ROBERT I. TILLING *U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii National P*
Hawaii 96718

Boulder Batholith, Montana: A Product of Two Contemporaneous but Chemically Distinct Magma Series

ABSTRACT

Rocks of the Late Cretaceous composite Boulder batholith, though successively emplaced in a relatively small segment of the Earth's crust within a very brief time span (78 to 68 m.y.), can be grouped chemically into two magma series: (1) the *main series*, defined principally by plutons in the central and northern parts of the batholith; and (2) the *sodic series*, defined mostly by plutons in the southern part. For any given SiO_2 content, the rocks of the main series tend to be higher in K_2O and lower in Na_2O than rocks of the sodic series. The chemical distinction between the two series proposed is also expressed by variation patterns for U, Th, Rb, and Sr abundances, by lead isotope compositions, but not by strontium isotope compositions.

The prebatholith Elkhorn Mountains Volcanics (Late Cretaceous), especially the mafic members, are chemically and isotopically similar to the rocks of the main series, confirming geologic evidence of the genetic association between them. The postbatholith Lowland Creek Volcanics (early Eocene), though chemically more closely related to the sodic series, isotopically are more akin to, but slightly more radiogenic than, the main series. Post–Lowland Creek volcanic rocks (Miocene or Pliocene) are compositionally similar to the sodic series rocks. Spatial distribution of the batholith and the volcanic rocks exhibits a very crude chemical zonation of the region: for a given silica content, relatively more potassic rocks (main series and prebatholith volcanic rocks) tend to occur mainly in the north and east, whereas relatively more sodic rocks (sodic series and postbatholith volcanic rocks) predominate in the south and west.

Available field, chemical, and isotopic evidence collectively suggests that the observed compositional variations for the Boulder batholith are most reasonably interpreted in terms of a model involving two magma series derived from two or more magma sources within the lower crust or upper mantle. These source regions are inferred to vary chemically and isotopically, either laterally or vertically; in view of the rather small areal extent of the Boulder batholith, however, a vertically zoned source region is more probable.

INTRODUCTION

The Boulder batholith of southwestern Montana (Fig. 1) is a classic, though relatively small, representative of the epizonal Mesozoic plutonic masses of the Western United States. This batholith, host for the rich ore deposits of the Butte mining district, its satellitic stocks, and surrounding terrane have been the subject of many studies, principally by members of the U.S. Geological Survey (Weed, 1899, 1912; Barrell, 1907; Knopf, 1913, 1950, 1957, 1963; Pardee and Schrader, 1933; Klepper and others, 1957, 1971; Becraft and others, 1963; Ruppel, 1963; Smedes, 1966; Hanna, 1967, 1973; Doe and others, 1968; Tilling, 1968; Tilling and others, 1968; Tilling and Gottfried, 1969; Al-Hashimi and Brownlow, 1970; Suttner and Leininger, 1972). Impressed by the apparent homogeneity of the rocks, early investigators thought the batholith to be a single, relatively uniform intrusion (Weed, 1912; Knopf, 1913; Billingsley, 1915; Pardee and Schrader, 1933). This notion of a single-intrusion batholith is understandable, because most of the early work was done in connection with ore exploration within one particularly favorable pluton, the areally extensive Butte

Geological Society of America Bulletin, v. 84, p. 3879–3900, 19 figs., December 1973

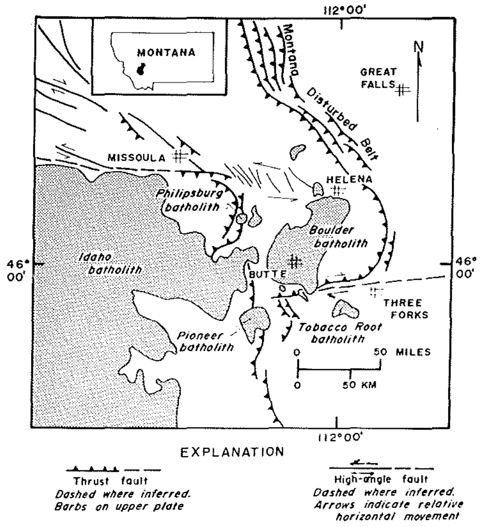

Figure 1. Geologic sketch showing location and tectonic setting of the Boulder batholith in relation to other Montana batholiths and the Idaho batholith (slightly modified from Smedes and others, 1968, Fig. 1). Axes of major folds in en echelon belt between Helena and Missoula shown by thin lines. Areas underlain by plutonic rocks are stippled.

Quartz Monzonite (Fig. 2). Although compositional and textural variations were recognized, these were interpreted as local "facies" or "phases" of the main mass.

It was not until the systematic field and petrographic studies of the late Adolph Knopf (beginning in 1938) that the northern part of the Boulder batholith was shown to be composite and built up by successive emplacement of magmas differing in time and composition (Knopf, 1957, 1963). Subsequent and continuing work by Klepper and associates of the U.S. Geological Survey clearly demonstrates the composite nature of the batholith as a whole. Implicit in even the recent work on the batholith, however, is the premise that the different plutons represent members of one magma series. (In this paper, "magma series" means a group of rocks associated in time and space that have similar or relatable petrologic and chemical characteristics.) For example, the multiple-intrusion but one-magma-series model served as the framework for interpretation of K-Ar age data (Tilling and others, 1968). But lead and isotope data for the batholith (Doe and others, 1968) suggested that the one-magma-series model was inadequate to account for the observed isotopic variations and that two or more magma sources were required to produce the batholith rocks. This spurred a re-examination of existing observations and a systematic attempt to acquire additional chemical data to determine, if possible, whether the isotopic variations also are reflected in some manner in rock chemistry.

This report summarizes available chemical, isotopic, and other pertinent data for the batholith and, to a lesser extent, for the pre-batholith and postbatholith volcanic rocks of the region. Except for minor occurrences of monzonitic and alkalic gabbros, all these igneous rocks clearly characterize the Boulder batholith region as a calc-alkalic magma province. The data presented herein, including many unpublished chemical analyses, will be considered in terms of a new working hypothesis that the Boulder batholith is formed of rocks representing two magma series, emplaced during a single limited time span but chemically and isotopically distinct.

GEOLOGIC SETTING AND IGNEOUS HISTORY

The general features and some specific aspects of the Boulder batholith have been considered at length in the published works cited above; hence, only a brief summary of the batholith's geologic setting need be given here. The batholith, which measures approximately 100 x 50 km, was emplaced within a crustal block defined by the distinct bulge in the structural grain of the Montana Disturbed Belt and other major tectonic zones of the region (Fig. 1; see also Smedes, 1958, 1973). Gravity data do not indicate any sharp break between the Boulder batholith and the nearby and considerably larger Idaho batholith to the west and southwest (Biehler and Bonini, 1969). In contrast, aeromagnetic data show the Idaho batholith to have weak magnetic expression, and the Boulder batholith to have strong expression, suggesting that these two batholiths probably are not connected beneath a thin cover of younger rock (Zietz and others, 1971). Field and K-Ar age data (Tilling and others, 1968) demonstrate that the constituent plutons of the Boulder batholith most likely were emplaced within a 10-m.y. interval (78 to 68 m.y.) of the Late Cretaceous and intrude country rock ranging from pre-Belt metamorphic rocks metamorphosed approximately 1,600 m.y. ago (Giletti, 1966) to the Elkhorn Mountains Volcanics ($\gtrsim$ 78 m.y.). As detailed

