DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

In cooperation with Montana Bureau of Mines and Geology as part of the COGEOMAP Program

OPEN-FILE REPORT
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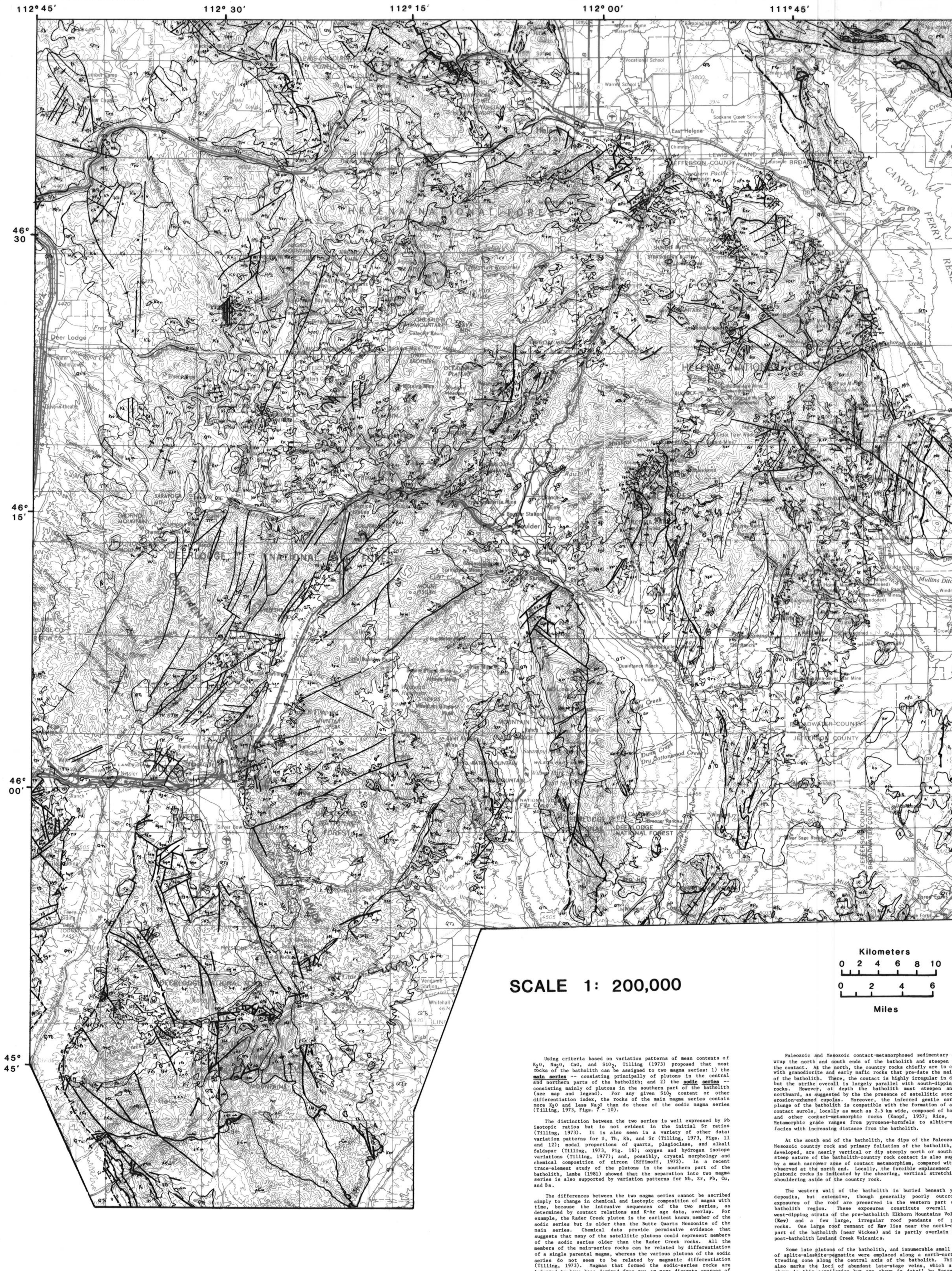

SCALE 1: 200,000

Kilometers: 0 2 4 6 8 10
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EXPLANATION

(For details, see DESCRIPTION OF MAP UNITS)

QUATERNARY AND TERTIARY

- **QTs** Sedimentary deposits (Quaternary and Upper Tertiary)
- **Tb** Basalt lavas (Upper Miocene or Lower Pliocene)
- **Tri / Trv** Rhyolite lava and tuff of the Avon Volcanics and associated intrusve rocks, **Tri** (Upper Eocene and Lower Oligocene (?))
- **Tli / Tlv** Lowland Creek Volcanics and associated intrusive rocks, **Tli** Quartz latite (Middle Eocene)

CRETACEOUS AND TERTIARY — Upper Cretaceous and Paleocene

ROCKS OF THE BOULDER BATHOLITH

ROCKS OF THE MAIN MAGMA SERIES

fqm | pr | h | a | bqm | gp granite porphyry

Butte Quartz Monzonite and related silicic facies

- **a**, alaskite and/or aplite
- **h**, Homestake quartz monzonite
- **pr**, Pulpit Rock quartz monzonite
- **fqm**, felsic quartz monzonite, compositionally similar to **h** and **pr**
- **bqm**, Butte Quartz Monzonite

u | bp

- **u**, Unionville Granodiorite of Knopf (1963)
- **bp**, granodiorite of Burton Park; provisional assignment to series

m mafic rocks, mostly gabbroic

ROCKS OF THE SODIC MAGMA SERIES

lg | pg | mc | mt | d | ap/hc | gr/cg

Leucocratic granodiorites and quartz monzonites

- **cg**, Climax Gulch pluton and associated younger granitic bodies, **gr**
- **hc**, Hell Canyon pluton and associated aplite, **ap**
- **d**, Donald pluton
- **mt**, Moosetown pluton
- **mc**, Moose Creek pluton
- **lg**, unnamed plutons
- **pg**, porphyritic granodiorite of Knopf (1963); provisional assignment to series

mb / rc

- **rc**, granodiorite and quartz monzonite of the zoned Rader Creek pluton
- **mb**, mafic bodies that cut the pluton

BATHOLITH ROCKS AND SATELLITIC BODIES NOT ASSIGNED TO MAGMA SERIES

sl | si | sgd | sm

Age relations among these units not known; their relative positions in the overall intrusive sequence uncertain but probably span entire period of batholith emplacement

- **sl**, leucocratic rocks
- **si**, intermediate rocks
- **sgd**, granodioritic rocks
- **sm**, mafic rocks

