

As a result of differentiation, the magma chamber is compositionally zoned prior to eruption of ash-flow tuffs. The more evolved or more silicic portion of the magma chamber is at the top and becomes more mafic downward (Hildreth, 1979). When pressures become great enough in the magma chamber, magmas are erupted onto the surface (Blake, 1984). Once the uppermost silicic portion of the magma chamber is erupted, the more mafic, deeper portions of the magma chamber are tapped. Thus an idealized section of ash-flow tuffs from a single eruptive cycle should be compositionally zoned, the most silicic portion being the airfall tuff directly preceeding the violent ash-flow eruption. This zonation of rocks at the surface directly reflects a chemical zonation within the magma chamber.

Figure 1c shows the post-caldera formation stages. Resurgent doming (Stage V) may occur due to continued rise of the subvolcanic pluton, the greatest uplift occurring in
the area of greatest collapse. Lava domes and flows occur along ring fractures (Stage VI) and, along with volcaniclastic sediments, fill in the caldera moat.

More than one caldera may form if a regeneration of magma produces other ash-flow tuff eruptions in the same general area. The result is clustered or nested calderas. These nested calderas are probably all related to one large magma chamber although the individual volcanic products may vary locally. Steven and Lipman (1976) have identified seventeen separate caldera collapses and as many large volume (>100 Km3) ash-flow tuffs in the San Juan volcanic field. They also found that the size of the ash-flow sheets directly relates to the size of the caldera and the style with which the caldera collapses. The large volume ash-flows produce well developed circular depressions which usually resurge fairly quickly. The smaller volume ash-flow tuffs produce either one sided faulted margins that form a "trap door" style of collapse or depressions that sag and have no bounding faults at all (Lipman et al., 1984). The smaller calderas generally do not resurge.

In the last stages of the caldera cycle the central pluton continues to rise and may intrude the intracaldera tuffs. Fumarolic and hydrothermal activity (Stage VII) along with possible mineralization dominate the last phase of the caldera cycle. The central pluton crystallizes when the volatile content of the magma prevents further
eruptions onto the surface and the caldera cycle is complete (Lipman, 1984).

REGIONAL SETTING

The Boulder batholith and associated Elkhorn Mountains Volcanics are located in southwestern Montana, east of the Idaho batholith and west of the leading edge of the Cordilleran Fold and Thrust Belt (Figure 2). The Sapphire tectonic block dominates the structural setting west of the Boulder batholith (Hyndman and others, 1975). This block has roughly the same north-south dimensions as the batholith. To the north of the Sapphire block lies a west-trending basement graben which is on strike with the northern edge of the Idaho batholith. The northeastern boundary of the Boulder batholith is dominated by thrusting in the Montana Disturbed Belt. The southern edge is marked by a zone of folds and faults that is related to Laramide deformation.

K-Ar dating in the Boulder batholith indicates that it was emplaced in the Late Cretaceous over a ten million year time span from 78-68 Ma (Tilling and others, 1968). The Elkhorn Mountains Volcanics have been dated at 78 Ma and thus overlap emplacement of the batholith.

The mode of emplacement of the Boulder batholith has been subject to debate (Hamilton and Myers, 1974a, 1974b;
Figure 2. Regional geologic setting of the Boulder batholith and associated Elkhorn Mountains Volcanics. After Schmidt and others (1979).
Klepper and others, 1971, 1974; Hyndman and others, 1975). The thickness of the batholith may be less than 5 km (Hamilton and Myers, 1974) or as thick as 15-25 km (Klepper and others, 1971). The configuration of the floor of the batholith and the direction of spreading is also controversial. Hamilton and Myers (1974) suggest that the batholith spread over a floor of pre-magmatic rocks and formed as a thin and shallow mass that caused thrusting to the east and folding in the west. Hyndman and others (1975) suggest that the batholith was injected east of the Sapphire block from magmas which spread beneath the Sapphire tectonic block. Emplacement of the batholith may have been fault controlled but the batholith did not cause faulting to the east or to the west. Klepper and others (1974) suggest that the batholith is a steep sided thick pluton that rose along preexisting basement faults and was a result rather than the cause of regional structures.

The Boulder batholith is an elongate body, roughly 100 X 50 km, that trends north-northeast (Klepper and others, 1971). It is a calcalkaline composite, epizonal plutonic mass comprised of at least 15 separate plutons. The plutons range in composition from gabbro to alaskite but are dominated by quartz monzonite. The plutons generally fall into one of the following groups: 1) Early mafic rocks, 2) granodiorite, 3) Butte Quartz Monzonite, 4) leucocratic and felsic rocks (Smedes, 1973). The Butte
Quartz Monzonite is the largest plutonic mass and comprises approximately 75% of the Boulder batholith. It was emplaced between 76-74 Ma (Tilling and others, 1968) and is surrounded by older mafic rocks and granodiorite. The felsic and leucocratic rocks are the youngest stages of the batholith and cut all the other plutons.

Chemical and isotopic (Doe and others, 1968) data indicate that the batholithic rocks originated from a two magma series, the main series and the sodic series (Tilling, 1973). The main series consists of rocks in the northern and central area of the plutonic mass and is characterized by higher K2O and lower Na2O values. The sodic series is volumetrically minor compared to the main series. It consists of rocks in the southern area of the batholith and is characterized by lower K2O and higher Na2O values. Doe and others (1968) used Pb and Sr isotope data to conclude that the magma which formed the Boulder batholith and associated Elkhorn Mountains Volcanics was derived from partial melting of the lower continental crust or upper mantle. Eruption or shallow emplacement of large volumes of andesitic magma implies that the water content of the magma was low when it melted and continued to be dry until it reached the surface (Hyndman, 1981). These large volumes of andesitic magma dictate a source in the lower continental crust (Hyndman, Alt, and Sears, 1986).
The Boulder batholith intrudes Precambrian to Cambrian sedimentary rocks and the Upper Cretaceous Elkhorn Mountains Volcanics. The volcanics make up the roof and most of the margins of the batholith (Figure 2). The Elkhorn Mountain Volcanics are remnants of a plateau-like volcanic field that once may have covered as much as 26,000 Km² and may have been 2-3 Km thick (Klepper and others, 1957; Smedes, 1966).

The Elkhorn Mountains Volcanics were named by Klepper and others (1957) and the type area is in the Elkhorn Mountains which lie on the eastern edge of the Boulder batholith. The volcanic field consists of three generalized units. No formal stratigraphy has ever been published. This is due in part to the occurrence of many of the same rock types in all three units. Virtually no rock type is restricted to one particular unit. The lithologies of the three informal units may be summarized as follows. The lower unit contains basaltic, andesitic, and rhyodacitic lava flows, breccias, epiclastic, and pyroclastic rocks. A few quartz-latitic ash-flow tuffs are also present in the lower unit. The middle unit is characterized by large welded rhyolitic ash-flow tuff sheets and some interbedded units similar to those mentioned above in the lower unit. The upper unit contains water laid andesitic and basaltic sedimentary rocks and pyroclastic beds (Smedes, 1966).
Remnants of two calderas have been identified on the eastern edge of the batholith (Lipman, 1984; Rutland, 1985). The western margin of a caldera identified in the Elkhorn Mountains is marked by ring dikes that separate a chaotic intracaldera sequence from stratigraphically coherent units of the Elkhorn Mountains Volcanics. No other sources for the volcanic rocks have been specifically identified, which may indicate that the volcanic rocks collapsed into the underlying plutonic mass due to caldera formation (Smedes, 1973).

Chemical, isotopic, and field evidence indicate that a genetic relationship exists between the Elkhorn Mountains Volcanics and the Boulder batholith. Tilling (1973, 1974) used chemical and isotopic data (Doe and others, 1968) to relate the bulk of the Elkhorn Mountains Volcanics to the more mafic rocks of the main series of the batholith. Hamilton and Myers (1967, 1974) considered the Butte Quartz Monzonite to be the equivalent of the middle unit of the Elkhorn Mountains Volcanics. Although a few chemical analyses plot in the silicic field of the Butte Quartz Monzonite, few analyses of the middle unit of the Elkhorn Mountains Volcanics correlate chemically to the bulk of the Butte Quartz Monzonite. This may mean that the rhyolitic ash-flows that erupted onto the surface came from the highly evolved upper portions of the magma chamber. The
remaining less silicic portion of the chamber eventually crystallized to form the Butte Quartz Monzonite (Tilling, 1974).

PRESENT STUDY

The study area encompasses approximately 52 square miles of the southeast quarter of the 15' Deerlodge quadrangle east of Deerlodge, Montana (Figure 3). The area contains both Elkhorn Mountains Volcanics and the Boulder batholith and thus provides an excellent setting in which to study the relations between the intrusive and extrusive forms of the same magma. The southeast quarter of the Deerlodge quadrangle is partially located in the Deerlodge National Forest and is bounded on the east by the Basin quadrangle (Ruppel, 1963), on the south by the Butte North quadrangle (Smedes, 1966), and on the north and west by the Deerlodge quadrangle (Derkey, in progress). The northern section is located in Powell County, the southwestern portion in Deerlodge County, and the southeastern portion in Jefferson County. Elevations range from 4000 feet in the valley to 8300 feet along the continental divide which runs through the eastern portion of the study area. Access into the area is gained through two principal dirt roads: the Emery road to the north and the Peterson Creek road to the south. Other small roads and trails are present but foot travel is necessary over much of the area.
Figure 3. Location of study area. Approximate boundaries of Boulder batholith shown in crystalline pattern.
Previous work in the southeast quarter of the Deerlodge quadrangle was done by Ruppel (1961) when he mapped the Deerlodge quadrangle in reconnaissance fashion for the U.S. Geological Survey (MF-174).