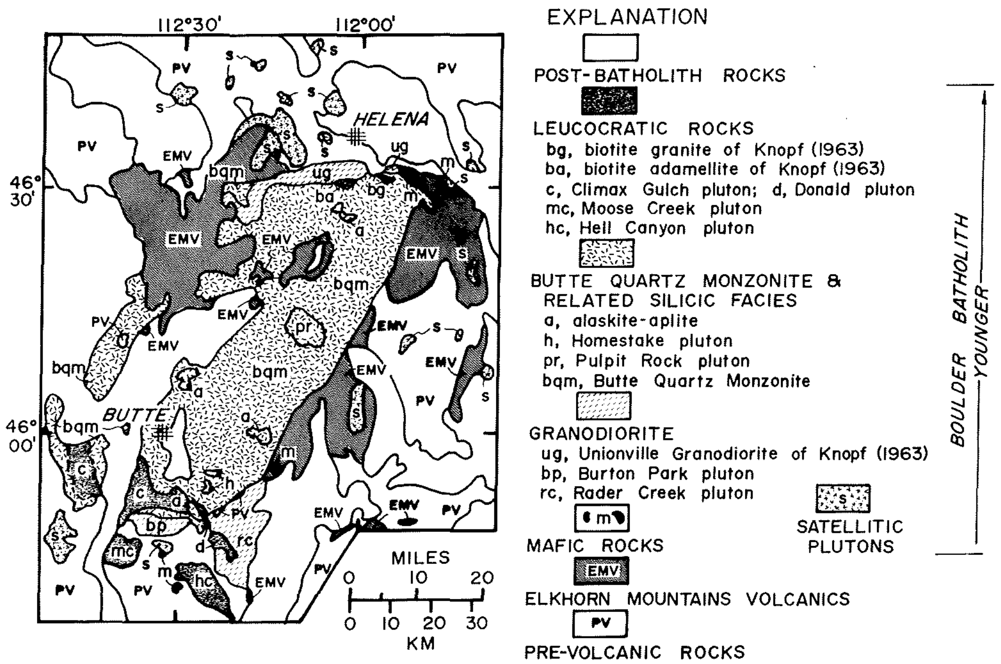

Figure 2. Generalized geologic map of the Boulder batholith region (modified from Tilling and Gottfried, 1969, Fig. 2). The satellitic plutons are arbitrarily placed early in the intrusive sequence on the basis of compositional evidence. The postbatholith rocks include the Lowland Creek Volcanics (early Eocene), post-Lowland Creek volcanic rocks, and sedimentary rocks; the prevolcanic rocks include strata of Mesozoic, Paleozoic, and late Precambrian (Belt) age and metamorphic rocks of early Precambrian age.

by Robinson and others (1968), the processes of tectonism, plutonism, and volcanism overlapped in the Boulder batholith region.

Composed of rocks ranging from syenogabbro to alaskite, the Boulder batholith is dominated by the Butte Quartz Monzonite, the largest single pluton of the batholith (Fig. 2). In general, crosscutting relations and the K-Ar ages of the plutons are in good agreement: the felsic rocks tend to be younger than the mafic rocks, which are volumetrically minor, occurring around the periphery of the batholith. Many plutons have steep, straight (fault-controlled) contacts, such as the eastern boundary of the Butte Quartz Monzonite. The western and southwestern parts of the batholith are injected and mantled by the Lowland Creek Volcanics of early Eocene age (Smedes, 1962; Smedes and Thomas, 1965).

Except for extremely limited and sporadic intrusion of small dikes and sills of mafic rocks during the late Precambrian (see, for example, Knopf, 1963; Robinson and others, 1968), no significant igneous activity occurred before the late Mesozoic. The igneous history of the region really began with the volcanism during the Late Cretaceous that produced the extensive Elkhorn Mountains Volcanics. The original thickness of the Elkhorn Mountains volcanic pile probably exceeded 10,000 ft (Klepper and others, 1957; Smedes, 1966), and its volcanic field originally covered an area several times as large as that indicated by its remnants (Klepper and Smedes, 1959; Klepper and others, 1971, Fig. 4). Radiometric and paleontologic evidence is compatible with the idea that plutonism commenced before volcanism ceased, but wherever crosscutting relations have been observed, the earliest batholith rocks invariably cut the Elkhorn Mountains Volcanics.

Plutonism essentially terminated about 68 m.y. ago for the Boulder batholith (Tilling and others, 1968) but persisted in neighboring areas. K-Ar ages younger than 68 m.y. are reported for some rocks of the nearby Tobacco Root batholith (Giletti, 1966) and for some plutons of the Idaho batholith (McDowell and Kulp, 1969). Approximately 20 m.y. after the emplacement of the youngest plutons, igneous activity renewed in the Boulder batholith region with the extrusion of the predominantly quartz latitic and dacitic rocks of the Lowland Creek Volcanics of early Eocene age (48 to 50 m.y., Smedes and Thomas, 1965). Post–Lowland Creek volcanism is represented by compositionally bimodal rocks (predominantly rhyolite with subordinate basalt) that occur mainly as flows and isolated plugs in the northern part of the region (from Helena westward; Fig. 2). The ages of these rocks are believed to be Miocene or possibly Pliocene (Knopf, 1913; Ruppel, 1963).

TWO-MAGMA-SERIES MODEL FOR THE BOULDER BATHOLITH

The idea that a batholith may be formed by rocks representing more than one magma series—though novel for the Boulder batholith—has been suggested for other well-studied batholiths; for example, the central part of the Sierra Nevada batholith was formed by rocks representing nine provisional "sequences" emplaced in five intrusive epochs within the Mesozoic. ("Sequence" is essentially synonymous with "magma series" as used in this paper and refers to a group of "rocks emplaced during a single intrusive epoch, which field, petrologic, and chemical data indicate are comagmatic" [Bateman and Dodge, 1970, p. 411].) Each epoch lasted 10 to 15 m.y., and the epochs are separated by intervals of approximately 30 m.y. (Bateman and Dodge, 1970; Evernden and Kistler, 1970; Kistler and others, 1971.) Several lines of evidence discussed below suggest the possible existence of two magma series for the Boulder batholith; however, the case for the Boulder batholith is distinct from that for the Sierra Nevada batholith because the two magma series, though different in composition, were emplaced within the same brief (10-m.y.) time interval and within a very restricted segment of the crust.

Chemical Evidence

More than 250 chemical analyses of the Boulder batholith and its satellitic plutons are now available, and these have been summarized by means of a composite Harker variation diagram (Fig. 3). The data points in Figure 3 show considerable scatter, which is fairly typical and expectable of such plots for plutonic rocks (Larsen, 1948; Bateman and others, 1963; Ross, 1969; Bateman and Dodge, 1970; Lee and Van Loenen, 1971). Such scatter in part reflects intrapluton chemical variations—well exhibited, for example, by the Rader Creek pluton (Tilling, 1964, 1968)—which tend to diffuse and obscure major compositional trends defined by interpluton variations. For the Boulder batholith, if we exclude the samples with less than 58 percent SiO_2 that represent the volumetrically minor gabbroic rocks, the scatter in the plotted data is significantly reduced.

Composite diagrams such as Figure 3, though useful to show the over-all chemical variation in the batholith, may mask small but real differences between constituent plutons if the data are treated in terms of subgroups. To test this, Harker variation diagrams were constructed with the samples grouped as follows: (1) plutons in the central or main part of the batholith, (2) plutons in the northern part of the batholith (essentially the area mapped by Knopf, 1963), (3) plutons in the southern part of the batholith, and (4) satellitic plutons. With the notable exception of K_2O, Na_2O, and perhaps CaO, these diagrams show no detectable systematic variation between the above four subgroups in terms of the major oxides versus SiO_2.

Relations between SiO_2, K_2O, and Na_2O. Figure 4A illustrates the variation of K_2O and SiO_2 for rocks of the main (central) part of the batholith. The apparent gap between the field for the Butte Quartz Monzonite and related silicic facies and that for aplite-alaskite probably reflects a sampling quirk, for field evidence indicates a continuum between the Butte Quartz Monzonite, its silicic variants, and the aplite-alaskite. Both broadly gradational and sharp contacts between members in this continuum are observed; if in sharp contact, the more felsic member is generally the younger.