MESOZOIC AND PALEOZOIC

- **Kb** Basalt flows and flow breccias (Upper Cretaceous)
- **Ki / Kev** Elkhorn Mountains Volcanics and associated intrusive rocks, **Ki** (Upper Cretaceous)
- **MPz** Mesozoic and Upper Paleozoic sedimenary rocks
- **Pz** Paleozoic sedimentary rocks

PRECAMBRIAN

- **p€i / p€s** Precambrian sedimentary rocks and associated intrusive rocks, **p€i** (Proterozoic)
- **p€m** Precambrian metamorphic rocks (Archean)

Inclusions in plutonic rocks

Contact (Shown as solid line regardless of actual nature of contact)

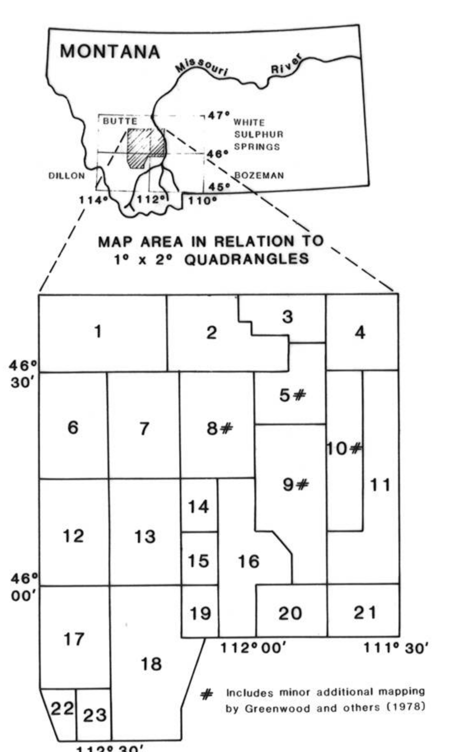
Normal and reverse faults, dashed where inferred; **U**, upthrown side **D**, downthrown side

Thrust fault; teeth on side of upper plate

Tear fault; arrows indicate relative motion, and wavy lines indicate broad zones of shearing

Syncline and overturned syncline

Anticline and overturned anticline



INDEX TO SOURCE DATA
(See References Cited)

1. Prostka (1964)
2. Knopf (1963)
3. Schmidt (1978)
4. Mertie and others (1951)
5. Smedes (1966)
6. Ruppel (1961)
7. Ruppel (1963)
8. Becraft and others (1963)
9. Klepper and others (1957)
10. Klepper and others (1971a)
11. Freeman and others (1958)
12. Smedes (1968)
13. Smedes and others (1962)
14. Becraft and Pinckney (1961)
15. Pinckney and Becraft (1961)
16. Weeks (1974)
17. Smedes (1967)
18. Klepper and Tilling (1970, 1972)
19. Prostka (1966)
20. Indiana University (1964)
21. Robinson (1963)
22. Smedes (1958)
23. Smedes (1959)

INTRODUCTION

Because the Boulder batholith region hosts many rich ore deposits, the rocks of the batholith, its satellite plutons, and surrounding terrane have been the targets of many mapping and topical studies [see, for example, the references cited in Klepper and others (1957), Robinson and others (1968), and Tilling (1973, 1974)]. In the mid-1950's, the U.S. Geological Survey (USGS) began a major effort, directed by (the late) Montis R. Klepper, to map the entire Boulder batholith region at a scale of 1:24,000 or 1:48,000. These geologic mapping and related topical studies (informally called "the Boulder batholith project") were essentially completed by the late 1960's; minor additional mapping was done in the late 1970's in connection with the mineral resource assessment of the Elkhorn Wilderness Study Area (Greenwood and others, 1978, plate 1). Since then, systematic geologic mapping (scale 1:250,000) and geophysical surveys of the Butte, Dillon, and White Sulphur Springs 2-degree sheets--which include the Boulder batholith region--have been in progress as part of the USGS' regional mapping and/or mineral-resource assessment programs (see, for example, Ruppel and others, 1983; Wallace and others, 1987).

This compilation draws from published and unpublished maps of the component plutons of the Boulder batholith and its satellites, and of the distribution and principal structures of pre- and post-batholith rocks and deposits. The purpose of the map and accompanying brief text is twofold:

1) to summarize the available mapping and other data on the plutonic rocks, at a scale that allows the entire batholith to be portrayed in a single map sheet of manageable size (for field use); and

2) to serve as a general guide for future studies to better understand this classic igneous terrane, whether through more-detailed mapping or by topical investigations.

Geologic information from which the map was compiled is indicated in the index to source data. Other than the segment along the northern part of the batholith mapped by Adolph and Eleanora B. Knopf (Knopf, 1963), the bulk of the mapping was done by members of the U.S. Geological Survey (USGS). The stratigraphic and structural details of the pre- and post-batholith rocks shown in the source geologic maps have been highly generalized in our compilation, not only to accentuate the plutonic units, but also to avoid unnecessary repetition of detail shown in source geologic maps already published and in the final 1:250,000 maps of the Butte, Dillon, and White Sulphur Springs 2-degree sheets scheduled to be published in the near future. Therefore, this map focuses on plutonic rocks of the Boulder batholith and its satellites. More-detailed compilation of the pre- and post-batholith rocks, we believe, would be better, and more appropriately, done by those actively involved in the current regional mapping studies.

ACKNOWLEDGMENTS

This compilation would not have been possible without the maps, cooperation, and encouragement of our USGS colleagues who have worked, or currently are working, in and around the Boulder batholith region. Throughout the years of the Boulder batholith project, the Montana Bureau of Mines and Geology (MBMG) was most helpful and supportive. Special thanks go to E-an Zen (USGS, Reston) and Edward T. Ruppel (Director, MBMG) for their constructive criticism and helpful suggestions on earlier versions of this map and accompanying text, and to Jerry Russell, Karen Gray, and Lori Moore (USGS, Reston and Menlo Park) for cartographic advice and assistance in the preparation of the map. Last but not least, we (HWS and RIT) dedicate this map to the memory of Montis (Monty) R. Klepper--our associate, friend, mentor, and the driving force behind the Boulder batholith project. Even during the final months before his death in November 1978, Monty, when physically able, participated actively in this compilation.