This study was undertaken with support from the Montana Bureau of Mines and Geology. Financial aid and chemical analyses were provided by the Bureau. Field work was done during the period June-September, 1985. Mapping was done on a 1:24,000 scale on the southeast quarter of the Deerlodge Quadrangle base map.

Twenty-two major units were mapped within the area. All units were mapped in the field using outcrop characteristics and hand sample mineralogies and textures. Thin section work lead to the reclassification of some units.

The area is heavily forested and most contacts are obscured. Few units could be traced laterally or vertically for any distance and no section was measured. The paucity of contacts between units made stratigraphic and structural relations difficult to interpret. Many relations between units are based on sections measured by previous workers near the area (Ruppel, 1963; Robertson, 1953; Smedes, 1966).
CHAPTER II
Description of Map Units

Rocks in the southeast quarter of the Deerlodge quadrangle consist of basaltic and basaltic-andesite lava flows and flow breccias, andesitic airfall tuffs, ash-flow tuffs, tuff-breccias, and lavas, and welded rhyolitic ash-flow tuffs, all assigned to the Cretaceous Elkhorn Mountains Volcanics. Gabbros and quartz monzonites of the Cretaceous Boulder batholith are also present. Other rocks include Tertiary tuffs and flows of the Lowland Creek Volcanics, Tertiary gravels, and Quaternary glacial sediments, colluvium, and alluvium. The rocks are described beginning with the oldest unit present in the area. Many of the Elkhorn Mountains Volcanics units interfinger and overlap. The inferred stratigraphic relations between the units are shown in Figure 4.

ELKHORN MOUNTAINS VOLCANICS

Basalts (Kb)

Basaltic and basaltic-andesite lava flows crop out in the north-northwestern section of the map area. A section was not measured by this author but Robertson (1953) estimates that at least 266 meters of lavas are present in the Emery Mining District in the northern section of the
Figure 4. Stratigraphic relations between units in study area.
map area. Three separate types of basalts were recognized in the field, a plagioclase phenocryst basalt (Kbo), a pyroxene phenocryst basalt (Kbp), and a plagioclase and pyroxene phenocryst basalt (Kbb). A fourth type, basaltic breccia (Kbx), was mapped as a separate unit but probably represents brecciated portions of all three types of basalt. Individual flows were difficult to map in the field. The flows have been extensively altered by hydrothermal activity and lack good distinguishable marker horizons. Phenocryst mineralogy is also probably a poor way to distinguish flows since the various types appear to grade into one another.

Amygdaloidal zones are present in all of the flows and occur at various positions within the flows and thus cannot be used as a distinct mappable feature. The amygdules range in size from 1/8 mm to approximately 15 cm in diameter. They are generally oval but some are irregularly shaped. They are most often filled with quartz but locally are filled with calcite. The basalts are generally massive though in some cases they exhibit columnar jointing.

Ruppel (1963) and Robertson (1953) interpreted the basalts as younger than the other volcanics present in the area and placed them at the top of the Elkhorn Mountains Volcanics stratigraphic section. Basalts in the southeast quarter of the Deerlodge quadrangle interfinger with other lithologies of the lower unit of the Elkhorn Mountains
Volcanics. Basalts in the southwest quarter of the Deerlodge quadrangle have been contact metamorphosed indicating that they are older than the adjacent Boulder batholith (Derkey, 1986). The basalts appear to have been extruded semi-continuously during the time the other volcanic rocks were being erupted.

**Plagioclase Basalt (Kbo)**

Plagioclase basalt is considered the oldest "unit" of the basalts (Derkey, 1986). The basalt is dark gray to black and contains conspicuous plagioclase phenocrysts. The phenocrysts occasionally are round and flat and resemble rolled oats but most often occur as lath shaped phenocrysts of labradorite (An62-An68) as much as 1 cm. long. The plagioclase exhibits minor normal zoning and undulatory extinction. The crystals show no preferred orientation but often occur in glomeroporphyritic clusters.

Lesser amounts of pyroxene are present as phenocrysts in the rock. Subhedral hypersthene locally poikilitically encloses the plagioclase. Augite is present as subhedral crystals that also locally poikilitically enclose the plagioclase phenocrysts. Some exhibit simple twinning.

The holocrystalline groundmass makes up the greatest percentage of the rock. It consists of plagioclase microlites and minor secondary chlorite (Figure 5).
Table 1. Mineralogy of the plagioclase basalt (Kbo) unit.

<table>
<thead>
<tr>
<th>Mineralogy</th>
<th>Grain size and shape</th>
<th>Properties</th>
<th>Comments, alteration, textures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase 15%</td>
<td>subhedral laths 1 mm to 1 cm in length</td>
<td>An_{62-68} (determined by albite-Carlsbad method)</td>
<td>Glomerophyritic texture, altered to sericite</td>
</tr>
<tr>
<td>Hypersthene</td>
<td>subhedral, 1 mm in size</td>
<td></td>
<td>altered to biotite, poikilitically encloses plagioclase</td>
</tr>
<tr>
<td>Augite 2%</td>
<td>subhedral, up to 1 mm</td>
<td>simple twins</td>
<td>same as hypersthene</td>
</tr>
<tr>
<td>Groundmass 75-80%</td>
<td>microlitic plagioclase</td>
<td></td>
<td>secondary chlorite, holocrystalline texture</td>
</tr>
</tbody>
</table>

Figure 5. Sketch of plagioclase basalt (Kbo) in thin section.
Accessory minerals include biotite, growing at the expense of the pyroxene, and sericite, an alteration product of the plagioclase. Table 1 summarizes the mineralogy of this unit.

Plagioclase-pyroxene basalt (Kbb)

Plagioclase-pyroxene basalts are dark green to black and weather dark brown. The basalts contain conspicuous phenocrysts of whitish-gray plagioclase and dark green to black pyroxene that are generally about 2 mm long but may be as much as 5 mm long. The mineralogy of this unit is similar to that of the plagioclase basalt unit. The pyroxene phenocrysts are larger and are more prominent in hand sample in this unit than they are in the plagioclase basalt.

Plagioclase occurs as subhedral lath-shaped phenocrysts of bytownite (An70-An84) 2-5 mm long. It exhibits both oscillatory and normal zoning and may show a slight preferred orientation. The plagioclase often occurs in glomeroporphyritic clusters (Figure 6).

Augite and enstatite occur as euhedral to subhedral 4 and 8 sided prismatic crystals that locally poikilitically enclose the plagioclase. They have largely been altered to chlorite. A few augite crystals are zoned.

The hypohyaline groundmass of this basalt consists of microlitic plagioclase crystals, devitrified glass, and
Table 2. Mineralogy of the pyroxene-plagioclase basalt (Kbb) unit.

<table>
<thead>
<tr>
<th>Mineralogy</th>
<th>Grain size and shape</th>
<th>Properties</th>
<th>Comments, alteration, textures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase 25%</td>
<td>subhedral laths up to 5 mm</td>
<td>An-70-An-84 (determined by albite-carlsbad method)</td>
<td>glomeroporphyritic, slight preferred orientation</td>
</tr>
<tr>
<td>Augite 10%</td>
<td>euhedral to subhedral crystals</td>
<td>inclined extinction, slight zoning</td>
<td>altered to chlorite</td>
</tr>
<tr>
<td>Enstatite 5%</td>
<td>subhedral crystals</td>
<td></td>
<td>locally encloses plagioclase</td>
</tr>
<tr>
<td>Groundmass 50-60%</td>
<td>plagioclase microlites, devitrified glass</td>
<td>secondary calcite, cryptocrystalline and hypohyaline texture</td>
<td></td>
</tr>
</tbody>
</table>

Accessory Minerals: magnetite

Figure 6. Sketch of pyroxene-plagioclase basalt (Kbb) in thin section.
some secondary chlorite. Accessory minerals include magnetite in the groundmass. The mineralogy of this unit is summarized in Table 2.

**Pyroxene basalt (Kbp)**

Pyroxene basalts are generally dark greenish black and contain conspicuous dark green to black pyroxene phenocrysts up to 1 cm long. The pyroxene basalts locally have been hydrothermally altered to a light green color which makes the pyroxene phenocrysts even more prominent.

Augite occurs as euhedral to subhedral phenocrysts, some of which are twinned. It has been largely altered to chlorite. The groundmass consists of plagioclase microlites that exhibit a sub-trachytic texture, augite, and some magnetite (Figure 7). Plagioclase may be present as small lath shaped crystals that are smaller than the pyroxene phenocrysts. The composition averages An60 (labradorite). The plagioclase is commonly both carlsbad and albite twinned and may occur in glomeroporphyritic clusters.

**Basaltic breccia (Kbx)**

Basaltic breccias occur throughout the basaltic section. All the basalts appear to have brecciated zones that may either represent the bottoms or tops of flows or an autobrecciated lava flow. Zeolites generally occupy the
### Table 3. Mineralogy of the pyroxene basalt (Kbp) unit.

<table>
<thead>
<tr>
<th>Mineralogy</th>
<th>Grain size and shape</th>
<th>Properties</th>
<th>Comments, alteration, textures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augite 20%</td>
<td>subhedral to euhedral, up to 1 cm.</td>
<td>some twinning</td>
<td>altered to chlorite</td>
</tr>
<tr>
<td>Groundmass 75%</td>
<td>microlites of plagioclase and augite</td>
<td></td>
<td>subtrachytic, pilotaxitic</td>
</tr>
<tr>
<td>Zeolites</td>
<td></td>
<td>growing around margins of augite</td>
<td></td>
</tr>
<tr>
<td>Opaques</td>
<td>subhedral</td>
<td>in groundmass</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7.** Sketch of pyroxene basalt (Kbp) in thin section.
Figure 8. Sketch of basaltic breccia in thin section.
spaces formed by brecciation (Figure 8).