Most samples from the northern part of the batholith (Fig. 4B) fall into or near fields observed for the central part. Exceptions are the shonkinite and leucomonzonite, which represent small, isolated bodies believed by Knopf (1957) to have assimilated carbonate country rock. For reasons discussed later, Knopf's porphyritic granodiorite and granodiorite undivided (denoted by P and K, respectively, Fig. 4B) may not be part of the magma series defined by other rocks in the central and northern parts. Knopf's analysis

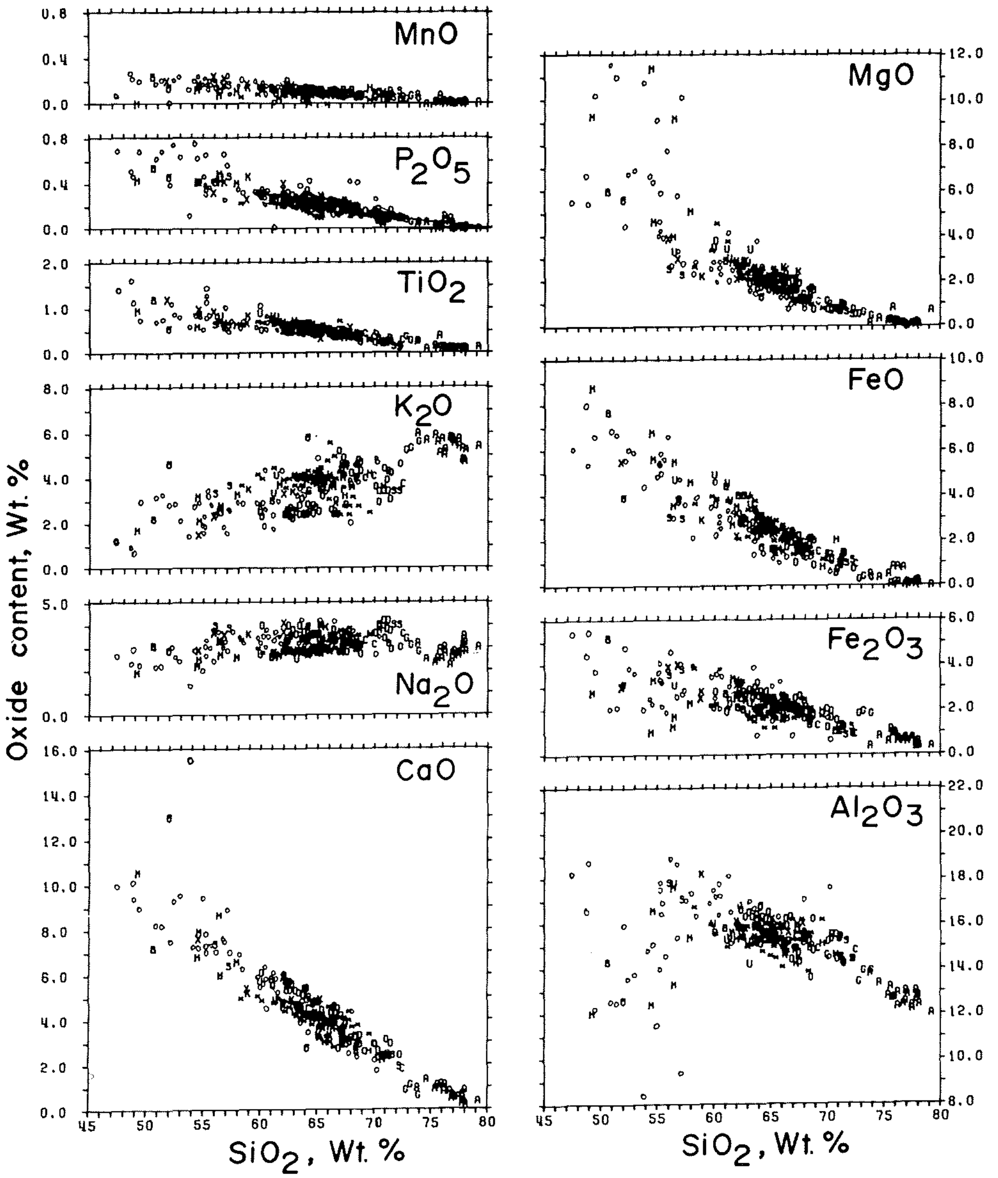

Figure 3. Composite Harker variation diagrams for rocks of the Boulder batholith undivided as to pluton or area of occurrence (that is, the differences in the plotting symbols should be disregarded). The large scatter in data points for low SiO_2 rocks expresses the variability in composition of the mafic rocks, which are volumetrically minor (Fig. 2). The data for K_2O, Na_2O, and CaO provide the basis for grouping the rocks into two chemically distinct series (see Figs. 4 through 10 and text). Sources of data plotted given in captions for Figures 4 and 5.

(1957, Table 3) for Clancy Granodiorite, which is coextensive with the Butte Quartz Monzonite, is not plotted in Figure 4B and has been included with the Butte Quartz Monzonite analyses in Figure 4A.

The plutons in the southern part of the batholith (Fig. 5A) are chemically distinct from those in the central and northern parts. In general, these rocks tend to be less potassic for a given silica content. The sample from the Burton Park pluton (denoted by B, Fig. 5A) lowest in SiO_2 contains abundant mafic schlieren and is not truly representative of the pluton. The Rader Creek and Burton Park plutons are older than the Butte Quartz Monzonite, but the other plutons in the southern part (Donald, Hell Canyon,[1] Moose Creek, Climax Gulch plutons) are the youngest rocks of the batholith (Tilling and others, 1968). Therefore, because the rocks in the southern part may be older or younger than those farther to the north, the differences in composition cannot be ascribed solely to variations with time.

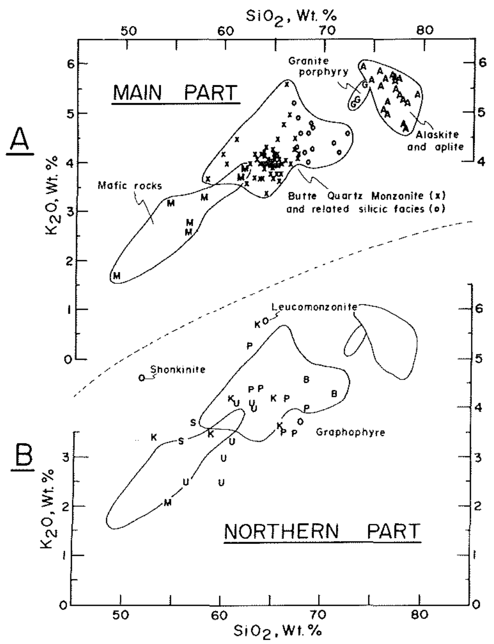

Figure 4. A. K_2O-SiO_2 variation for rocks from the main part of the Boulder batholith (see Fig. 2 for areal distribution of the plutons). Although the granite porphyry (G) (too small to be shown in Fig. 2) cuts the Butte Quartz Monzonite, its relation to the compositionally similar alaskite-aplite is not known. Data for the Butte Quartz Monzonite include analyses for the coextensive Clancy Granodiorite (Knopf, 1957, 1963). Data sources: Weed (1912); Knopf (1957); Klepper and others (1957); Becraft and others (1963); Ruppel (1963); Smedes (1966); Smedes and others (1968); Tilling (1973, unpub. data). B. K_2O-SiO_2 variation for rocks from the northern part of the Boulder batholith mapped by Knopf (1963). Symbols: U, Unionville Granodiorite; M, granogabbro (a "basic facies" of the Unionville Granodiorite); B, biotite adamellite; P, porphyritic granodiorite; K, granodiorite, undivided; S, syenodiorite; and O, miscellaneous small bodies. The fields outlined are those shown in A for the major plutons of the main part of the batholith. Data sources: Knopf (1957); Tilling (1973, unpub. data).

Chemical zonation of the Rader Creek pluton is clearly shown in Figure 5A; the various compositional zones ("felsic," "normal," and "potassic"), arbitrarily defined (Tilling, 1964, 1968), grade imperceptibly into one another. Although some rocks of the potassic zone of the Rader Creek pluton plot into the field for Butte Quartz Monzonite, they differ considerably in texture and mineralogy. The potassic Rader Creek rocks can have conspicuous plagioclase phenocrysts but are entirely lacking in large K-feldspar megacrysts, which are very common in the Butte Quartz Monzonite. Moreover, as previously noted by Doe and others (1968) and discussed later, the Rader Creek pluton is notably dissimilar to the Butte Quartz Monzonite in isotopic composition of lead and strontium.

A plot of K_2O versus SiO_2 for the satellitic plutons of the Boulder batholith is not diagnostic, and the data points overlap the fields for the central-northern and the southern parts of the batholith (Fig. 5B). Because of their isolated occurrence, the satellitic plutons cannot be fit into the intrusive sequence of the batholith. They tend to be largest in size and most abundant to the north and east of the batholith proper (Fig. 2), and many are composite bodies (Klepper and others, 1971). Perhaps a significant point here is that only a few of the satellitic plutons plot into the fields for the Butte Quartz Monzonite or younger rocks (Fig. 5B). In the batholith proper, the more mafic rocks tend to be older than felsic rocks; if this generalization holds for the satellitic plutons, then one may speculate that most are relatively early in the intrusive sequence.