NOMENCLATURE OF IGNEOUS ROCKS

Virtually all the geologic mapping used for this compilation was done before 1972, the year when the International Union of Geological Sciences (IUGS) endorsed the classification and nomenclature agreed upon by the IUGS Submission on the Systematics of Igneous Rocks (Streckeisen, 1973, 1976). The classification and nomenclature used in nearly all the original sources cited (see index) was a slight modification of the scheme proposed by Johannsen (1939), as shown in Figure 1a. Because of the widespread use of the modified Johannsen scheme in the previous studies upon which this compilation is based, for continuity and consistency we also use that scheme in this compilation, rather than the (now) commonly accepted classification and nomenclature of Streckeisen (1973) shown in Figure 1b. In his mapping of the north-central and northwestern margin of the map area, Knopf (1963) used Nockolds' (1954) classification, which is similar to that used in this compilation except for the use of adamellite instead of quartz monzonite. Also, in the Nockolds' classification, adamellite is a rock in which alkali feldspar makes up 40 to 60 percent of total feldspar, whereas, in the modified Johannsen scheme we use, quartz monzonite refers to a rock in which alkali feldspar makes up 35 to 65 percent of total feldspar.

The description of pyroclastic units in the pre- and post-batholith volcanic rocks in this compilation largely follows the terminology of Wentworth and Williams (1932), conforming with usage in the original data sources.

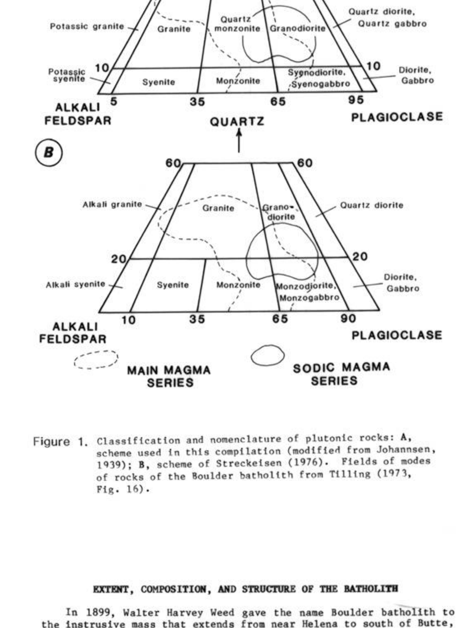


Figure 1. Classification and nomenclature of plutonic rocks: A, scheme used in this compilation (modified from Johannsen, 1939); B, scheme of Streckeisen (1976). Fields of modes of rocks of the Boulder batholith from Tilling (1973, Fig. 16).

EXTENT, COMPOSITION, AND STRUCTURE OF THE BATHOLITH

In 1899, Walter Harvey Weed gave the name Boulder batholith to the instrusive mass that extends from near Helena to south of Butte, Montana (Weed, 1899). Since then, hundreds of papers, maps, and geochemical and geophysical surveys have been published on the batholith and vicinity, and its nature and mode of emplacement have been vigorously debated (Hamilton and Myers, 1967, 1974; Klepper and others, 1971b, 1974; Hyndman and others, 1975). The brief discussion below only highlights selected aspects of the batholith appropriate to the scale and information content of this compilation map.

Composite nature and age relations

The batholith is an elongate north-northeast-trending composite epizonal body of calc-alkalic plutonic rocks--approximately 100 km long and 50 km wide, covering an area of about 5,700 km². It is made up of numerous coalesced plutons and isolated satellitic plutons that range from potassic ultramafic rocks and melagabbro, through granodiorite and quartz monzonite, to granite and syenite. However, a single pluton, the Butte Quartz Monzonite (**bqm**), constitutes nearly 73% of the exposed batholith (Tilling, 1974). The other plutons of granodiorite and mafic rocks border the **bqm** on its north, south, and southeast edges. Collectively, the batholith rocks were emplaced over a 10 million-year time span, approximately 80 to 70 Ma. [K-Ar ages cited in this compilation have been recalculated using the new conventional decay constants of Steiger and Jager (1977) now used in geochronology and thus are slightly older than the published ages.] In general, the younger batholith rocks tend to be more felsic than the older ones, the leucocratic granodiorites and quartz monzonites being the youngest (Knopf, 1956, 1957, 1963; Tilling and others, 1968).

Two-magma series model

Implicit throughout the systematic mapping and dating studies of the 1960's was the working premise that all the intrusions making up the composite batholith are part of a single magma series. As the results of isotopic studies became available, however, this long-held notion became suspect. Despite the narrow restriction of the batholith rocks in time and space, lead and strontium isotope data clearly preclude the derivation of all the rocks from a single, isotopically well-mixed magma source (Doe and others, 1968). This finding prompted a reexamination of all field and analytical data and the acquisition of additional chemical analyses to ascertain whether the isotopic variations might also be expressed by variations in rock chemistry.

Using criteria based on variation patterns of mean contents of K_2O, Na_2O, CaO, and SiO_2, Tilling (1973) proposed that most rocks of the batholith can be assigned to two magma series: 1) the **main series** -- consisting principally of plutons in the central and northern parts of the batholith; and 2) the **sodic series** -- consisting mainly of plutons in the southern part of the batholith (see map and legend). For any given SiO_2 content or other differentiation index, the rocks of the main magma series contain more K_2O and less Na_2O than do those of the sodic magma series (Tilling, 1973, Figs. 7 - 10).

The distinction between the two series is well expressed by Pb isotopic ratios but is not evident in the initial Sr ratios (Tilling, 1973). It is also seen in a variety of other data: variation patterns for U, Th, Rb, and Sr (Tilling, 1973, Figs. 11 and 12); modal proportions of quartz, plagioclase, and alkali feldspar (Tilling, 1973, Fig. 16); oxygen and hydrogen isotope variations (Tilling, 1977); and, possibly, crystal morphology and chemical composition of zircon (Effimoff, 1972). In a recent trace-element study of the plutons in the southern part of the batholith, Lambe (1981) showed that the separation into two magma series is also supported by variation patterns for Nb, Zr, Pb, Cu, and Ba.

The differences between the two magma series cannot be ascribed simply to change in chemical and isotopic composition of magma with time, because the intrusive sequences of the two series, as determined by contact relations and K-Ar age data, overlap. For example, the Rader Creek pluton is the earliest known member of the sodic series but is older than the Butte Quartz Monzonite of the main series. Chemical data provide permissive evidence that suggests that many of the satellitic plutons could represent members of the sodic series older than the Rader Creek rocks. All the members of the main-series rocks can be related by differentiation of a single parental magma, whereas the various plutons of the sodic series do not seem to be related by magmatic differentiation (Tilling, 1973). Magmas that formed the sodic-series rocks are inferred to have been derived from two or more discrete sources of distinct Rb/Sr and strontium and lead isotopic ratios, or from a single heterogeneous source characterized by intrinsic differences in Rb/Sr and Sr and Pb isotopic ratios from one part to another.