Interpretation of the basalts

All of the rocks in this unit were determined microscopically to be basalts. The An content of the plagioclase ranges from An60 to An84 and all contain pyroxene. These basalts all appear to be extrusive lava flows as demonstrated by oriented microlites in the groundmass (Williams and McBirney, 1979, p. 118-119) and by the presence of glomeroporphyritic textures which would not be expected to survive fragmentation during a pyroclastic event. The basaltic breccias represent autobrecciated lava flows that form by slow moving hardening lava that has differing rates of internal advance (Williams and McBirney, 1979, p. 176).

Andesitic lava (Kal)

A large amount of andesitic lava crops out in the vicinity of Black Mountain in the middle portion of the map area and farther west. The lavas appear to be younger than or interfinger with the Kaf unit in the central portion of the map area. They interfinger with basalts and basaltic-andesites in the western portion of the area and do not crop out at all in the east.

The lavas are autobrecciated in some places, a feature
which can only be discerned on a weathered surface. The rocks are hard and have a glassy fracture. The lavas are generally blackish-green on a fresh surface and weather to a light brownish-green. In places the lava contains porphyritic crystals of andesine-labradorite (An45-An52) set in an aphanitic groundmass. The plagioclase occurs as subhedral to anhedral phenocrysts. Almost all of the crystals are carlsbad and albite twinned. Both normal and oscillatory zoning is present. Many of the plagioclase crystals are heavily altered to sericite. In most places the plagioclase grains are too small to be readily discerned in hand sample. The groundmass is heavily fractured and filled with chlorite and calcite. Biotite may be present in small glomeroporphyritic clusters. It is light tan to yellow-brown and poikilitically encloses small flecks of hornblende. Epidote is present as pseudomorphs of clinopyroxene, probably augite judging from the shape of the replaced crystals. Biotite and hornblende, where present, are enclosed within the epidote crystals.

The hypohyaline groundmass consists of oriented plagioclase microlites and devitrified glass with secondary chlorite, calcite, and epidote. Most of the porphyritic crystals are aligned parallel to the flow direction (Figure 9). Accessory minerals include sanidine, sodalite, magnetite, and hematite. The mineralogy of this unit is summarized in Tables 4 and 5.
Table 4. Mineralogy of the andesitic lava (Kal) unit.

<table>
<thead>
<tr>
<th>Mineral % of rock</th>
<th>Grain size and shape</th>
<th>Properties</th>
<th>Comments, alteration, textures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase up to 10%, usually 5%</td>
<td>subhedral to anhedral laths 2-5 mm</td>
<td>An$<em>{45}$-An$</em>{52}$ (determined using albite-Carlsbad method)</td>
<td>altered to sericite</td>
</tr>
<tr>
<td>Epidote</td>
<td>subhedral to anhedral, 2 mm</td>
<td>light tan, yellow-brown</td>
<td>altered product of cpx</td>
</tr>
<tr>
<td>Biotite</td>
<td>small anhedral specks</td>
<td>good 126-54° cleavage</td>
<td>glomeroporphyritic texture</td>
</tr>
<tr>
<td>Hornblende</td>
<td>small anhedral specks</td>
<td></td>
<td>hypohyaline texture, oriented parallel to flow</td>
</tr>
<tr>
<td>Groundmass 90%</td>
<td>microlite plagioclase and devitrified glass</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Accessory minerals: magnetite, hematite, sanidine, sodalite, quartz
Table 5. Mineralogy of the andesitic lava (Kal) unit.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>% of rock</th>
<th>Grain size and shape</th>
<th>Properties</th>
<th>Comments, alteration, textures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>50%</td>
<td>lath shaped microlites</td>
<td>oriented parallel to flow</td>
<td></td>
</tr>
<tr>
<td>Groundmass</td>
<td>50%</td>
<td>fractures in rock</td>
<td>devitrified glass, chlorite,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>calcite, epidote</td>
<td></td>
</tr>
</tbody>
</table>

Accessory minerals: Magnetite locally in groundmass

Figure 9. Sketch of andesitic lava flow (Kal) in thin section.
The lavas may be heavily fractured. The fractures are filled with epidote, chlorite, calcite, and quartz. In some places where the rock is heavily brecciated the fillings outline angular blocks of lava on the weathered surface.

**Interpretation**

Rocks in this unit are andesitic as determined in thin section. The An content is generally <An50 and hornblende is often present. The rocks are interpreted as lava flows based on the microlites of plagioclase in the groundmass (Williams and McBirney, 1979, p. 118-119). Brecciated portions of this unit may form from autobrecciation of the lava flow after extrusion onto the surface and during flow. Autobrecciation occurs when joints develop parallel to the flow direction of the lava. The joints develop mainly from differing rates of internal advance of the lava and partly by cooling and contraction. After formation of the joints the lava continues to flow and autobrecciation results (Williams and McBirney, 1979, p. 176). Autobrecciation, however, may also take place before extrusion. This happens by several mechanisms: 1) repeated swelling and subsidence of magmas within volcanic cones; 2) forceful injection of magma into solid lava; 3) differential rates of movement within intrusions; 4) near surface explosions.
(Williams and Mc Birney, 1979, p. 177). The exact mode of brecciation is not known since the brecciated portion of this lava unit does not occur at the bottom or top of the flow(s) nor at any particular stratigraphic horizon that can be distinguished in the field.

**Silicified tuff (Kst)**

Silicified tuffs generally occur at lower elevations on the western edge of the map area. The outcrops are generally small and scattered and are often in contact with the Boulder batholith. The color of the tuffs in hand sample is usually light green or gray or a pale greenish gray. The tuffs are very fine grained and resemble chert. Flow banding may be present. No mineralogy can be discerned in hand sample. The dominant mineral in thin section is quartz. The grains are anhedral and exhibit undulatory extinction. The boundaries are interdigitating and the grains appear to be subparallel. Accessory minerals include small albite twinned subhedral plagioclase crystals, sanidine, and hematite.

**Interpretation**

These silicified tuffs are quite possibly a metamorphic product of the Boulder batholith. The heat supplied by the batholith may have caused recrystallization of ash-flow tuffs of the Kaf unit into which the batholith
intruded. The silicified tuffs appear at the same stratigraphic position as the Kaf unit and are most likely directly related. The subparallelism of the quartz crystals may be relict flow textures of the ash-flow tuffs that were preserved during metamorphism.

**Andesitic ash-flow tuff (Kaf)**

This unit occupies a large area that extends from Cliff Mountain in the northwest half of the map area to Blizzard Mountain in the southern half of the map area. Outcrops often occur as tall cliffs, the tops of which form ridges. Many separate pyroclastic rock types are incorporated into a single map unit. There are several reasons for this:

1) The mineralogy of the different lithologies is so similar that identification of separate flows on the basis of mineralogy is virtually impossible;

2) Individual flows or lithologies cannot be traced laterally or vertically for any distance. They grade into one of the other lithologies or they are lost in heavily forested areas;

3) Mapping individual flows and small outcrops of various lithologies as separate units is not feasible during this project. The mapping of individual flows could lead to an excessive number of map units. The pyroclastic unit has
been divided into separate subunits. These include crystal tuff, semi-welded ash-flow tuff, and tuff breccia. All grade into one another, sometimes within a few feet.

The dominant lithology in the unit is an unwelded to semi-welded ash-flow tuff. Rocks of this unit are usually green, greenish-gray, or creamy-gray on the weathered surface and medium to dark gray-green on fresh surfaces. Lithic fragments of many different rock types are contained within the ash-flow tuffs. The lithics range in size from a few to 30 mm in diameter. They are generally dark green due to chloritization and epidotization. Pumice may be present and may contain plagioclase phenocrysts (Figure 10).

The groundmass is composed of small, essential crystals of plagioclase approximately 0.1-0.5 mm long and devitrified glass and comprises approximately 40-50% of the rock (lithics subtracted). Plagioclase laths make up approximately one third of the groundmass and the glass comprises the remaining two thirds. The plagioclase exhibits a subdued trachytic texture as evidenced by the subparallel alignment of the laths in the groundmass. The crystals are normally zoned, are fractured and broken, and are mainly labradorite-andesine in composition.

Sanidine is usually present as large subhedral crystals that comprise 10-20% of the rock. Hornblende is often present in amounts of 3-5% of the rock although
Figure 10. Photograph of andesitic semi welded ash-flow tuff in outcrop.
locally hornblende may comprise as much as 5-10% of the rock. Magnetite and biotite are present in some samples in amounts of 5%. Secondary minerals include calcite, chlorite, and epidote. Table 6 summarizes the mineralogy of this unit.

**Semi welded ash-flow tuff (Kafw)**

Several cliffs of semi-welded ash-flow tuff crop out in the map area. The mineralogy is virtually identical to the mineralogy described in the Kaf unit above. Pumice fragments exhibit length:width ratios of as much as 10:1. A eutaxitic texture is readily discernable. The pumice is altered to chlorite and epidote. Some of the plagioclase crystals may exhibit stress signs when oriented perpendicular to the flow direction (Table 6).