---

[1] The relatively low K_2O content for one of the Hell Canyon samples may represent an analytical error; this sample is being reanalyzed.

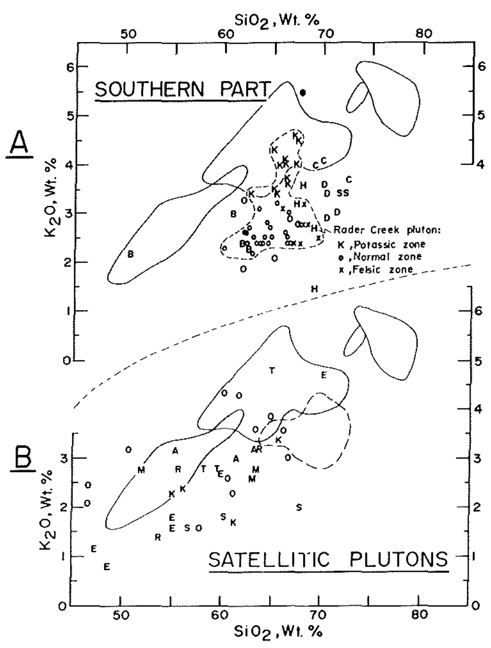

Figure 5. A. K_2O-SiO_2 variation for rocks from the southern part of the Boulder batholith. For comparison, data fields (solid lines) for the main part of the batholith are outlined as in Figure 4. The chemical zonation of the Rader Creek pluton (dashed field) is clearly evident. Symbols: The dot, syenite, represents an isolated outcrop surrounded by valley fill (too small to be shown in Fig. 2); its relation to the nearby Rader Creek pluton cannot be determined; B, Burton Park pluton; D, Donald pluton; H, Hell Canyon pluton, one sample of which appears to be anomalously low in K_2O and is being reanalyzed; C, Climax Gulch pluton; S, Moose Creek pluton and a small, nearby pluton (too small to be shown in Fig. 2); O, rocks that occur locally along the contact between the Rader Creek and Donald plutons, probably textural variants of the Rader Creek pluton. Data sources: Tilling (1964, 1968, 1973, unpub. data). B. K_2O-SiO_2 variation for satellitic plutons of the Boulder batholith; data fields (solid lines) for the main part of the batholith are shown for reference. The dashed field delimits the rocks in the southern part (A) exclusive of the Rader Creek and Burton Park plutons; these rocks are the youngest rocks of the batholith (Table 1). Very few of the satellitic plutons have compositions observed for the Butte Quartz Monzonite and younger rocks. Symbols: A, Antelope Creek stock; E, stocks in the vicinity of the Elkhorn mining district; K, Keating Gulch stock; M, Marysville stock; O, miscellaneous stocks, mainly in the southern Elkhorn Mountains; R, Spar stock; S, Sage Brush Park stock; and T, stocks in the Three Forks area. Data sources: Barrell (1907); Shenon (1931); Klepper and others (1957, 1971); Robinson (1963); Tilling (1973, unpub. data).

Robertson (1953), on the basis of the limited chemical data (13 analyses of volcanic rocks and 20 of batholith rocks) available to him, tentatively concluded that the rocks of the batholith and the pre- and post-batholith rocks are "genetically related" despite "distinct" differences in age. In the light of the data now available (Fig. 6), the chemical relations between the plutonic and volcanic rocks of the region are not as simple as suggested by Robertson's plots (1953, Pls. 1 and 2).

The prebatholith volcanic rocks are variable in composition, but most plot within or near the data fields for rocks of the central and northern parts of the batholith (Fig. 6A). On the other hand, the postbatholith volcanic rocks, both the Eocene Lowland Creek Volcanics and the post–Lowland Creek rocks, plot within or near the fields for plutonic rocks in the southern part of the batholith (Fig. 6B). Although there is some overlap, the prebatholith volcanic rocks differ appreciably from the postbatholith rocks in terms of K_2O-SiO_2 variation, particularly if two of the prebatholith samples from the Three Forks area are not considered. (These two samples, which plot in the shaded field in Figure 6A, are from the Buttleman laccolith, suggested by Robinson, 1963, to be prebatholith; however, their age limits bracketed geologically are sufficiently broad that the possibility of their being postbatholith cannot be dismissed. At any rate, these two samples are compositionally similar to the postbatholith, rather than the prebatholith, volcanic rocks.) For a given SiO_2 content, the postbatholith volcanic rocks tend to be less potassic than prebatholith volcanic rocks and plutons in the main part of the batholith.

Relations of K_2O and Na_2O to SiO_2 for all the igneous rocks of the Boulder batholith region, including the pre- and post-batholith volcanic rocks, are summarized in Figure 7 in terms of mean values. With the scatter in the data thus removed, two fairly well-defined fields are evident:

1. Plutons of the central and northern parts of the batholith are serially related, and define a magma series that hereafter will be referred to as the *main series*, composed of the mafic rocks (M), Unionville Granodiorite (UG; Knopf, 1957, 1963), Butte Quartz Monzonite and related silicic rocks (BQM, SBQM, A), and granite porphyry (GP; Figs. 2 and 7).
2. The Rader Creek and most other plutons in the southern part of the batholith appear to

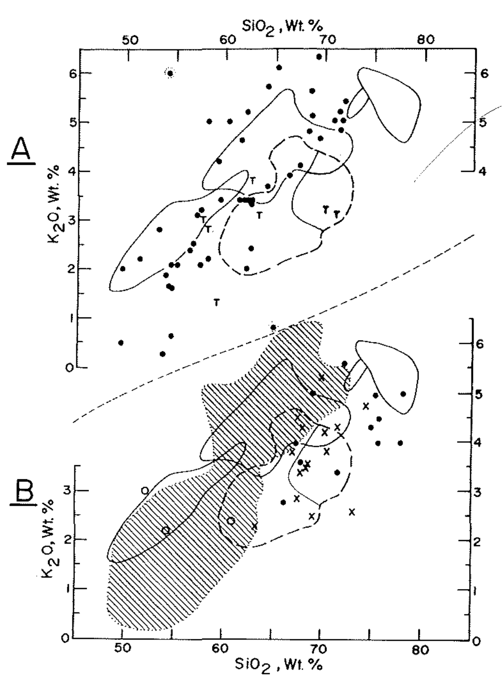

Figure 6. A. K_2O-SiO_2 variation for the prebatholith volcanic rocks of the Boulder batholith region. Symbols: dot, rocks from the main Elkhorn Mountains volcanic field; T, rocks from the southernmost part of the field (Three Forks area; see Robinson, 1963). Data fields (solid lines) for the main part of the batholith as given in Figure 4. The dashed line outlines the field for rocks in the southern part (the Burton Park, Rader Creek, Donald, Hell Canyon, Moose Creek, and Climax Gulch plutons shown in Fig. 2); the shaded part of this field excludes the Rader Creek and Burton Park rocks and represents the youngest batholith rocks. The two data points outlined by dotted circles are spurious and may represent samples affected by post-crystallization alteration. Data sources: Weed (1901, 1912); Knopf (1913); Winchell (1914); Klepper and others (1957, 1971); Robinson (1963); Ruppel (1963); Becraft and others (1963); Smedes (1966); Tilling (1973, unpub. data). B. K_2O-SiO_2 variation for the postbatholith volcanic rocks. Symbols: X, Lowland Creek Volcanics (early Eocene); dot, rhyolitic post–Lowland Creek rocks (Miocene or Pliocene); circle, basic post–Lowland Creek rocks. Data fields for the batholith rocks are as shown in A. Hachured area is the compositional field for the prebatholith volcanic rocks excluding two most silicic samples from the Three Forks area (see text). Data sources: Same as those given for A.

define another magma series, which shall hereafter be referred to as the *sodic series*, composed of the Rader Creek pluton (RC), Hell Canyon pluton (HC), Donald pluton (D), Climax Gulch pluton (C), and Moose Creek and Moosetown plutons (MS).