Both chemically and isotopically, rocks of the pre-batholith Elkhorn Mountains Volcanics (**Kev**) resemble the earliest members of the main-series plutonic rocks, confirming abundant field relations that suggest that they are genetically associated. However, the **Kev** rocks only show chemical affinity to rocks of the main magma series; there appears to be no **Kev** extrusive equivalents of the sodic magma series (Tilling, 1974). These observations, based on the limited chemical data, have been substantiated by a recent systematic study of the geochemistry of the Elkhorn Mountains Volcanics (Rutland and others, 1984; Rutland, 1985, 1986). In contrast, the post-batholith Lowland Creek Volcanics are chemically akin to the felsic members of the sodic magma series. However, isotopically they are more similar to the main series (especially Pb isotopes) but are somewhat more radiogenic in terms of both of Pb and Sr isotopic ratios than batholith rocks of either series (Tilling, 1973, Fig. 19).

Regional zonation

Except for three small bodies (**lg**) in the north-central part of the batholith, all bodies large enough to show at the compilation scale that can be unambiguously assigned (with currently available data) to the sodic magma series are restricted to the southwestern part of the region, i.e., south of Butte (lat. 46°N) and west of about longitude 112°10'. However, there are a few other bodies of sodic-series rocks (too small to be shown) that occur randomly to the north and east of these boundaries. Such areal distribution is grossly compatible with the long-known larger-scale regional zonation of increasing K2O eastward for the Western United States (e.g., Lindgren, 1915; Moore, 1959, 1962). Tilling (1973, Fig. 18) suggested that plutonic rocks to the west and south of the Boulder batholith (e.g., the Tobacco Root, Philipsburg, Pioneer, and Idaho batholiths) are similar to, or more sodic than, the sodic-series rocks. However, recent data indicate that the regional zonation is more complicated than first thought, at least in terms of Sr initial ratios (SIRs). Although the nearly contemporaneous rocks of the northeastern part of the Pioneer batholith are chemically akin to the sodic-series rocks, they are characterized by a range of initial Sr ratios (.7112-.7160) that is significantly higher than, and do not overlap, that for the entire Boulder batholith (.7055-.7092) (Zen and others, 1975; Snee, 1978, 1982; Hammarstrom, 1982; Marvin and others, 1983; Arth and others, 1986). The Big Hole Canyon pluton (west of map), a composite mass located between the Boulder and Pioneer batholiths near Dewey, Montana, is characterized by chemical affinity to the sodic-series rocks and has Sr, Rb/Sr, SIR values (.7051-.7077) similar to those for the Rader Creek pluton (Zinter, 1982; Zinter and others, 1983; L.W. Snee, oral communication, 1987). The composite McCartney Mountain stock of Boulder-batholith age (south of map), also located between the Boulder and Pioneer batholiths, is mineralogically and chemically similar to the sodic-series rocks (Friberg and Vitaliano, 1981).

In summary, chemical, isotopic, and mineralogic data for the Boulder batholith seem best interpreted in terms of two magma series, emplaced in the same brief time span but chemically and isotopically distinct (Tilling, 1973). Lambe (1981) suggests that the sodic magma series may be further split into two groups on the basis of rare-earth-element patterns. The main and sodic magma series of the Boulder batholith are believed to have been derived from two or more sources within the lower crust or upper mantle (Doe and others, 1968). However, for the rocks of the Pioneer batholith, with its high SIR values, a significant crustal component is required (Arth and others, 1986). Because of the Boulder batholith's limited areal extent, Tilling (1973) favors vertically zoned source regions, whereas Lambe (1981) prefers two laterally separated sources on the basis of tectonic and compositional arguments.

For reasons not fully understood, the main-series rocks host the rich ore deposits that made the Boulder batholith region famous, whereas the sodic-series rocks contain far fewer major deposits, none on the scale of those in the Butte District. According to Lambe (1981), the main-series rocks tend to host Au, Ag, Cu, Pb, Zn, Mn (and Mo at Butte) mineralization, but the sodic-series rocks are generally characterized by Au, Ag, Mo, W, Sn mineralization.

Shape and contact relations

The principal plutons of the batholith and the satellitic stocks are steep-walled bodies. Exceptions include many of the aplite-alaskite-pegmatite bodies (**a**, commonly gently dipping sheets), the Moose Creek pluton (**mc**, a moderately inclined irregular laccolith; Smedes and others, 1980), and the granitic facies of the Climax Gulch pluton (**gr**, overall sheet-like). The east margin of the large Butte Quartz Monzonite (**bqm**), which cuts principally the Elkhorn Mountains Volcanics (**Kev**) and the Rader Creek pluton (**rc**), is remarkably linear. This feature is interpreted as evidence for the emplacement of the eastern part of the **bqm** along a pre-existing fault zone of north-northeast trend, parts of which were obliterated by stopping during emplacement. North of the batholith, the presence of the fault zone is reflected by intensely sheared, vertically stretched, injected and recrystallized volcanic rocks. Near the northern end of the eastern margin, a downward-tapering screen of sheared and thermally metamorphosed volcanic rocks separates the main batholith mass from a large dike-like lobe to the east. Near the southern end of the eastern margin, a narrow septum of sheared rocks, Late Precambrian to Late Cretaceous in age, separates the Butte Quartz Monzonite and the older Rader Creek pluton.

Paleozoic and Mesozoic contact-metamorphosed sedimentary strata wrap the north and south ends of the batholith and steepen toward the contact. At the north, the country rocks chiefly are in contact with granodiorite and early mafic rocks that pre-date the main mass of the batholith. There, the contact is highly irregular in detail, but the strike overall is largely parallel with south-dipping host rocks. However, at depth the batholith must steepen and dip northward, as suggested by the the presence of satellitic stocks and erosion-exhumed cupolas. Moreover, the inferred gentle northward plunge of the batholith is compatible with the formation of a broad contact aureole, locally as much as 2.5 km wide, composed of hornfels and other contact-metamorphic rocks (Knopf, 1957; Rice, 1977). Metamorphic grade ranges from pyroxene-hornfels to albite-epidote facies with increasing distance from the batholith.

At the south end of the batholith, the dips of the Paleozoic and Mesozoic country rock and primary foliation of the batholith, where developed, are nearly vertical or dip steeply north or south. The steep nature of the batholith-country rock contact is also suggested by a much narrower zone of contact metamorphism, compared with that observed at the north end. Locally, the forcible emplacement of the plutonic rocks is indicated by the shearing, vertical stretching and shouldering aside of the country rock.