**Interpretation**

The Kaf and Kafw units are interpreted as having an ash-flow origin. Pumice, now completely altered to chlorite and epidote, is present. Pumice is "a highly vesicular volcanic glass produced by the exsolution of water vapor from the glass at high temperatures as magma comes to the surface." The presence of pumice is the most important factor in determining pyroclastic origin (Ross and Smith, 1961). The plagioclase crystals are normally
<table>
<thead>
<tr>
<th>UNIT FEATURE</th>
<th>Kwt Welded ash-flow tuff</th>
<th>Kwt Welded ash-flow tuff</th>
<th>Kwt Welded ash-flow tuff</th>
<th>Kaf Ash-flow tuff</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMPLE NUMBER</td>
<td>WS-298</td>
<td>WS-141</td>
<td>WS-167</td>
<td>WS-6</td>
</tr>
<tr>
<td>PHENOCRYSTS</td>
<td>% of rock</td>
<td>8%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>mineralogy</td>
<td>5% plagioclase-Ab22</td>
<td>3-5% plagioclase-carlsbad and albite twinning, heavily altered</td>
<td>5-10% plagioclase-carlsbad twinning, altered to sericite</td>
<td>50% plagioclase-as fractured crystals and laths in groundmass.</td>
</tr>
<tr>
<td></td>
<td>3% alkali feldspar</td>
<td>2% sanidine-up to 3mm</td>
<td>2% alkali feldspar</td>
<td>Andesine, normal zone</td>
</tr>
<tr>
<td></td>
<td>magnetite</td>
<td>2% biotite-bent, opaque inclus.</td>
<td>biotite</td>
<td>20% sanidine-subhedral crystals</td>
</tr>
<tr>
<td></td>
<td>hematite</td>
<td>2% magnetite, chlorite, epidote-sericite</td>
<td>epidote</td>
<td>1-2% olivine, magnetite, hornblende</td>
</tr>
<tr>
<td>size and shape</td>
<td>0.5-5mm-subhedral</td>
<td>1cm-subhedral</td>
<td>1-5mm-subhedral, anhedral</td>
<td>0.01-5mm-subhedral</td>
</tr>
<tr>
<td>SHARDS</td>
<td>50% flattened, devitrified</td>
<td>40-50% flattened, devitrified</td>
<td>40-50% flattened, devitrified</td>
<td>30% devitrified</td>
</tr>
<tr>
<td>LITHIC FRAGMENTS</td>
<td>2% up to 1.5cm in diameter, recrystallized to quartz and feldspar</td>
<td></td>
<td></td>
<td>10% basaltic? lava flow-seriate texture</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>basaltic? lava flow with glomeroporphyritic plag.</td>
</tr>
<tr>
<td>PUMICE</td>
<td>40% streaky bands up to 3cm in length coarse grained quartz and feldspar, halos of calcite and epidote</td>
<td>40% coarse quartz and feldspar intergrowth</td>
<td>30% quartz and feldspar intergrowths</td>
<td>? few % small, noncompacted, devitrified, altered to chlorite</td>
</tr>
<tr>
<td>COMMENTS</td>
<td>eutaxitic texture</td>
<td>eutaxitic texture</td>
<td>eutaxitic texture</td>
<td>chlorite and calcite alt.</td>
</tr>
</tbody>
</table>

Table 6. Mineralogy of the ash flow units.
zoned and are fractured and broken, indicating that they were crystallizing and reacting with the melt (thus their zoning) and then were explosively ejected onto the surface (thus the broken and fractured crystals).

**Crystal tuff (Kaft)**

Crystal tuff is found interfingered throughout the Kaf unit. The crystal tuff commonly displays crude bedding and is usually green or creme-gray. The tuff consists of crystal fragments up to 2 mm in diameter. Plagioclase (andesine) is commonly carlsbad and albite twinned and comprises up to 20% of the rock. Sericite is commonly found as an alteration product of the plagioclase. Angular sanidine and orthoclase crystals are present in amounts up to 20%. The orthoclase is larger than the sanidine and contains some inclusions. Biotite may be present in small, ellipsoidal forms and in the groundmass. Quartz is minor and is generally smaller than the feldspars. The groundmass is hypocrystalline, very fine grained, contains devitrified glass, and comprises approximately 50% of the rock.

Another rock type included in this crystal tuff unit and similar to it in hand sample is somewhat different in mineralogy than the rock described above. The rock is composed of crystal fragments up to 3 mm in size. Dominant crystals in hand sample are phenocrysts of white to gray
plagioclase and green pyroxene. In thin section the plagioclase is anhedral, up to 2mm long, and exhibits zoning and carlsbad and albite twinning. It is heavily altered to calcite and is present in amounts up to 25%. The composition of the plagioclase crystals could not be determined due to their altered nature.

Hornblende is present in amounts up to 5% as subhedral to anhedral crystals. Olivine is present in some samples as subhedral crystals that appear to be altering to fibrous amphiboles. The crystals may be up to 1 mm in diameter and make up 5% of the rock. Augite occurs as large subhedral phenocrysts that have been heavily altered. It represents only a minor percentage of the rock. Magnetite makes up a few percent of the rock and is partly replaced by calcite. Chlorite and epidote are also seen in hand sample. The groundmass is a green very fine grained tuff and represents 20-30% of the rock. This rock type may show crude bedding or may be massive. It is found throughout the Kaf unit and at various stratigraphic levels.

Lithic fragments up to 5mm in diameter are present and are typically a reddish-brown color. Several types of lithic clasts were identified. 1) Basalt with microlitic plagioclase; 2) A mosaic of quartz and feldspars, probably a recrystallized tuff; 3) Porphyritic rock consisting of a microlitic groundmass with glomeroporphyritic plagioclase
phenocrysts.

Interpretation

The first rock type described seems to represent an airfall tuff. The angularity of the crystals seems to be the result of an explosive pyroclastic eruption. The grains are all similar in size and shape. The presence of bedding also points to an airfall origin.

The second rock type described may also be an airfall tuff. The tuffaceous matrix, abundant crystals, and lithic fragments may have quickly settled out of the air and may indicate the close proximity of a vent. The lack of bedding may indicate that the tuff was deposited by high intensity eruptions that prohibited gravity sorting. Alternatively, a lack of bedding may indicate that the tuff may have been remobilized by the addition of water and thus the bedding was destroyed (Williams and Mc Birney, 1979, p. 135-137). The rock may also represent the bottom or near bottom of a graded and sorted ash-flow tuff. Crystals are more dense than the tuff matrix and thus settle to the bottom of the flow whereas the pumice is less dense than the matrix and rises to the top of the flow (Ross and Smith, 1961).

Tuff breccia (Kafb)

This subunit consists of a fine grained greenish-gray
tuff matrix with angular to subrounded cobbles and boulders of various types of volcanic rocks. The lithics range in size from 3 mm to a meter in diameter, the most common being approximately 3-15 mm in diameter (Figure 11). The lithics are most commonly porphyritic lavas, microlitic lavas without phenocrysts, and fine grained tuffaceous fragments. No pumice was observed.

**Interpretation**

This unit may represent the base of a large ash-flow tuff that has incorporated many foreign fragments from the surrounding terrain. The limited extent of the breccia seems to preclude that interpretation. This unit is most likely a lahar or volcanic mud flow. Ross and Smith (1961) describe lahars as "any volcanic breccia with a matrix of tuffaceous aspect which came to rest as a single unit and was originally mobilized by the addition of water, gravity alone being the motivating force. Lahars typically are heterogeneous and unsorted." No features were present to indicate that the flow was hot. The flow probably resulted when debris on a volcanic slope was mobilized by the addition of rain or snow.

**Red ash-flow tuff (Kra)**

This unit is minor in the map area but becomes more
Figure 11. Photograph of tuff-breccia in outcrop.
abundant in the northern portions of the Deerlodge quadrangle. It crops out in the northernmost section of the map area in the vicinity of Sugarloaf Mountain. Small, isolated outcrops appear to be interbedded with basalt flows. The welded tuffs are dark red to dark brown in the field. Flattened fiamme are generally lighter in color and are most often orange. The fiamme are composed of a coarse grained mosaic of quartz and feldspar and comprises 30% of the rock. The dark brownish red devitrified glassy groundmass comprise approximately 20% of the rock.

Large plagioclase phenocrysts may be twinned and are present in amounts up to 30%. The crystals are partially altered to chlorite. Magnetite phenocrysts commonly poikilitically enclose the plagioclase. Sanidine occurs as subhedral altered crystals. Augite and and rare olivine crystals may be present and are heavily altered to calcite. Hematite is a common accessory mineral. Lithic fragments may comprise up to 10% of the rock and consist largely of porphyritic lava flow rock with heavily sericitized plagioclase and chloritized groundmass (Table 6).

Interpretation

This unit is interpreted as an ash-flow tuff based on the presence of pumice fragments, bent and broken crystals, welding, and incorporated lithic fragments. The mineralogy is similar to the Kaf unit and may represent a welded flow
of similar composition.

**Welded rhyolitic ash-flow tuff (Kwt)**

Welded ash-flow tuff crops out on the eastern edge of the map area from the vicinity of Cliff Mountain in the north to the east side of Rock Creek in the south. It is the youngest Elkhorn Mountains Volcanics unit in the area as demonstrated both stratigraphically (it sits on top of Kaf) and structurally (it is generally associated with the downthrown block of faults). The welded tuff unit forms massive cliffs with large associated scree slopes. The entire unit is densely welded. No lower or upper semi-welded or unwelded, portions of the flows were observed in the field. It is not known whether this welded ash-flow tuff unit represents a single flow or a cooling unit made up of several flows. It is a fairly constant thickness in the field area, averaging approximately 200-250 meters. This may be a misrepresentation of the actual thickness since the base of the unit generally was unobserved, most likely due to faulting. Ruppel (1963) estimates the thickness of a welded tuff unit in the Basin quadrangle, immediately east of the map area, as being 160-350 meters.