For any given silica content, the rocks of the sodic series tend to be lower in K_2O and higher in Na_2O relative to rocks of the main series (Fig. 7). For each series, field evidence indicates that the more silicic rocks tend to be later in the intrusive sequence of that series. However, for the batholith taken as a whole, the over-all order of emplacement constructed from field relations and K-Ar age data appears not to be influenced by the distinction between the two series (Table 1). The age of Knopf's (1963) porphyritic granodiorite, though not radiometrically dated, is considered to be relatively young because it crosscuts its neighboring pluton, the granodiorite undivided of Knopf (1963), dated at approximately 72 m.y. From compositional considerations, most satellitic plutons may be inferred to be older than the Butte Quartz Monzonite.

Three of the major plutons cannot be assigned unambiguously to one or the other of the two series proposed. In terms of mean SiO_2 and K_2O contents, the Burton Park pluton (BP) in the southern part of the batholith probably should be assigned to the sodic series; whereas, in terms of mean SiO_2 and Na_2O contents, this pluton appears to fit better into the main series (Figs. 2 and 7). Because of similar incompatibilities in K_2O-SiO_2 and Na_2O-SiO_2 variation, the granodiorite undivided (GU) and the porphyritic granodiorite (PG) of Knopf (1963) in the northern part of the batholith also cannot be assigned specifically. In the case of the Burton Park pluton, however, if variations in a CaO-Na_2O-K_2O ternary plot are considered (Fig. 10), then an argument can be made for provisionally placing this pluton in the main series.

The bulk of the Elkhorn Mountains Volcanics gives an average that plots near the average for the Unionville Granodiorite, which is volumetrically the most important mafic member of the main series (Fig. 7). In contrast, the postbatholith Lowland Creek Volcanics (LCV) have average K_2O, Na_2O, and SiO_2 contents that fall in or just outside the fields for the sodic series (Fig. 7). The predominantly rhyolitic post–Lowland Creek volcanic rocks (PLC–R) plot near the silicic extension of the field for the sodic series; though based on only three analyses, the more mafic post–Lowland Creek rocks (PLC–B) have an average that might be expected for the mafic extension of the sodic-series field (Fig. 7).

In general, Na_2O varies antipathetically with K_2O (Fig. 7). Because within each series Na_2O changes little with variation in SiO_2, a plot of $K_2O/(K_2O + Na_2O)$ against SiO_2, as expected, also shows a clear separation of the two series (Fig. 8). Only a few samples of the main series plot within the area of overlap between the main and sodic series. Moreover, of 72 samples of the sodic series, only 20 plot within the overlap area, and half of these represent the potassic zone of the Rader Creek pluton; for clarity these points are not shown in Figure 8.

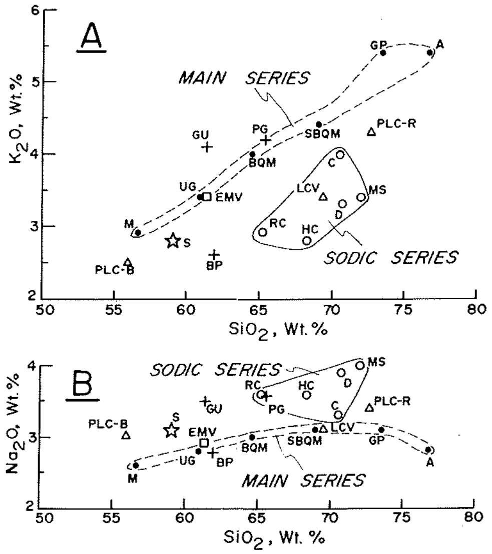

Figure 7. A. Variation patterns defined by mean SiO_2 and K_2O contents for igneous rocks of Boulder batholith region (refer to Fig. 2 for areal distribution of the rocks). Symbols: Dots enclosed by dashed line represent rocks of the main series (see text); M, mafic rocks; UG, Unionville Granodiorite (Knopf, 1957, 1963); BQM, Butte Quartz Monzonite; SBQM, silicic facies of Butte Quartz Monzonite; A, aplite and alaskite; GP, granite porphyry; circles enclosed by solid line represent rocks of the sodic series (see text); RC, Rader Creek pluton; HC, Hell Canyon pluton; D, Donald pluton; C, Climax Gulch pluton; MS, Moose Creek pluton; +, plutonic rocks that cannot be assigned unambiguously to one or the other of the two series; PG, porphyritic granodiorite of Knopf (1963); GU, granodiorite undivided of Knopf (1963); BP, Burton Park pluton; star, average for the satellitic plutons (S); square, the prebatholith volcanic rocks (EMV) excluding two samples from the Three Forks area (see Fig. 6B and text); triangles, the post-batholith volcanic rocks; LCV, Lowland Creek Volcanics; PLC–R, rhyolitic post–Lowland Creek rocks; PLC–B, basic post–Lowland Creek rocks. Summarized from data plotted in Figures 4, 5, and 6. B. Variation patterns defined by mean SiO_2 and Na_2O contents for igneous rocks of the Boulder batholith region. Symbols plotted same as in A; data sources are those given in the captions for Figures 4, 5, and 6.

Relations between CaO, K_2O, and Na_2O. Although the two proposed magma series are defined primarily in terms of K_2O-SiO_2 and Na_2O-SiO_2 variations, the fact that some of the plutons cannot be uniquely assigned to one or the other of the series indicates the need to test the chemical distinction between the two series by using other oxides. As shown in the composite Harker variation diagram (Fig. 3), variations in other major oxides, with the possible exception of CaO, are not particularly diagnostic. Plots of mean K_2O and Na_2O contents against mean CaO content (Fig. 9) are essentially comparable to plots of these oxides against SiO_2 (Fig. 7), even to the extent of having the same ambiguities as to series assignment for the Burton Park pluton (BP), porphyritic granodiorite (PG), and granodiorite undivided (GU). This is to be anticipated from the well-defined linear relation between CaO and SiO_2 (Fig. 3). That CaO variations also should be considered in defining the two series is strongly suggested by the ternary plot K_2O-Na_2O-CaO (Fig. 10). In fact, the chemical distinction between the two series is best shown

TABLE 1. ORDER OF EMPLACEMENT OF MAJOR PLUTONS OF THE BOULDER BATHOLITH, MONTANA, THAT CAN BE ASSIGNED UNAMBIGUOUSLY TO THE PROPOSED MAIN SERIES OR SODIC SERIES.

Main series		Sodic series
	↑	7. Moose Creek pluton (MS) Climax Gulch pluton (C) Hell Canyon pluton (HC) Donald pluton (D)
6. Aplite-Alaskite (A)		
5. Silicic facies of Butte Quartz Monzonite (SBQM)	Younger	
4. Butte Quartz Monzonite (BQM)		
		3. Rader Creek pluton (RC)
2. Unionville Granodiorite (UG)		
1. Mafic rocks (M)		

Note: The emplacement order is constructed from field evidence and K-Ar age data reported by Tilling and others (1968).

Abbreviations for the plutons (in parentheses) are the same as given in Figures 2, 7, and 9.

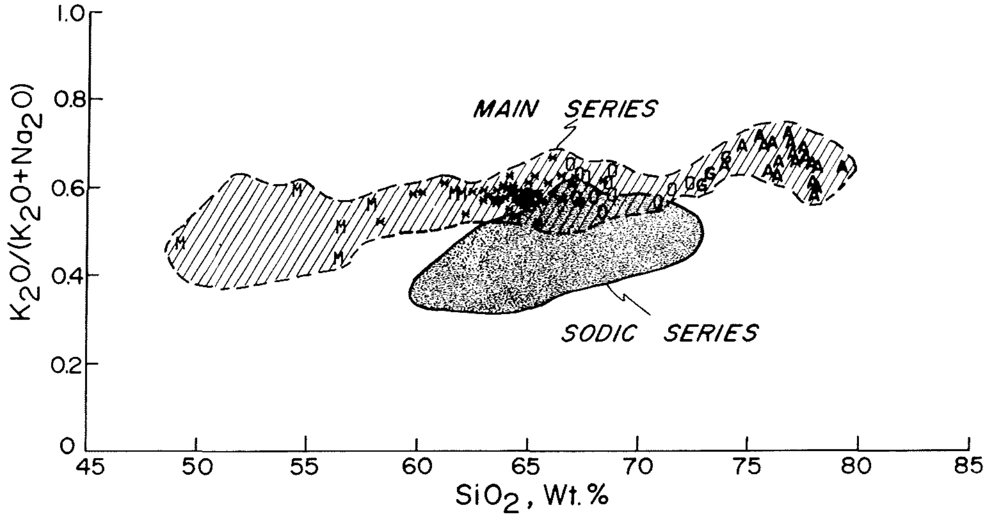

Figure 8. $K_2O/(K_2O + Na_2O)$-SiO_2 variation patterns for the main series (hachured field) and sodic series (shaded field). Letter symbols for the main series: M, mafic rocks; *, Butte Quartz Monzonite; O, silicic facies of Butte Quartz Monzonite; G, granite porphyry; and A, alaskite and aplite. For clarity, data points for the sodic-series field are not shown (see text).

in this plot; only a few samples of the main series plot within the overlap area, and only 11 samples of the sodic series, 8 of which are from the potassic zone of the Rader Creek pluton, would plot (if shown) in the area of overlap (Fig. 10). Although the Burton Park (BP) samples plot into the field for the main series, the samples of the granodiorite undivided (GU) and the porphyritic granodiorite (PG), if shown in the ternary plot, still cannot be assigned unambiguously as to magma series.