The western wall of the batholith is buried beneath younger deposits, but extensive, though generally poorly outcropping, exposures of the roof are preserved in the western part of the batholith region. These exposures constitute overall gently west-dipping strata of the pre-batholith Elkhorn Mountains Volcanics (**Kev**) and a few large, irregular roof pendants of pre-**Kev** rocks. One large roof remnant of **Kev** lies near the north-central part of the batholith (near Wickes) and is partly overlain by the post-batholith Lowland Creek Volcanics.

Some late plutons of the batholith, and innumerable small bodies of aplite-alaskite-pegmatite were emplaced along a north-northeast-trending zone along the central axis of the batholith. This zone also marks the loci of abundant late-stage veins, which are not shown in this compilation but are shown in detail by Becraft and others (1963) and Smedes (1966), as well as dikes and plugs of post-batholith quartz latite and rhyolite. Discontinuous screens of pre-batholith volcanic and older rocks and fault zones lie near the western limit of the exposures of the batholith.

Collectively, these observations related to the shape and contact relations of the plutons indicate that faults of north-northeast trend played a prominent role before, during, and after batholith emplacement and post-batholith volcanism.

Internal structures

As earlier noted by Grout and Balk (1934), most rocks of the Boulder batholith are largely massive and do not exhibit strongly expressed rock fabric. However, the marginal parts of some plutons and, less commonly, their interiors show internal structures, defined by steeply dipping planar foliation marked by alinement of minerals and/or platy inclusions or by gently dipping schlieren in the roof zone. Locally, particularly along contacts against country rock or other batholith rocks, the plutonic rocks contain abundant mafic inclusions, composed of sharply outlined to diffuse aggregates of ferromagnesian minerals and plagioclase of the same composition as in the host rock. These probably represent large semi-solid blocks of inclusion-rich rock from near the roof or contact zones that have foundered into the less crystallized (less viscous) magma.

In places, two or more steep foliations are preserved in the same rock; these structures are well developed in some plutons (e.g., **bp**, **bqm**, and **cg**) in the southwestern part of the batholith. The older structure, consisting of alined mafic minerals, mafic inclusions, and plagioclase, is interpreted to be caused by primary flow during pluton emplacement; the younger structure, marked by alined large alkali- feldspar megacrysts, is interpreted to reflect late crystal growth along incipient joints that formed late in cooling history, when the pluton had largely solidified. Joints that formed still later in the cooling history of some main-series plutons, especially the **bqm**, became the loci for injection of felsic rocks (principally aplite, alaskite, and pegmatite) and, very rarely, mafic rocks of undetermined composition. In the Rader Creek pluton, the emplacement of mafic bodies (**mb**) was in part joint controlled. Some later generations of fractures were occupied by metalliferous quartz veins and/or by thin dikes of diverse composition.

Satellitic plutons

The Boulder batholith is fringed by a number of satellitic plutons within 50 km of its margins. These plutons vary widely in size, composition, texture, grain size, and relationship to country rock. The larger satellites [e.g., the Hell Canyon (**hc**), Moose Creek (**mc**), and Moosetown (**mt**) plutons] nearest to the main intrusive mass are considered to be part of the batholith proper in this and most previous studies of the Boulder batholith region.

Most of the satellite bodies intrude Proterozoic (Belt) and younger sedimentary rocks or the Elkhorn Mountains Volcanics; very few, most notably the Hell Canyon pluton (**hc**), intrude Archean metamorphic rocks. The northwesterly elongation of the Hell Canyon, and possibly also the Donald pluton, appears to be controlled by faults in the Archean basement rocks (see Schmidt and others, 1975). Some satellites are uniform in composition, and others are heterogeneous because they are contaminated, are highly differentiated, are composite or zoned plutons. Available chemical data suggest that satellitic rocks tend to have compositions distinct from those of the batholith rocks proper and that, if anything, they show closer affinity to the sodic-series rather than main-series rocks (Tilling, 1973, Fig. 5).

Post-batholith igneous history

Calc-alkalic volcanism in the region occurred episodically during the Cenozoic after the cessation of plutonism. After the batholith and its related metalliferous quartz veins were eroded to a surface of mature relief, the Lowland Creek Volcanics and related intrusive rocks (**Tlv**, **Tli**) of quartz-latite composition were erupted or intruded during the Middle Eocene (48-50 Ma). Extensional block-faulting of basin-and-range style occurred before and during this volcanism and continued intermittently throughout the Cenozoic. During Late Eocene to Lower Oligocene (?) time, volcanism recurred, producing rhyolitic lavas, tuffs, and associated intrusive rocks (**Trv**, **Tri**) of the Avon Volcanics. Volcanic ash is a principal component of Cenozoic deposits that filled intermontane basins, which were faulted episodically during Oligocene, Miocene, and Pliocene time. Ore deposits occur locally in the **Tlv** (e.g., in the Lowland Creek area) and in the **Trv** (e.g., near Rimini and along Warm Springs Creek). Basaltic lava flows (**Tb**) along Crow Creek (east-central margin of the map) represent the youngest known igneous activity in the compilation area (most probably Upper Miocene or Lower Pliocene).

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DESCRIPTION OF MAP UNITS

QTs CLAY, SILT, SAND, AND GRAVEL, UNDIVIDED (QUATERNARY AND TERTIARY)

Includes alluvium, colluvium, glacial deposits, terrace deposits, and lake deposits.

VOLCANIC ROCKS AND RELATED HYPABYSSAL INTRUSIVE ROCKS (TERTIARY)

Tb Basalt lava flows, most probably Upper Miocene or Lower Pliocene, but could be as old as Oligocene (Klepper and others, 1971a).

Trv Rhyolite lava flows and tuffs of the Upper Eocene and Lower Oligocene (?) Avon Volcanics of the Helena Volcanic field.

Tri Rhyolite dikes and plugs, intrusive equivalents of the Avon Volcanics (**Trv**).

Tlv Quartz-latite tuff, welded tuff, and lava flows of the Middle Eocene Lowland Creek Volcanics.

Tli Quartz-latite intrusive rocks contemporaneous with the Lowland Creek Volcanics (**Tlv**). Shown separately only where not coincident with extrusive rocks and in the roof pendant near Wickes in the Jefferson City quadrangle.

ROCKS OF THE BOULDER BATHOLITH AND ITS SATELLITE STOCKS (UPPER CRETACEOUS AND PALEOCENE)

Note: The boxes in the map legend for the main and sodic magma series are arranged according to relative position in the intrusive sequence, if known from field relations and/or radiometric age data (recalculated using the new conventional decay constants of Steiger and Jager, 1977).