The tuffs range in color from a light grayish-white with darker gray fiamme to a reddish brown to medium gray with lighter gray fiamme. Phenocrysts of plagioclase
averaging 4-5 mm in length may be present in amounts of 5-10% of the rock. Locally plagioclase may either comprise up to 20% of the rock or not be present at all. The plagioclase is white to gray in color and generally is broken or fractured. Some of the crystals are aligned parallel to the flow direction but others are randomly oriented. Both carlsbad and albite twinning are common. The plagioclase composition averages An25 (oligoclase) and most of the phenocrysts show signs of alteration to sericite or calcite.

Lithic fragments up to a centimeter in diameter are locally present though lithic fragments are generally sparse in this unit, comprising only a few percent of the rock. All lithic fragments observed have been recrystallized to a quartz-feldspar intergrowth similar to that observed in the groundmass.

Eutaxitic texture is readily discernable in hand sample (Figure 12). The flattened fiamme average 0.5 mm in thickness and average 2 cm in length but may be up to 5 cm. Fiamme are draped around crystals and lithic fragments. The fiamme represent what once used to be flattened pumice fragments. They are coarsely recrystallized to quartz and feldspar intergrowths as a result of devitrification. Pumice bands are coarser than the rest of the rock and tend to devitrify more readily than do shards (Ross and Smith, 1961). Elongate quartz lenses are commonly found in the
pumice bands.

Devitrified glass now consisting of a very fine grained mosaic of intergrown quartz and feldspar dominates in thin section. It is darker in color in plane polarized light than the pumice fragments. The cores of the flattened shards are coarser grained than are the rims and may be aggregates of feldspar, although the minerals cannot be identified petrographically. Subhedral sanidine crystals up to 3 mm long are locally present. They are pitted looking and enclosed by the groundmass and comprise <5% of the rock. Biotite is present in some samples as angular or bent anhedral crystals and is included by opaque minerals. Hornblende is rare; only small amounts were observed in one sample.

Magnetite and hematite are almost ubiquitous in amounts up to a few percent of the rock. Magnetite is clustered along the edges of the quartz and feldspars. Hematite occurs along fractures and between grains in the groundmass (Table 6).

Interpretation

The welded rhyolitic ash-flow tuff is assigned to the middle unit of the Elkhorn Mountains Volcanics. The middle unit is characterized by large volumes of rhyolitic ash-flow tuffs (Klepper and others, 1957; Smedes, 1966). It is
Figure 12. Photomicrograph of rhyolitic welded ash-flow tuff (Kwt) showing eutaxitic texture. Field of view is 2 mm.

Figure 13. Photograph of rhyolitic welded ash-flow tuff in hand sample. Scale is 5 cm.
the only Elkhorn Mountains Volcanics unit in the map area not assigned to the lower unit.

This unit is interpreted as having an ash-flow tuff origin based on the presence of flattened fiamme, now composed of a mosaic of quartz and feldspar due to devitrification, welding, eutaxitic structures formed by the flattening and compaction of the tuff (Figure 13), broken phenocrysts indicative of an explosive origin, and bent biotite flakes which result from differential compaction of the ash-flow (Ross and Smith, 1961; Williams and Mc Birney, 1979).

BOULDER BATHOLITH

Butte Quartz Monzonite (Kbqm)

Quartz monzonitic rocks crop out in the southern half of the map area. The quartz monzonite is texturally and mineralogically similar to the Butte quartz monzonite which crops out in the Basin quadrangle on the eastern margin of the map area and farther east (Ruppel, 1963; Smedes, 1966; Klepper and others, 1957) and in the Butte North quadrangle to the south of the map area (Smedes, 1961). The batholith is in contact with rocks of the Elkhorn Mountains Volcanics in the northern portion of the map area and has Tertiary Lowland Creek Volcanics unconformably overlying it in places in the southern portion of the map area.
The batholithic rocks were not divided into separate rock types in the field. Both coarse grained and fine grained rocks are included in the single unit. The batholithic rocks range in color from overall light gray to pink to a bluish hue. The rocks weather to a chalky white color and generally form rounded outcrops (Figure 14).

Many quartz and aplite veins are present in the batholith but were not mapped due to the size and abundance. The veins range in size from several centimeters in width to several meters, and may be several hundred meters long.

Two separate batholith samples are described. The mineralogy is summarized in Tables 8 and 9. Plagioclase generally occurs as euhedral to subhedral crystals that range in size from <1mm to 1cm. The plagioclase is normally zoned and exhibits carlsbad and albite twinning. The composition of the cores range from An40-An60, An45 being the average. The cores of some of the plagioclase crystals are starting to alter to sericite but the rims are unaltered.

Orthoclase occurs as anhedral masses around plagioclase crystals, as subhedral to anhedral phenocrysts, or as small irregular granules with quartz in an aplitic groundmass. Feldspars display undulatory extinction and some show carlsbad twinning. Quartz is abundant as
Figure 14. Photograph of Butte Quartz Monzonite in outcrop.
Table 7. Mineralogy of the Butte Quartz Monzonite (Kbqm) unit.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>% of rock</th>
<th>Grain size and shape</th>
<th>Properties</th>
<th>Comments, alteration, textures</th>
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</thead>
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<td>An$_{40-47}$ (determined using albite-Carlsbad method)</td>
<td>altered to sericite in center of crystals</td>
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<tr>
<td>Orthoclase</td>
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<td>anhedral, 3 mm</td>
<td>undulatory extinction</td>
<td>seriate to interstitial</td>
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<tr>
<td>Hornblende</td>
<td>15%</td>
<td>subhedral to anhedral</td>
<td>good 126°-54° cleavage</td>
<td>minor alteration to chlorite</td>
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<tr>
<td>Biotite</td>
<td></td>
<td>euhedral books up to 5 mm to anhedral small (less than 0.5 mm) clusters</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Allanite</td>
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Table 8. Mineralogy of the Butte Quartz Monzonite (Kbqm) unit.

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<th>Properties</th>
<th>Comments, alteration, textures</th>
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<td>An$_{58}$ (determined using albite-Carlsbad method)</td>
<td>minor alteration to sericite</td>
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<td>Quartz</td>
<td>5-10%</td>
<td>&quot; &quot;</td>
<td>undulatory extinction</td>
<td>poikilitically enclosed within hornblende</td>
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<tr>
<td>Biotite</td>
<td>15%</td>
<td>euhedral to anhedral books and clusters up to 5 mm</td>
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<td>minor chlorite alteration</td>
</tr>
<tr>
<td>Hornblende</td>
<td>5-10%</td>
<td>subhedral crystals up to 5 mm</td>
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<td></td>
</tr>
<tr>
<td>Accessory minerals: magnetite</td>
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</table>
irregular granules within the groundmass or as interstitial masses. It is generally anhedral and displays undulatory extinction.

Biotite is common as euhedral books up to 5mm in length and as small, scattered anhedral clusters in the finer grained samples. It is brown in plane polarized light, brownish-yellow to orange under crossed polars. It commonly occurs in clusters with hornblende.

Hornblende occurs both as euhedral to subhedral phenocrysts and as irregular masses clustered with biotite and opaque minerals. Some of the hornblende poikilitically encloses opaque minerals and locally small biotite flecks. The phenocrysts display good 126-54 cleavage. The color is green in plane polarized light and orangy-yellow under crossed polars. Accessory minerals include magnetite associated with hornblende and biotite, epidote, and allanite.

The textures tend to be seriate in the coarser grained rocks (Figure 15) and porphyritic with plagioclase, orthoclase, biotite, and hornblende phenocrysts set in an aplitic groundmass for finer grained rocks (Figure 16).

Interpretation

Based on the textural and mineralogical similarities this quartz monzonite is assigned to the Boulder batholith.
Figure 15. Photomicrograph of Butte Quartz Monzonite (Kbqm) showing seriate texture. Field of view is 3 mm.

Figure 16. Photomicrograph of Butte Quartz Monzonite showing aplitic groundmass. Field of view is 3 mm.
Intrusive (Ki)

A gabbroic intrusive body crops out in the middle section of the map area just east of Black Mountain. The outcrop forms a nearly vertical resistant cliff that is approximately 40 meters long and 10 meters high. In the field the rock is a grayish-white with greenish hornblende crystals 0.5-5 mm in length speckled throughout it. Large metamorphosed xenoliths up to a meter in diameter are present. The xenoliths resemble chert or a very fine grained tuffaceous material. Plagioclase comprises 75% of the rock. It exhibits both carlsbad and albite twinning in euhedral to subhedral broken crystals. The composition averages An68 (bytownite) but labradorite was also observed. The plagioclase appears to be strained, bent, and kinked.

Hornblende makes up 25% of the rock. It is cloudy looking and appears to be a replacement product of pyroxene.

Interpretation

The intrusive nature of the unit is readily observed in outcrop. The intrusion is surrounded by large talus blocks but the Kaf unit sits above and on all sides of the outcrop. Xenoliths, presumably from the ash-flow tuff it intrudes, are common in the gabbro. Gabbros are widespread
in the Boulder batholith (Smedes, 1966; Klepper, 1957), and may represent the early mafic stages of the batholith.