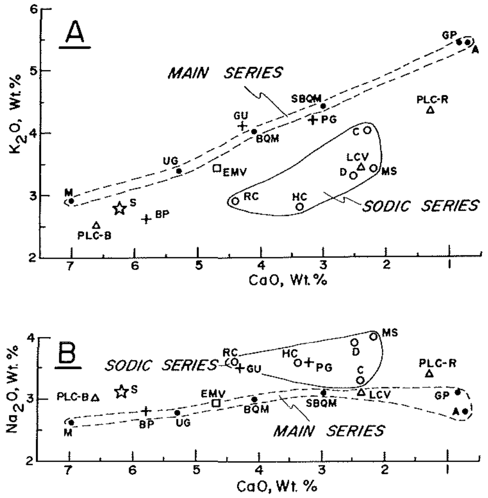

Figure 9. A. Variation patterns defined by mean CaO and K_2O contents for the main series and sodic series. Symbols and data sources for A and B are the same as for Figure 7. B. Variation patterns defined by mean CaO and Na_2O contents for the main series and sodic series.

Relations between SiO_2, U, Th, Rb, and Sr. Although few quantitative trace-element data exist for rocks of the Boulder batholith, a plot of radiogenic heat production versus SiO_2 (Fig. 11) clearly shows the distinction between the two proposed magma series. As radiogenic heat is calculated from the abundances of the radioelements U, Th, and to a minor extent, K, the data plotted in Figure 11 indicate that the main series and sodic series are distinguishable in terms of U and Th (Tilling and Gottfried, 1969, Table 8). Variation patterns for Sr and Rb, though based on fewer data, also clearly show the distinction between the two magma series proposed; with the exception of one point, there is no overlap at all between the two series (Fig. 12).

Isotopic Evidence

Lead and strontium isotope data may provide clues to the chemical makeup of the possible source(s) for igneous rocks (Hedge, 1966; Hedge and Walthall, 1963; Tatsumoto, 1966a, 1966b; Doe, 1967; Peterman and Hedge, 1971; Scott and others, 1971; Hedge and others, 1972; Kistler and Peterman, 1972); for example, limited data indicating relatively uniform lead isotope compositions of some representative rocks of the southern California batholith were interpreted as evidence that these rocks were derived from a common source despite differences in bulk chemistry (Patterson and others, 1956). In contrast, significantly different strontium isotope compositions observed for individual ash-flow sheets also have been interpreted as indicating a common but chemically and isotopically zoned source, that is, a zoned magma chamber (Noble and Hedge, 1969; Dickinson and Gibson, 1972).

It was isotopic evidence (Doe and others, 1968) that first hinted that a one-magma-series (or single-source) model was inadequate. The possible existence of two magma series has been established on the basis of chemistry, and a reexamination of the isotope data in terms of the two-magma-series model now allows a more refined interpretation of the isotopic variations. The isotopic compositions of lead are different in the two proposed magma series defined by major- and minor-element data; however, the strontium isotope data do not delimit separate fields for the two series.

Lead Isotopic Composition. Initial Pb^{206}/Pb^{207} ratios (Fig. 13) of batholith and pre- and post-batholith volcanic rocks, plotted in terms of the two magma series defined by chemical variations and against time of emplacement or extrusion as determined from the K-Ar ages, show no overlap between the main and sodic

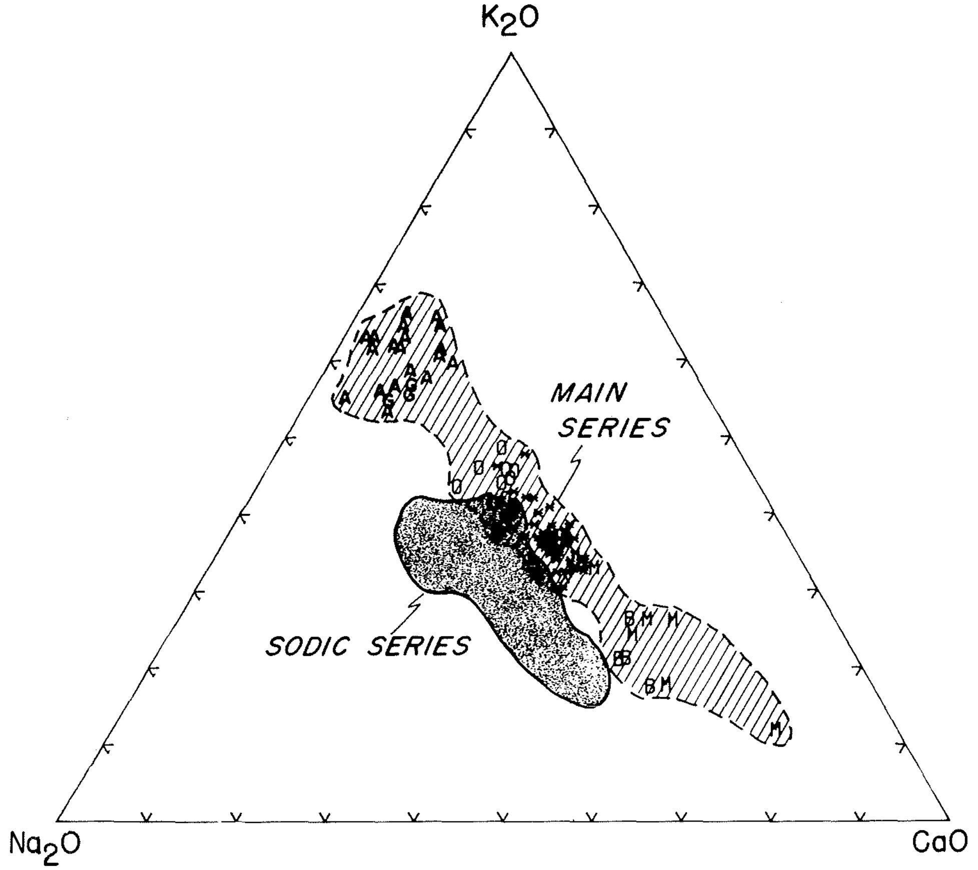

Figure 10. K_2O-Na_2O-CaO variation patterns for the main series (hachured field) and sodic series (shaded field). The field for the sodic series excludes the sample of the Hell Canyon that is anomalously low in K_2O (see Fig. 5A). In this plot, the field for the main series includes rocks of the Burton Park pluton, indicated by the symbol B. Other letter symbols are the same as in Figure 8; for clarity, data points for the sodic series are not shown. The proposed two-magma series show the least overlap in this ternary plot (see text).