ROCKS OF THE MAIN MAGMA SERIES

LEUCOCRATIC ROCKS

a Aplite, alaskite, granite pegmatite, quartz-monzonite pegmatite, potassic leucogranite, quartz pegmatite, and quartz-tourmaline pegmatite, undivided; aplite and alaskite predominate. Generally small bodies of variable texture and structure, occurring as pods, dikes, sheets, and complexes, only few of which are entirely of a single rock type. Quartz, sodic plagioclase and alkali feldspar typically make up at least 98% of the rock, with biotite and lesser amounts of magnetite, sphene, apatite, zircon, and, occasionally, allanite constituting the remaining 2%. Bodies commonly are layered, either regularly or irregularly, and some are zoned. Textures commonly change along as well as across the layers. Miarolitic cavities are common in these rocks, containing well-formed crystals of quartz (clear, smoky, or amethyst), alkali-feldspar (microcline, orthoclase, perthite and microperthite), albite-oligoclase, tourmaline, and silvery green muscovite (?); locally, molybdenite, epidote, pyrite, magnetite, sphene, and allanite are conspicuous.

gp Granite porphyry, light to pinkish gray with phenocrysts of quartz and alkali feldspar, occurs as bodies large enough to show at the scale of this compilation only in the central part of the batholith. Compositionally similar to aplite-alaskite, but is distinctly more porphyritic and generally sheared and strongly altered. It shows both gradational and cross-cutting contact against Butte Quartz Monzonite (**bqm**); its relationship to the other silicic facies of the **bqm** is unknown. Because of their gradation into the **bqm**, these relatively rare rocks are believed to be nearly contemporaneous with the **bqm**. The granite porphyry almost certainly is not related to the quartz porphyry dikes that cut the **bqm**, but pre-date mineralization, in the Butte district. As described by Brimhall (1977), the quartz porphyry dikes always show sharp contacts with the **bqm** and are distinctly younger (<64 Ma; Meyer and others, 1968).

h Quartz monzonite of the Homestake pluton, well exposed in the Northern Pacific Railroad cut at Continental Divide (southeast of Butte). Field relations show that rocks of this pluton represent a continuous gradational series between the Butte Quartz Monzonite (**bqm**) and the alaskite-aplite (**a**); accordingly, the texture and mineralogy of these rocks may vary widely, ranging between those characteristic of the two end members. Most are light gray and some have pinkish cast, depending on the amount of alkali feldspar.

Contacts between the variants in the series can be gradational or sharp, in which case the more felsic of the two rocks in contact invariably is the younger. Many bodies of rock similar to those of the Homestake pluton occur throughout the Butte Quartz Monzonite but are too small to be shown at compilation scale.

pr Coarse-grained quartz monzonite of the Pulpit Rock pluton, located in the central part of the batholith (west of Boulder); overall light gray, but pinkish alkali feldspar is conspicuous. Mineralogically and texturally similar to the coarser grained varieties of the Butte Quartz Monzonite (**bqm**) but containing more quartz, plagioclase, and alkali feldspar and less ferromagnesian minerals. Can be highly porphyritic locally with large phenocrysts (or "megacrysts") of alkali feldspar, which commonly contain inclusions of earlier crystallized minerals alined along crystal faces. Generally grades into but locally cuts **bqm**. In contrast to the Homestake-type rocks, the Pulpit Rock quartz monzonite rarely shows gradational contacts against aplite-alaskite bodies that intrude it.

fqm Felsic quartz monzonites of unnamed plutons similar in color, texture, and composition to rocks of the Homestake and the Pulpit Rock plutons. Can range widely in grain size and texture. Commonly grades into the Butte Quartz Monzonite (**bqm**) but cross-cutting contacts, where observed, always show the **bqm** to be older. Some typical bodies of these rocks occur along the southern border of the Butte Quartz Monzonite (e.g., Spire Rock, west of Whitetail Basin).

bqm Butte Quartz Monzonite (= Clancy Granodiorite of Knopf, 1957, 1963). Quartz Monzonite and subordinate granodiorite, mostly light gray to pinkish gray in color; locally, the marginal parts of the body appear darker gray because of greater abundance of ferromagnesian minerals. The rocks grade into and are cut by the silicic facies described above; locally and very rarely, thin dark dikes of undetermined composition (lamprophyre?), commonly highly altered, also cut the **bqm**. The general ranges in the principal constituent minerals (by volume) are: plagioclase 20 to 48%, alkali-feldspar 15 to 45%, quartz 15 to 40%, biotite < 1 to 12%, hornblende < 1 to 8%, pyroxene sparse but locally as much as 5%. These wide ranges reflect the gradation of **bqm** between its related silicic facies. Average grain size commonly varies from < 1 to 3 mm, and textures also vary widely, including xenomorphic, hypidiomorphic, equigranular, and seriate. Much of the **bqm** is distinctly porphyritic, with conspicuous subhedral to euhedral phenocrysts of poikilitic alkali feldspar, whose length can be as great as 5 cm or more.

Despite mappable textural, color, and compositional variants--of which more than a dozen have been mapped (for example, see Becraft and others, 1963; Ruppel, 1963; and Smedes, 1966)--all the rocks that constitute the Butte Quartz Monzonite (**bqm**) are considered to be parts of a single large pluton because of the predominance of gradational contacts between the **bqm** variants and of close chemical and isotopic similarity (Doe and others, 1968; Tilling, 1973). The textural and mineralogical differences are attributed to intermittent magma movement and mixing of magma fractions that reached different degrees of crystallization. These differences are best developed in parts of the pluton in proximity to country rock or older batholith rocks and are less common in the interior of the pluton.

GRANODIORITE

u Unionville Granodiorite and granogabbro of Knopf (1963), undivided; mostly light- to medium-gray, seriate augite-hornblende-biotite granodiorite locally including dark-gray hypersthene granogabbro near contacts. Biotite commonly occurs as large bronze-colored, irregular poikilitic plates that continued to grow late in the crystallization history of the rock. The rocks typically are medium grained and equigranular, xenomorphic to hypidiomorphic, in texture.

bp Granodiorite of the Burton Park pluton; medium-grained, bluish-gray equigranular rock, containing poikilitic biotite, that forms a moderate-size pluton near southern end of the batholith. Several smaller satellitic bodies of granodiorite (**sgd**) cutting Proterozoic rocks in the area are similar in appearance to the Burton Park granodiorite and possibly correlative. Even though compositionally similar to the Unionville Granodiorite, the Burton Park rocks can only be assigned provisionally to the main magma series (Tilling, 1974). In contrast to the Butte Quartz Monzonite, both the Unionville Granodiorite and Burton Park plutons contain very few aplite-alaskite bodies.