Samples from the Elkhorn Mountains Volcanics and Boulder batholith are plotted on an IUGS classification diagram (Figure 17). All samples were plotted except for the felsic ash-flow tuffs. With one exception, all of the rocks in the Kaf pyroclastic unit plot in the "andesite" field of the diagram. The lava flows are mainly basaltic although one andesitic lava unit is present. Batholith samples plot near the quartz monzonite-quartz monzodiorite line and the Ki intrusive unit plots within the gabbro field.

**Tertiary Lowland Creek Volcanics (Tl)**

Small patches of felsic rocks assigned to the Lowland Creek Volcanics (Smedes, 1966) crop out in the southern portion of the map area. The Tertiary volcanics can easily be distinguished from the Cretaceous Elkhorn Mountains Volcanics in the field by their less altered, more felsic nature. The volcanics are invariably found unconformably overlying the Boulder batholith. Saratoga Mountain in the southern-middle portion of the map area is composed of rocks that are white and tuffaceous. Phenocrysts seen in hand sample are up to a few mm in diameter. Quartz phenocrysts make up 5-10% of the rock and are generally
Figure 17. Modal mineralogy plotted on IUGS diagram.
grayer and rounder than any feldspar phenocrysts. Alkali feldspar makes up 20% and is present as subhedral broken phenocrysts. Plagioclase phenocrysts typically show inclusions and range in size from 0.2-2 mm. Biotite visible in thin section is bent and kinkeed and makes up 5% of the rock. Groundmass makes up about 40-45% of the rock and is glassy and tuffaceous. Lithic fragments are absent. When plotted on an IUGS classification diagram, the rocks fall within the quartz latite field.

Two large knobs of Tertiary volcanics crop out in the vicinity of the southern part of Rock Creek in the southwestern portion of the map area. The mineralogy is similar to that of the rocks found on Saratoga Mountain but the groundmass contains very fine grained lath-shaped microlites of plagioclase and glass and comprises 50% of the rock. Quartz makes up <10% of the rock as rounded phenocrysts up to 2 mm in diameter. Plagioclase makes up 15% of the rock, is generally euhedral to subhedral, and is both carlsbad and albite twinned. Glomeroporphyritic clusters were observed. Large (up to 5 mm) subhedral phenocrysts of alkali feldspar amount to 15-20% of the rock. Biotite amounts to 5% of the rock.

Just north of Saratoga Mountain a rock with phenocryst mineralogy similar to that described above crops out. The groundmass makes up 50% of the rock and is composed entirely of glass with perlitic fractures. In hand sample
the glass is a dark brown-black color and the phenocrysts are white to clear. Plagioclase is present as large (1-6 mm) euhedral to subhedral phenocrystals with carlsbad and albite twinning.

Interpretation

The white tuff on Saratoga Mountain appears to be an airfall tuff. Phenocrystals are fractured and broken and indicate an explosive origin. The glass in the groundmass indicates that the tuff was still hot when it was deposited. Fragments in the tuff seem to be fairly well sorted. Sorting is a function of wind velocities and distance of transport and works best among sand and fine gravel sized ejecta (Williams and McBirney, 1979, p. 135).

The rocks near Rock Creek appear to be lava flows. The groundmass contains microlites, indicative of flows. Unbroken and glomeroporphyritic clusters of phenocrystals are present. The glomeroporphyritic clusters would not be expected to survive an explosive origin (Williams and McBirney, 1979, p. 116-119).

The rocks just north of Saratoga Mountain seem to represent a vitrophyre or quickly cooled glassy base of a lava flow. The similarity of the mineralogy to the lava flow described above probably means that this is its equivalent.
Tertiary and Quaternary unconsolidated deposits (Tg, Qg, Qa1, Qc)

Tertiary gravels and Quaternary glacial deposits, alluvium, and colluvium cover much of the study area. These deposits were not studied in detail but are included as separate map units.

**SUMMARY**

Rocks in the southeast quarter of the Deerlodge quadrangle may be grouped into three principal categories: 1) The Upper Cretaceous Elkhorn Mountains Volcanics; 2) Upper Cretaceous Boulder batholith; 3) Tertiary Lowland Creek Volcanics.

The Elkhorn Mountains Volcanics comprise the largest volume of rocks in the map area. They consist of basaltic and andesitic lava flows and flow breccias, pyroclastics including airfall tuffs, ash-flow tuffs, laharic deposits, and welded rhyolitic ash-flow tuffs. The Boulder batholith is largely quartz monzonite but includes an early mafic small intrusion. Tertiary Lowland Creek Volcanics are present as minor tuffs and flows.

The Elkhorn Mountains Volcanics and Boulder batholith occur in close proximity and are coeval. The next chapter presents chemical data to further substantiate the cogenetic nature between the Elkhorn Mountains Volcanics
and Boulder batholith.
Chapter III
Chemistry

Whole rock chemical analyses were obtained for twelve samples in the study area. Chemical analyses are important in proving that the Boulder batholith and Elkhorn Mountains Volcanics are genetically related. Two samples were taken from the basalt unit (Kb), three from the andesitic lava unit (Kal), three from the ash-flow tuff/pyroclastic unit (Kaf), two from the welded ash-flow tuff unit (Kwt), one from the batholith (Kbqm), and one from the intrusive or early stage batholith (Ki) unit. The analyses were performed by X-Ray Assay Laboratories in Toronto, Ontario. The analyses are listed in Table 10.

Total iron was originally reported as Fe2O3. A recalculation utilizing the formulas
\[
\% \text{ Fe}_2\text{O}_3 = \% \text{ TiO}_2 + 1.5
\]
\[
\% \text{ FeO} = (\% \text{ Fe}_2\text{O}_3 - \text{ TiO}_2 - 1.5) \times 0.8998
\]
was obtained before normalized oxide values and normative minerals were calculated (Irvine and Baragar, 1971). The normalized oxides recalculated anhydrous and with two Fe oxides are found in Table 11. Normative minerals for the rocks found in the study area were calculated using a computer program from the U.S. Geological Survey modified by the Montana Bureau of Mines and Geology. The normative minerals are listed in Table 12.
Table 9. Whole rock chemical analyses of study area rocks.

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Table 10. Whole rock chemical analyses normalized anhydrous and with two Fe oxides.

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Table 11. Normative mineral content, in wt. %, of study area rocks; analyses listed in Table 11.

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<th>Or</th>
<th>Ab</th>
<th>An</th>
<th>Wo</th>
<th>En</th>
<th>Fs</th>
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Alteration of the rocks in the study area is pervasive. Sampling for rocks to be used for chemical analysis involved freshest, least altered samples. However, both hydrothermal alteration and contact metamorphism (albite-epidote hornfels) affects virtually every rock in the study area in differing amounts. The welded tuffs show the least hydrothermal and metamorphic alteration, probably due to their low porosity, but are all devitrified and recrystallized. The lava flows and pyroclastics all show chlorite and epidote minerals, and a few samples are heavily sericitized. Original compositions may be somewhat different from the altered compositions. This must be considered in analyzing the data.

The Elkhorn Mountains Volcanics and Boulder batholith are considered to be calcalkaline (Tilling, 1973). The term "calcalkaline" applies to rocks that have mineralogy consisting dominantly of feldspars with hornblende and/or augite also present. Feldspathoids, sodic pyroxenes, and sodic amphiboles are absent. The term originally was used to contrast gabbros, diorites, and granodiorites and their volcanic equivalents from alkaline rocks (Irvine and Baragar, 1971). One accepted method is to classify calcalkaline rocks on an A-F-M diagram. Rocks sampled in the study area are plotted on the ternary diagram $A=K_2O+Na_2O$, $F=FeO+0.9 \ Fe_2O_3$, and $M=MgO$ in Figure 18. The
Figure 18. A-F-M plot of rocks of the study area with calc-alkaline and tholeiitic fields delineated (Irvine and Baragar, 1971).
fields for calcalkaline and tholeiitic rocks have been delineated on the diagram. Rocks in the study area plot within the calcalkaline field and show a slight enrichment in iron. Calcalkaline suites generally have the following characteristics: They are typified by the basalt-andesite-dacite-rhyolite association, with the andesites being the most voluminous rock type; the basalts and andesites are high in aluminum, containing between 16 and 20% Al₂O₃; they generally have orthopyroxene and minor quartz in the normative mineralogy; no normative nepheline is present; and plagioclase is the dominant phenocryst with hypersthene, hornblende, and olivine also being present (Irvine and Baragar, 1971; Gill, 1981). The rocks analyzed in the study area exhibit all of the above characteristics. Basalts, andesites, dacites, and rhyolites are all present within the study area and the andesites are the most abundant rock type (Figure 19). The Al₂O₃ contents of the basalts and andesites range from 15.2 to 20.5, 17% being average. All of the rocks show orthopyroxene in the norm and none show nepheline (Table 12). Plagioclase phenocrysts are dominant in thin section and hypersthene, hornblende, and olivine are all common.

SiO₂ values for the volcanic rocks range from 50-74%. Differences in the silica values probably reflect original variations within the magma chamber. When deeper, less evolved levels of the magma chamber are tapped the
Figure 19. Silica percentages of analyzed rocks from study area. Values from Table 11.
resulting silica values in the volcanic rocks are lower. Consequently, the silica values in the evacuated uppermost evolved portion of the chamber are in the 70% range (Hildreth, 1979, 1981; Smith and Bailey, 1966). Silica variations may also result from the phenocryst mineralogies and amounts present in a specific rock. SiO₂ may vary due to density sorting in flows where heavier crystals settle to the bottom of the flow and due to the incorporation of xenoliths bearing phenocrysts. Figure 19 shows the SiO₂ contents of the samples plotted on a diagram dividing the silica contents into basalts, basaltic-andesites, andesites, dacites, and rhyolites. The majority of the rocks analyzed plot in the andesite range. The two rhyolites are the welded tuff samples from the middle unit of the Elkhorn Mountains Volcanics. The batholith sample with the least SiO₂ represents the early mafic stage of the batholith and the other batholith sample is Butte quartz monzonite. The pyroclastic units plot in the andesite-dacite field.