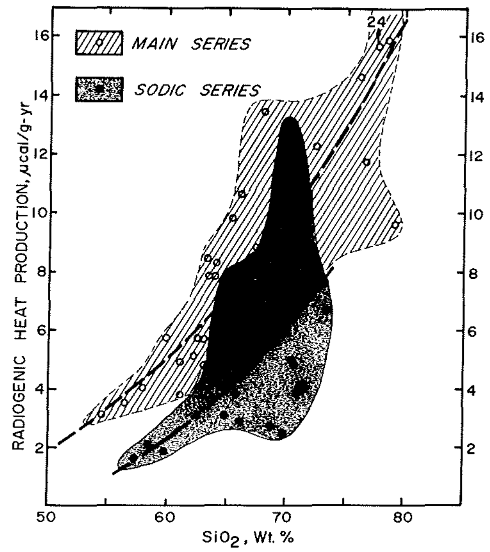

Figure 11. Variation of radiogenic heat production with SiO_2. As radiogenic heat production reflects primarily abundances of U and Th, the distinction between main and sodic series, defined by major-element variations, is also valid in terms of these two trace elements. Data source: Tilling and Gottfried (1969).

series. The use of a relative time scale (older to younger), rather than the geochronometric scale, would not substantively alter the variation patterns. Although the Burton Park pluton (BP) cannot be specified uniquely as to magma series, it has Pb^{206}/Pb^{207} ratios typical of the plutons of the main series.

The prebatholith Elkhorn Mountains Volcanics (EMV) have a lead isotope composition like those of the rocks of the main series. This is compatible with both the chemical evidence presented in this paper and with field relations (Robinson and others, 1968); thus, the available data indicate that the Elkhorn Mountains Volcanics are genetically related to at least the early members, if not all the members, of the main series. The postbatholith volcanic rocks (LCV and PLC, Fig. 13) have lead isotope compositions that are slightly more radiogenic than those for the main series and considerably more radiogenic than those of the sodic series. Chemically, however, the postbatholith volcanic rocks are more similar to the rocks of the sodic series than to those of the main series.

Strontium Isotope Composition. A plot of initial Sr^{87}/Sr^{86} ratios, unlike the plot for the initial Pb^{206}/Pb^{207} ratios, does not clearly

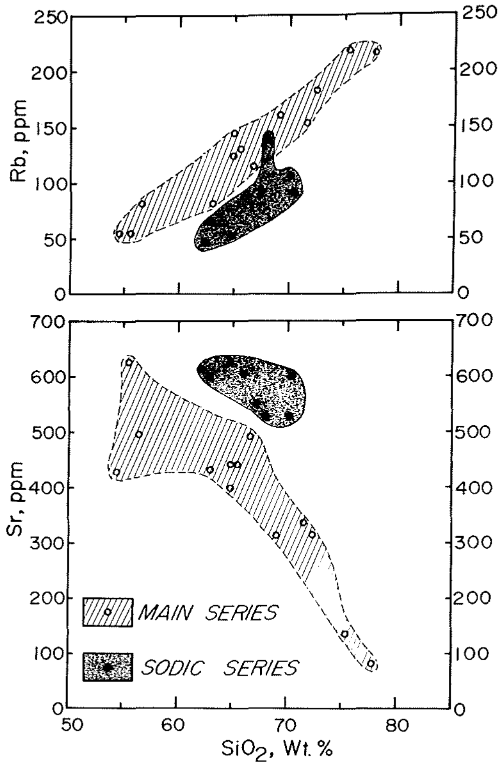

Figure 12. Variation of Rb and Sr with SiO_2 for the main and sodic series, showing the clear separation of the two series. Data sources: Doe and others (1968); Smedes (1966); Klepper and others (1971); Tilling (1968, 1973, unpub. data).

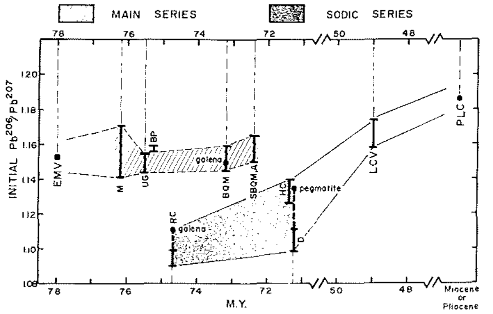

Figure 13. Variation of initial Pb^{206}/Pb^{207} ratios in terms of the proposed two-magma series and the means of K-Ar ages. Bars give ranges of lead isotope values; points denote single analyses. Symbol legend of the various units is as given in Figure 7. (See text and Figs. 7 and 9 for basis for extrapolating the variation pattern for the sodic series to include the postbatholith volcanic rocks [LCV and PLC].) Data sources: Doe and others (1968); Tilling and others (1968).

distinguish between the main and the sodic series (Fig. 14); nevertheless, the relatively unradiogenic character of the Rader Creek pluton is shown by the Sr isotope data as well as by the Pb isotope data. The data fields shown in Figure 14 were drawn on the basis of the chemical distinctions and of the Pb isotope data. The inclusion of the Lowland Creek Volcanics within the sodic-series field by extrapolation, however, is consistent with the plot of initial Sr^{87}/Sr^{86} against the ratio of Rb/Sr (Fig. 15), which indicates that the variation patterns fit a two-magma-series model.

Variation of initial Pb^{206}/Pb^{207} and Sr^{87}/Sr^{86} with Rb/Sr (Fig. 15) seems to preclude a possible genetic link between the postbatholith Lowland Creek Volcanics and the rocks of the main series, for initial Sr^{87}/Sr^{86} ratios are greater than any measured for main samples. Because the early members of the main series (M and UG, Fig. 15) plot within the data field for the sodic series, we cannot dismiss the possibility that these early rocks of the main series could be linked in some manner to the same source related to rocks of the sodic series and perhaps ultimately of the Lowland Creek Volcanics as well. However, the data for the Lowland Creek Volcanics plot along the projection of the field for the sodic series, and this relation lends support to the validity of extrapolations shown in Figures 13 and 14.

The wide variation in Rb/Sr with essentially constant initial Sr^{87}/Sr^{86} ratios for the main series (Fig. 15) is one that might be expected for a series of rocks related by magmatic differentiation. The variation pattern for the sodic series, which involves increase in the initial Sr^{87}/Sr^{86} ratios with increase in Rb/Sr, cannot be explained by magmatic differentiation and more likely reflects intrinsic differences in Rb/Sr in the source. This aspect is discussed further in the section dealing with possible sources of the magmas.

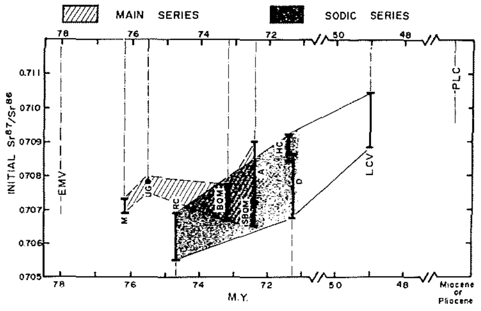

Figure 14. Variation of initial Sr^{87}/Sr^{86} ratios in terms of the two proposed magma series and the mean K-Ar ages. Data plotted as in Figure 13. Data sources: Smedes and Thomas (1965); Doe and others (1968); Tilling and others (1968).

Mineralogic Evidence

The chemical distinction between the main series and the sodic series is reflected also in the mineralogy of the batholith rocks. As might be expected from the fact that the bulk compositions of analyzed K-feldspars representative of the major plutons of the batholith tend to cluster around Or_{80} (R. I. Tilling, 1973, unpub. data), differences in K_2O contents between rocks are reflected in large part by differences in the modal amount of K-feldspar in the rocks. However, because the K_2O content of a rock is also determined (to a lesser degree) by the amount of biotite present, the relation between

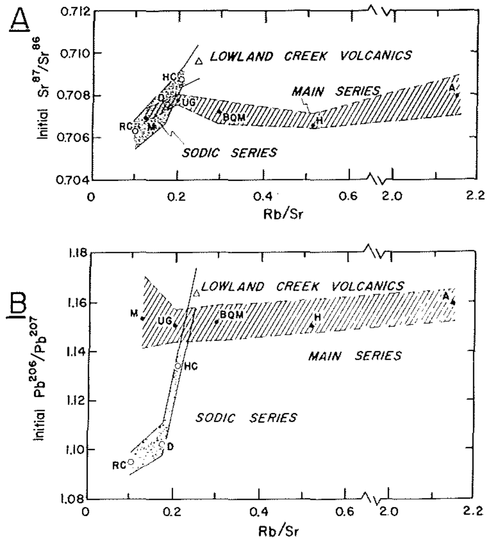

Figure 15. A. Variation of initial Sr^{87}/Sr^{86} ratios with Rb/Sr in terms of the main and sodic series. The widths of the variation patterns give the ranges of the isotopic values; the plotted symbols give the mean values. Symbols: Dots represent the main series (hachured field); circles, the sodic series (shaded field); H, the Homestake pluton, a silicic variant of the Butte Quartz Monzonite; other notations are as given in Figures 7 and 9. The extrapolation to include the Lowland Creek Volcanics (triangle) within the extension of the field for the sodic series is based on chemical variations (see text). Modified from a similar plot of Doe and others (1968, Fig. 5). B. Variation of initial Pb^{206}/Pb^{207} ratios with Rb/Sr. Symbol explanation and notation as given in A.

the K_2O content of the rock and modal K-feldspar may not be simple. Nonetheless, although the overlap is rather considerable, a plot of the modal amounts of quartz, plagioclase, and K-feldspar shows the rocks of the main series tending to have more K-feldspar than those of the sodic series (Fig. 16).