MAFIC AND ULTRAMAFIC ROCKS

m Mafic and ultramafic rocks, undivided; includes melanorite, hyperite, gabbro, syenogabbro, mafic monzonite, syenodiorite, augite quartz monzonite, and rare layers of peridotite in gabbro. These rocks, highly variable in composition and texture, may occur as a single rock type or, more commonly, form a complex of diverse rock types. Field relations and geochronometric data indicate the mafic and ultramafic rocks are the earliest products of the Boulder batholith, found almost exclusively along its margins. A representative suite of these complex rocks has been well characterized petrographically and chemically by Smedes (1966).

ROCKS OF THE SODIC MAGMA SERIES

LEUCOCRATIC ROCKS

cg Leucocratic quartz monzonite and granodiorite of the Climax Gulch pluton. Cuts the Butte Quartz Monzonite and the Burton Park granodiorite. This pluton varies widely in texture, mineralogy, and chemical composition, but the predominant rock type is a fine- to medium-grained, light gray to pinkish-gray, highly porphyritic quartz monzonite, which locally may contain as many as 300 phenocrysts (as large as 2 x 4 cm) of alkali feldspar per square meter. Compared to the Butte Quartz Monzonite, the Climax Gulch rocks tend to contain relatively more quartz and plagioclase, and fewer ferromagnesian minerals. Ranges in modal composition (by volume) are as follows: plagioclase 35 to 45%; alkali feldspar 20 to 35%; quartz 24 to 30%; hornblende 0 to 4%; biotite 4 to 8%; and accessory minerals < 1 to 2%. Locally, the rocks grade into, and are cut by, a more-felsic and finer-grained facies, which, where large enough, is shown as **gr** on the map. The youngest K-Ar age determinations for the Boulder batholith, 69.5 to 70.5 Ma, were obtained on biotite and hornblende, respectively, in the one sample of Climax Gulch pluton dated (see Tilling and others, 1968, Table 2).

gr More-granitic, finer-grained, and slightly younger facies of the Climax Gulch pluton. Grades into and locally cuts the **cg**.

hc Quartz monzonite of the Hell Canyon pluton, which forms the southern tip of the batholith. Although compositionally homogeneous, the pluton varies from medium-grained, light gray, slightly porphyritic rocks at its narrow southern end to coarse-grained, highly porphyritic varieties in the central and northern parts. Alkali-feldspar phenocrysts as large as 3 x 6 cm (Mathews and others, 1977), commonly contain inclusions of nearly all other minerals in discontinuous strings parallel to crystal faces. A distinctive feature of many of the Hell Canyon rocks is the presence of conspicuous, equant quartz "eyes," some of which may attain 1 cm in size. The Hell Canyon rocks are cut by rare, generally small, bodies of aplite (**ap**).

ap Rare aplite bodies that cut the Hell Canyon pluton; though virtually indistinguishable from the abundant aplites associated with the Butte Quartz Monzonite, these aplites are assumed to be related genetically to the Hell Canyon rocks because of spatial association.

d Leucocratic granodiorite of the Donald pluton; mineralogically similar to but slightly more felsic than rocks of the Hell Canyon pluton. Equigranular, medium-grained, light gray varieties predominate, but highly porphyritic rocks, with large pinkish alkali-feldspar phenocrysts also are common, locally forming spectacular castellated craggy exposures. This unit, like most other leucocratic rocks of the sodic magma series, is virtually devoid of aplitic or pegmatitic bodies.

mc Granodiorite and quartz monzonite of the Moose Creek pluton; consists of a probably early facies in the northern part of medium- to fine-grained, light gray granodiorite that contains abundant inclusions of diorite, and a main mass of medium- to coarse-grained, mostly porphyritic muscovite-biotite quartz monzonite with phenocrysts of alkali feldspar and quartz. Locally cut by small dikes and irregular bodies of quartz porphyry. Except for the presence of minor muscovite, the rocks are mineralogically and chemically similarly to those of the Donald pluton. Moreover, like the Donald rocks, the Moose Creek pluton locally is well exposed as high, spire-like outcrops (e.g., the Humbug Spires, 8 km ENE of Divide; see Smedes and others, 1980).

mt Leucocratic rocks of the poorly exposed Moosetown pluton. In color, mineralogy, texture, and grain size resemble those of the nearby Moose Creek pluton (**mc**).

lg Fine- to medium-grained, light gray, granodiorite and quartz monzonite, mostly equigranular; in places moderately to strongly altered. Lithologically similar to the finer-grained varieties of the Donald and Hell Canyon plutons. Several unnamed plutons in the central and northern part of the batholith represent the only bodies of **lg** rocks large enough to show at the scale of this compilation. The **lg** rocks satisfy the chemical criteria (see Tilling, 1973) used to define the sodic-series rocks in the southern end of the batholith. These rocks, none of which have been dated radiometrically, cut the Butte Quartz Monzonite; their specific relation to the other sodic-magma-series rocks is problematic.

pg Porphyritic granodiorite of Knopf (1957, 1963), typically light gray and coarse grained; a homogeneous pluton characterized by phenocrysts of alkali feldspar (as large as 2 x 3 cm) uniformly distributed throughout. A representative mode (by volume) is: plagioclase 40%, alkali feldspar 24%, quartz 25%, biotite 7%, hornblende 3%, with magnetite, sphene, apatite, and zircon making up the remaining 1%.

This rock cuts the adjacent "granodiorite undivided" of Knopf (1963). Two K-Ar age determinations on biotite in the only sample of this pluton dated averaged 73.6 Ma, within the range of ages found for other leucocratic rocks of the batholith (Tilling and others, 1968, Fig. 2). The rocks are chemically similar to some of the rocks of the Climax Gulch pluton (**cg**), but available analytical data only permit provisional assignment to the sodic magma series (Tilling, 1974, Table 1).

GRANODIORITE

rc Granodiorite and quartz monzonite of the zoned Rader Creek pluton, the largest of the plutons of the sodic magma series. The weathered surfaces of these rocks generally are darker (brownr) than those of the adjacent Butte Quartz Monzonite and Donald pluton. In fresh exposures, however, most Rader Creek rocks are distinctly bluish gray. The southwestern part of the pluton is composed of medium-grained, equigranular granodiorite, which grades continuously and nearly imperceptibly into quartz monzonite in the northeastern part. Also, rocks in the northernmost end of the exposed pluton are conspicuously porphyritic rather than equigranular; these rocks are the only ones in the entire batholith to have the porphyritic texture expressed by plagioclase phenocrysts (dark gray and as long as 1 cm), rather than alkali-feldspar phenocrysts. Detailed descriptions of the mineralogical and chemical zonation of the Rader Creek pluton are given in Tilling (1964, 1968).