Plots of silica vs. nine other oxides are shown in Figure 20. Harker diagrams with curved or straight continuous trends provide evidence that a rock suite was derived through some evolutionary process from a common magma source (Wilcox, 1979). Curved trends indicate evolution by fractional crystallization and straight trends
Figure 20. Variation diagrams. Values from Table 11.
indicate evolution by magma mixing or assimilation (Hyndman, 1985, p. 109). Whether curved or straight lines provide the best fit for the data is sometimes difficult to decide. For this study straight lines were drawn for the purpose of simplicity and to show how much certain samples deviate from the trend. Good trends against silica are evident for P2O5, FeO, CaO, TiO2, and K2O. Fairly good trends are present for MgO, Al2O3, and MnO. Na2O is the only oxide that does not show an evident trend, perhaps because of hydrothermal effects and the mobility of Na2O. Several factors suggest that hydrothermal alteration was pervasive in the area. Plagioclase is commonly sericitized, the tuffs have undergone devitrification of the groundmass to an intergrowth of silica minerals and feldspars, mafic minerals have commonly altered to magnetite and/or hematite, and carbonate minerals are often present as secondary alteration products. Argillic-sericitic alteration produced by H+ metasomatism commonly result in the characteristics mentioned above (Hemley and Jones, 1964). The H+ metasomatism probably accounts for the scatter in the Na2O and MgO trends. However, K2O and CaO commonly are affected in a similar manner to Na2O but in this study show strong linear trends.

The lava flows generally are less evolved than are the pyroclastics, though some overlap does exist. The less evolved rocks consistently show greater CaO, MgO, FeO, MnO,
P205, and TiO2 and lesser K2O and Na2O than do the more evolved rocks in the suite. The only rocks assigned to the middle unit of the Elkhorn Mountains Volcanics consistently are isolated from the other samples in all the diagrams. They are the densely welded tuffs of the Kwt unit and have the highest SiO2, K2O, and Na2O values of all the rocks sampled, consistent with the middle unit of Klepper and others (1957).

Two other samples stand out in the K2O, P205, TiO2, and to some extent the CaO trends. These samples are from different units as determined both in the field and in thin section. Both are lava flows, one from the plagioclase basalt unit (Kbo) and the other from the andesitic lava unit (Kal). The two samples were taken from the same locale and thus probably underwent similar hydrothermal alteration. In both cases the plagioclase is heavily sericitized.

Tilling (1973) recognized two separate magma series in the batholith, a main series and a sodic series. The main series is lower in Na2O and higher in K2O than is the sodic series at a given silica content. The two separate fields are readily apparent when plotted on a K2O-CaO-Na2O ternary diagram (Figure 21). The volcanic and plutonic units present in the study area all plot in the main series field. This is consistent with Tilling's conclusions that
Figure 21. Rocks from study area plotted on $K_2O$-$Na_2O$-$CaO$ diagram. Main and sodic fields delineated (after Tilling, 1973).
the Elkhorn Mountains Volcanics are chemically related to the main series plutons rather than to the volumetrically minor sodic series. Another means to divide the main series from the sodic series contrasts rubidium and strontium values with silica values (Figure 22 and 23). The rubidium values for the volcanics and plutonics plot closer to the main series field than to the sodic series field. The strontium diagram does not illustrate the main vs sodic series very well, probably due to the mobility of strontium, but a general affinity for the main series is apparent.

Based on the chemical affinity of all the rocks in the study area and the close proximity in which they occur, the rocks sampled appear to belong to a single, comagmatic suite. Chapter IV discusses the suite of rocks in terms of a caldera environment and proposes an explanation for the origin of the magmas which produced the Elkhorn Mountains Volcanics and Boulder batholith.
Figure 22. Rocks from study area plotted on a rubidium vs. silica diagram. Main and sodic series delineated (after Tilling, 1973).

Figure 23. Rocks from study area plotted on strontium vs. silica diagram. Main and sodic series delineated (after Tilling, 1973).
Figure 22.

Figure 23.
It is suggested above that the Elkhorn Mountains Volcanics formed within a caldera environment. Caldera remnants are difficult to interpret in a region such as that in the Boulder batholith area. The age and extensive glacial deposits which occur in the region obscure any remnants which may be present. A topographic expression has long been eroded away and what remains is the roots of a caldron and the underlying batholith.

Two possible models for the origin of the lithologies present in the study area are offered. Neither presents irrefutable evidence for the origin of a particular unit or the structures present within the area. Before possible models for the origin of rocks in the study area are presented, it is important to review the major aspects of lithologies present within the study area.

The volume of lavas approximately equals the volume of pyroclastic material present in the area. Relatively few intrusive lithologies are present although the abundance of lavas in the area would obscure dikes which may have fed the lava flows. The Kaf unit is composed of several overlapping lithologies of pyroclastic origin. The Kwt welded tuff unit consists of 160-350 meters of densely welded tuff and no top or base of the unit is exposed. The
Boulder batholith crops out in the southern portion of the map area and farther east and south.

Model 1

The first interpretation can be represented in terms of a facies diagram (Figure 24) which views the area in terms of proximity to a vent or caldera. The sequence of events can be thought of in terms of a caldera cycle. Large volumes of intermediate and mafic lavas were extruded in the pre- and post-caldera stages. If the Boulder batholith area consisted of a series of nested calderas as are inferred for the San Juan volcanic field (Steven and Lipman, 1976) then lavas could be extruded almost continually during the entire volcanic episode. Basalts present within the study area are interpreted as interfingering with the lower unit of the Elkhorn Mountains Volcanics in the area and are found stratigraphically above the middle unit welded tuffs to the north (Derkey, 1986). Smaller eruptions of intermediate pyroclastic material and lavas may be extruded before the development of a silicic upper portion of the magma chamber. Pyroclastic eruptions may be numerous but not of sufficient volume or explosive nature to cause caldera collapse.

The andesitic pyroclastic unit (Kaf) contains ash-flow tuff, airfall tuff, and laharc deposits. Typical outflow
Figure 24. Study area shown in relation to proximity to a caldera. Study area is on western flanks of caldera. Inset shows close up of study area and stratigraphic relations between units.
ash-flow tuffs, that is, those which occur outside the caldera boundaries, are tens of meters to 300 meters thick (Lipman, 1984). Although the actual thickness of individual flows was not measured, it is inferred that the thickness of any one ash-flow tuff present in the Kaf unit certainly does not exceed 300 meters and probably does not exceed 100 meters. The presence of airfall tuffs throughout the sequence of pyroclastics certainly precludes the interpretation of one thick flow. The Kaf unit all but disappears to the north of the study area. It has already been stated that the basalts both pre- and postdate the volcanic units present in the area. The most likely explanation for the lack of ash-flow tuff to the north is that it has been covered up by the voluminous lavas present in that area.

Laharic deposits are considered to be initiated solely by gravitational forces. It would seem likely that the flanks of a caldera would be a perfect site for generation of such flows. The small size of the fragments in the mudflow(s) seem to preclude the deposit being a collapse breccia which is generated by collapse of caldera walls immediately following voluminous eruption of ash-flow material.

The rhyolitic densely welded ash-flow tuff which occurs in the area might also be an outflow tuff. Outflow tuffs can travel great distances from their source and are
generally of a uniform thickness (Lipman, 1984). The welded tuff in the study area appears to be of a fairly uniform thickness. The welded tuff described by Ruppel (1963) in the Basin quadrangle also appears to be of a fairly uniform thickness. The top of the flow seems to have been eroded away since all of the unit appears to be densely welded and the degree of welding does not appear to change much throughout the flow. Steven and Lipman (1976) describe most of the San Juan volcanic field outflow tuff sheets as being rhyolitic in composition and the intracaldera tuffs as being quartz latitic in composition. This suggests that by the time sufficient magma was removed in the form of ash-flow tuffs to collapse and form a caldera, the uppermost silicic portion of the chamber was exhausted. Based on the consistent nature, rhyolitic composition, and very large inferred volume of the Kwt unit, it probably represents a caldera-forming outflow ash-flow tuff.

This model interprets the lithologies of the study area as being deposited on the flanks of a caldera. The actual caldera and intracaldera structures and lithologies are interpreted as having been present to the east in the location now occupied by the Butte Quartz Monzonite. The actual caldera or calderas probably foundered into the rising pluton (Figure 24).
The stages of development may be inferred as follows utilizing Smith and Bailey's (1968) stages of caldera formation:

1) Regional tumescense;
2) Lava flows and intermediate pyroclastics, lahars from steepening slopes of future caldera (units Kb, Kal, Kaf);
3) Ash-flow tuff eruption and caldera formation (Kwt);
4) Post collapse caldera margin volcanism--lava flows (Kb);
5) Ring fracture volcanism not present in the study area but may be represented by the dikes that occur to the east of the study area.
6) Rise of the pluton into the intracaldera sequence, probably to the east where the largest volume of plutonic rocks are present (Kbqm);
7) Hot spring activity which altered the rocks in the area.