The Rader Creek pluton is cut by the Butte Quartz Monzonite. Its age relations to the granodiorites of the main magma series (the Unionville and Burton Park) are unknown because nowhere are these rocks in contact. However, K-Ar ages for the Rader Creek rocks (74.4-78.4 Ma) and the Unionville Granodiorite (74.0-79.5 Ma) largely overlap, but possibly the Unionville rocks are in part slightly older (Tilling and others, 1968, Table 3). Locally, the pluton is cut by rare aplite bodies (too small to show at compilation scale) and also by a number of mafic ("lamprophyric") intrusions (**mb**), which contain inclusions of the Rader Creek as well as aplitic rocks (see below).

mb Fine- to coarse-grained mafic bodies that intrude the Rader Creek pluton; occur as irregular plugs and ring dikes, and, much less commonly, as thin dikes (only the larger bodies could be shown on map). Some of the masses are uniform in lithology, but others are composed of several distinct lithologies. Compositionally, these rocks are heterogeneous and predominantly dioritic to gabbro, but granodioritic rocks may make up much of the ring-dike complexes, generally the interior portions. These mafic bodies probably were intruded before the emplacement of the Butte Quartz Monzonite. Detailed descriptions of several of the Rader Creek mafic bodies is given in Smedes and others (1968).

The relative proportion of late mafic intrusions in the Rader Creek pluton is much higher than that in the Butte Quartz Monzonite. The relationship among late mafic bodies associated with different plutons of the batholith is not known.

BATHOLITH ROCKS AND SATELLITIC BODIES NOT ASSIGNED TO MAGMA SERIES

Many small plutons within the batholith and most satellitic bodies cannot be assigned to one or the other of the magma series, because either the chemical criteria cannot be met unambiguously or the pertinent compositional data are lacking. Moreover, because the satellitic bodies occur as isolated masses in country rock and very few of them have been dated radiometrically, their positions in the intrusive sequence cannot be established. Accordingly, for this compilation, we only show them by gross compositional type regardless of age as follows:

sl Leucocratic rocks, light gray granodiorite and quartz monzonite, undivided; variable in texture, fine- to medium-grained. These rocks are relatively sparse.

si Intermediate rocks, light- to medium-gray granodiorite to quartz monzonite, undivided; variable in texture and grain size, but coarse-grained varieties are rare.

sgd Granodioritic rocks, undivided; mostly equigranular, medium-grained, and dark gray.

sm Mafic and, less commonly, ultramafic brownish-weathering rocks, undivided; highly variable in texture and grain size. Includes some plutons that are composite bodies, composed of mafic rocks cut by more-felsic rocks.

PREBATHOLITH VOLCANIC AND VOLCANICLASTIC ROCKS AND CONTEMPORANEOUS HYPABYSSAL INTRUSIVE ROCKS (UPPER CRETACEOUS)

Kb Basalt and olivine-basalt lava flows and flow breccias, commonly poorly exposed and/or altered. In the reconnaissance map of Prostka (1964), this unit was considered to be Tertiary, possibly post-Avon Volcanics (**Trv**). More recent studies (Derkey, 1986; Watson, 1986) consider these rocks, certainly where mapped in detail in the Emery mining district, to be "separate, but time equivalent" to the middle and upper members of the Elkhorn Mountains Volcanics (**Kev**).

Kev Elkhorn Mountains Volcanics and Slim Sam Formation, undivided. Tuffaceous sedimentary rocks of the Slim Sam Formation and basalt lavas; basalt and andesite tuff, breccia, and agglomerate; and rhyolite welded tuff of the Elkhorn Mountains Volcanics.

Field relations and radiometric age data demonstrate that the **Kev** and the earliest batholith rocks are nearly contemporaneous, but, where diagnostic cross-cutting relationships can be observed, the batholith rocks are invariably the younger (Becraft and others, 1963; Robinson and others, 1968; Tilling and others, 1968). For example, the middle member of the **Kev** near the northeastern end of the batholith is cut by mafic rocks (**m**) of the main magma series. In the central part of the batholith, the upper sedimentary member of the **Kev** is cut by the Butte Quartz Monzonite (**bqm**).

Ki Basaltic and andesitic hypabyssal intrusive rocks contemporaneous with the Elkhorn Mountains Volcanics (**Kev**).

MPz MESOZOIC AND LATE PALEOZOIC SEDIMENTARY ROCKS, UNDIVIDED

Includes the Permian Phosphoria Fm., Jurassic Swift and Morrison Fm. and the Cretaceous Kootenai and Colorado Fms.

Pz PALEOZOIC SEDIMENTARY ROCKS, UNDIVIDED

Includes the Cambrian Flathead Quartzite, Wolsey Shale, Meagher Limestone, Park Shale, Pilgrim Fm., Hasmark Dolomite, and Red Lion Fm.; Devonian Maywood and Jefferson Dolomite; Devonian and Mississippian Three Forks Shale; Mississippian Lodgepole Limestone, Mission Canyon Limestone, and Amsden Fm.; and Pennsylvanian Quadrant Fm.

p€s SEDIMENTARY ROCKS OF THE BELT SUPERGROUP, UNDIVIDED (PROTEROZOIC)

(See original sources given in index for details concerning stratigraphic nomenclature of the rocks mapped).

Includes formations and units mapped in the northern part as Empire Fm., Spokane Fm., Helena Dolomite; Marsh Fm., and Greenhorn Mountain Quartzite; in the eastern part as Empire Shale, Spokane Shale, and Greyson Shale; and in the southern part as LaHood Fm., Quartzite of Table Mountain, Greyson Shale, Argillite of Red Mountain, Empire Fm., Helena Dolomite, and Highland quartzite.

p€i GABBRO, DIABASE, AND BASALT INTRUSIVE ROCKS CONSIDERED TO BE BELT AGE (PROTEROZOIC)

p€m METAMORPHIC ROCKS, UNDIVIDED (ARCHEAN)

Mostly gneiss and schist; lesser amounts of amphibolite and granite.

PRELIMINARY MAP OF PLUTONIC UNITS OF THE BOULDER BATHOLITH, SOUTHWESTERN MONTANA

By

Harry W. Smedes, Montis R. Klepper, and Robert I. Tilling

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This map is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes and does not imply endorsement by the USGS.