Model 2

A second model which may offer a plausible explanation for the lithologies in the study area may be presented in terms of a caldera in the immediate vicinity. The Rock Creek fault forms a nearly linear major structure in the eastern portion of the map area (Plate 1). This fault could represent a caldera boundary that separates a thick intracaldera sequence with no base exposed from preexisting
pyroclastics and lava flows. Several lines of permissive evidence support this idea. Examination of Ruopel's (1963) map of the Basin quadrangle has lead to the identification of a possible remnant of a caldera margin near the vicinity of Thunderbolt Mountain. Thunderbolt Mountain is approximately 2 miles southeast of Cliff Mountain which is in the northeastern section of the study area. Units include a megabreccia with fragments 1-10 meters in diameter overlain by poorly sorted and bedded conglomerate with locally derived clasts, several basaltic dikes, and thick densely welded ash-flow tuff similar to that present in the study area. Although I have not specifically examined field relations or rock samples from the area, the grouping of the lithologies may represent a partial margin of a caldera (Figure 25). The megabreccia may represent a caldera collapse breccia. Megabreccias may be present throughout an intracaldera sequence and indicate that the inner walls of the caldera are occasionally unstable (Lipman, 1984). The dikes may represent ring dikes that develop along caldera margins due to faulting caused during regional tumescense and caldera formation. The conglomerate may represent volcanic sedimentation which occurred during stage V of Smith and Bailey's (1968) caldera cycle. The welded ash-flow tuff unit (Kwt) may represent an intracaldera tuff. Although intracaldera
Figure 25. Stratigraphic relations between units in the Thunderbolt Mountain area (Basin quadrangle). Units may represent a caldera boundary.
tuffs generally are on the order of 1-2 Km thick, a substantial amount of erosion probably has taken place and the roots of the caldera system are exposed. This is substantiated by the vast amount of plutonic rocks present in the area. Intracaldera tuffs are generally more dense than are outflow tuffs owing to more welding, devitrification, and propylitic alteration (Lipman, 1984). The welded ash-flow tuff in the area is densely welded throughout the entire unit. It is at least 160-250 meters thick. Although it is common to have outflow units of this thickness, intracaldera sequences are generally much thicker. As mentioned above, erosion may have obliterated much of the intracaldera sequence. If the Rock Creek fault represents a partial caldera margin, and if the lithologies present in the vicinity of Thunderbolt Mountain also represent a partial caldera margin then the remaining caldera structure undoubtedly extends an unknown distance farther east (Figure 26). The eastern portion of the caldera probably foundered into the rising pluton present in the Basin quadrangle. Small calderas between 5 and 15 Km in diameter are common in the San Juan volcanic field (Steven and Lipman, 1976). Typically, small calderas do not form circular volcanic depressions. They exhibit "trap-door" -style subsidence. These small calderas are bounded on three sides by faults. The fourth side exhibits only monoclinal flexures. The formation of ring dikes is
Figure 26. Location map of possible caldera boundaries. Eastern portion of study area (on left) shown bounding the Basin quadrangle (on right).
incomplete at best. Such a "trap-door" configuration may be more compatible with structures and rocks in the study area. No ring dikes have been observed. The Rock Creek fault may represent the western boundary of a trap door style caldera. However, casual observation of geologic maps to the north, east, and south of the study area shows no structures which can be interpreted as caldera margins. This may mean that the structures have foundered into or been obliterated by the pluton, are obscured by erosion and vegetative cover, or are not present. Structural boundaries of collapsed calderas commonly are marked only by minor gouge and hydrothermally altered rock. If this is the case then the poor exposures in the area may preclude the identification of the precise location of any specific caldera related structures. If the welded tuff represents an intracaldera sequence then no outflow has been observed in the area. This may be due to 1) No sizable outflow may have been deposited; or 2) The outflow sheet has been preferentially eroded because it was topographically higher than the intracaldera sequence, probably was less welded, and was much thinner.

The lava flows occur on the periphery of the caldera margin. The lava flows probably were there before caldera formation and subsequent flows probably erupted from fissures on the outskirts of the caldera margin. The Kaf
pyroclastic unit may represent the flanks of a preexisting caldera or minor non collapsing eruptions of more mafic material before a silicic top was developed within the chamber.

This model may be summarized utilizing the stages of caldera formation from Smith and Bailey (1968) as follows:
1) Regional tumescense;
2) Emplacement of intermediate lavas and pyroclastics (Kb, Kal, Kaf);
3) "Trap-door"-style subsidence or larger circular style collapse of intracaldera block (Rock Creek fault and Thunderbolt Mountain) and intracaldera ash-flow tuffs deposited (Kwt);
4) Post caldera lavas extruded (Kb);
5) Resurgent doming probably did not occur in a caldera of this small size (Smith and Bailey, 1968);
6) Ring dikes emplaced along margins (Thunderbolt Mountain);
7) Hot spring activity as evidenced by the pervasive features of H+ metasomatism in the rocks of the study area.

Problems exist when interpreting the origin of volcanic units within a caldera environment for older and more deeply eroded calderas. Since structures are eroded or are obliterated by vegetative cover, only inference as to the caldera location(s) is possible. Problems also arise when attempting to determine how many caldera cycles
are represented by units in a given area. Overlap of units undoubtedly occurs in a nested caldera environment. Smedes (1966) mapped seven separate large volume ash-flow tuffs in the area of the northeastern Boulder batholith so at least seven probable caldera cycles existed in the region. Pyroclastic units may erupt but not form calderas. Preexisting calderas may also fill with material ejected from subsequent caldera forming episodes. All of the factors mentioned above contribute to the difficulty of interpreting deeply eroded roots of caldera systems.

The source and mechanism of magma generation which erupted the Elkhorn Mountains Volcanics and later crystallized to form the Boulder batholith is also only speculative. Several lines of evidence are used below to suggest the nature of the source.

The eruption or shallow emplacement of large volumes of intermediate magma in the form of the Elkhorn Mountains Volcanics and Boulder batholith implies that water content of the magma was low when it melted and continued to be fairly dry until it reached the surface (Hyndman, 1981). This implies that the lower crust was the source of the magma (Hyndman, Alt, and Sears, 1986). This is consistent with isotopic evidence presented by Doe and others (1968) that require a source in the lower crust or upper mantle to get isotopic signatures such as those that are present in
the Elkhorn Mountains Volcanics and Boulder batholith. Basalt-andesite-dacite-rhyolite calcalkaline rocks are associated with areas of deep subduction (Figure 27). As the oceanic slab is subducted, the hydrous alteration minerals dehydrate and drive water into the overlying wedge of mantle peridotite. This influx of water lowers the melting temperature of the mantle and hydrous basaltic magmas are generated. The basaltic magmas rise through the continental crust and cause partial melting of the crust. The more felsic partial melts of the continental crust in combination with the basaltic magmas form the andesite-dacite-rhyolites and their associated plutonic equivalents, usually granodiorite or quartz monzonite (Hyndman, 1985, p. 661-662). The overall system probably evolved by a combination of processes involving influx of new basaltic magmas and eruption of lavas and pyroclastics at various times. These early mafic magmas produced the rocks included in the lower unit of the Elkhorn Mountains Volcanics which form the majority of the rocks found in the study area. The middle unit rhyolitic ash-flow tuff erupted after the caldera-forming magma chamber differentiated a silicic cap. After eruption of the uppermost silicic portion of the chamber, the remaining magma eventually crystallized to form the Butte Quartz Monzonite.
More mafic, drier magmas from depth rise with variable differentiation and contamination to form arc volcanic rocks: basalt, andesite, dacite, rhyolite.

Partial melting of continental crust using heat from rising basalts, water from depth and from local dehydration reactions; rise of magmas to form granitic batholiths.

Greenschist facies

Oceanic crust-
basalt

Peridotite

Continental crust

Rising basalts

Partial melting

Partial melting

Lithosphere

Dehydration

Asthenosphere

Diagramatic cross section through an ocean-continent converging margin, illustrating possible development of basalt-andesite-dacite-rhyolite arc volcanic rocks at the surface. Greenschist amphibolite-facies regional metamorphism and major granitoid batholiths occur at deeper levels. With less water and closer approach to the surface, shallow granites, calderas, and major ash flows occur (After Hyndman, 1985, p. 661).
Conclusions

The Elkhorn Mountains Volcanics are considered to be cogenetic with the Boulder batholith. The Elkhorn Mountains Volcanics are present in the study area as basaltic-andesitic lava flows and breccias, andesitic ash-flow tuffs, airfall tuffs, and tuff-breccias, and rhyolitic ash-flow tuffs. The Boulder batholith is present in the area as quartz monzonite and gabbro.

Continuous chemical trends indicate that the volcanic and plutonic rocks are related by evolution of a single magmatic system. The Elkhorn Mountains Volcanics are chemically more similar to the main series of the Boulder batholith than to the sodic series as evidenced by the K2O, CaO, Na2O, Rb, and Sr contents. The rocks in the study area originated in a caldera environment. The exact source is not known but the caldera was probably to the east in the area now occupied by the Butte Quartz Monzonite of the Boulder batholith. An alternative explanation is that a caldera is present in the immediate vicinity of the map area and that the welded tuff unit represents an intracaldera sequence.

The source for the magmas that produced the Elkhorn Mountains Volcanics probably was the lower crust and/or the upper mantle. The exact mode of evolution of the caldera-forming magma chamber is not known but probably involved a
combination of processes including minor crystal fractionation, convection, and magma mixing. The Butte Quartz Monzonite represents the crystallized portion of the magma chamber which erupted the middle unit of the Elkhorn Mountains Volcanics.
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