From a detailed study of zircons from plutons in the northern part, Effimoff (1972) concluded that the rocks of the Boulder batholith may represent more than one magma series. He showed that zircons from the porphyritic granodiorite and granodiorite of Knopf (1963) are different in crystal morphology and chemical composition (in terms of Zr, Hf, Y, Th, and Si) from those in rocks of the main series. On the basis of a few partial chemical analyses of whole rock, Effimoff assigned the porphyritic granodiorite and granodiorite undivided to the sodic series. Additional and complete rock analyses, however, indicate that these two plutons (PG and KU, Fig. 5) cannot be assigned unequivocably to either one of the two series proposed in this report.

SPATIAL DISTRIBUTION OF THE TWO-MAGMA SERIES

Multiple lines of evidence—chemical, isotopic, and mineralogic—have been presented in support of, and are the basis for, the suggested two-magma-series model for the Boulder batholith. Equally important, however, most rocks of the proposed two series also can be separated in terms of their distribution in space. As has been emphasized, all rocks of the Boulder batholith were emplaced within a small time interval (~10 m.y.), comparable to that of the Late Cretaceous intrusive epoch (90 to 79 m.y.) in the Sierra Nevada batholith (Evernden and Kistler, 1970). By generally accepted geologic criteria, all the Boulder batholith rocks would be considered essentially contemporaneous. Except for two small plutons in the north-central part of the batholith, all other mappable bodies of rocks that definitely can be assigned to the sodic series are restricted to the southern and southwestern part of the batholith (Fig. 17). A few small, isolated bodies within the central and northern parts (too small to show at the scale of Fig. 17) also may belong to the sodic series. Moreover, many of the satellitic plutons, which on an average are chemically more akin to the sodic-series rocks (Fig. 7), might represent earlier, more mafic members of this series.

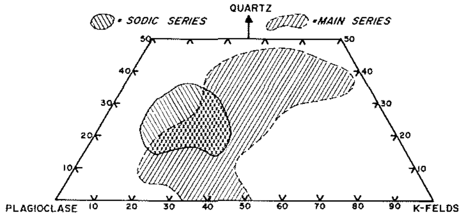

Figure 16. Distribution of modal quartz, plagioclase, and K-feldspar for the rocks of the Boulder batholith grouped into the two proposed magma series. The offset in compositional fields between the main and sodic series is consistent with the chemical variation patterns (see text). Data sources as given in Figures 4 and 5.

On a regional scale, the rocks of the Boulder batholith exhibit a crude zonal distribution of K_2O and Na_2O variation patterns. If the two small easternmost mappable bodies of the sodic series (lc, Fig. 17) are not considered, then the major members of this series lie west of a line approximately at long. 112°10′ W. However, if we do not consider Knopf's (1963) porphyritic granodiorite and the granodiorite undivided (the largest satellitic plutons in the northern part of the batholith that cannot be assigned as to magma series), then the bulk of the rocks of the sodic series would be further restricted spatially, occupying only the southwestern sector of the Boulder batholith region (south of Butte, lat 46°00′ N.; Fig. 17). Thus, for rocks of the batholith, there appears to be a general but poorly defined variation pattern of decreasing K_2O to the south and perhaps to the west as well.

The areal zonation of the chemical variation pattern defined by the batholith rocks is also evident to some extent in the volcanic rocks of the region. The general north-south decrease in K_2O suggested by the batholith rocks may be expressed also by the postbatholith rocks: the post–Lowland Creek volcanic rocks tend to be more potassic (and silicic) than the rocks of the Lowland Creek Volcanics farther to the south (Figs. 7A, 9A, and 17). An eastward zonation, however, is suggested if the pre- and post-batholith volcanic rocks are compared. The postbatholith volcanic rocks (LCV and PLC, Fig. 17) lie west of about long. 112°10′ W., the same line of demarcation observed for east-west zonation of the batholith rocks.

Considering *all* the igneous rocks (plutonic and volcanic) on a regional scale, we find that those in the south and west tend to be less

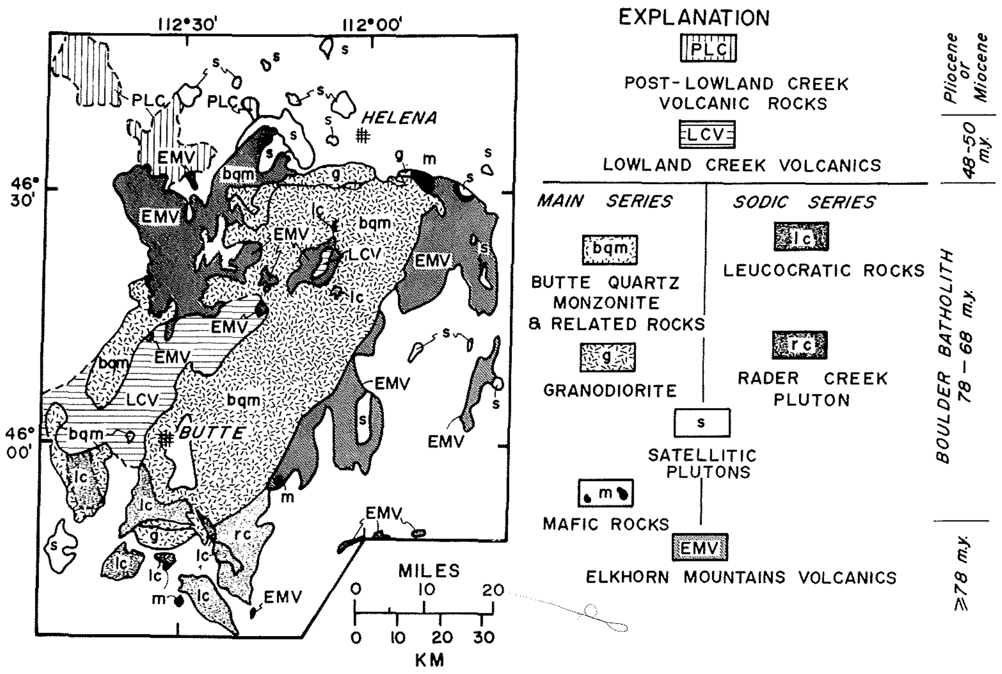

Figure 17. Generalized map showing spatial distribution of rocks of the Boulder batholith region grouped according to the two-magma-series model. The principal difference between this scheme and the one-magma-series model is the separation of the Rader Creek pluton from other granodiorite (compare with Fig. 2). The leucocratic rocks as now proposed would exclude the biotite adamellite (ba) and the biotite granite (bg) of Knopf (1963). With the exception of two small bodies in the north-central part of the batholith, all mappable bodies that can be assigned unambiguously to the sodic series are in the southern part of the batholith.

potassic than those in the north and east for a given silica content or any other differentiation index. Clearly, additional data are required, particularly for the Elkhorn Mountains Volcanics west of the batholith, before the nature of the chemical zonation in the region can be refined.

The chemical variation patterns observed for the Boulder batholith, though complex and not yet fully understood, invite comparison with the nearby batholiths in Montana and with the much larger Idaho batholith. Limited chemical data for the Tobacco Root, Philipsburg, and Pioneer batholiths of Montana and for the Idaho batholith (Fig. 1) clearly show that they are more sodic and calcic than the main-series rocks of the Boulder batholith (Fig. 18). This relation is compatible with gross regional variation of increasing K_2O eastward for the Western United States (Lindgren, 1915; Moore, 1959, 1962; Lipman and others, 1972; Christiansen and Lipman, 1972), but the Tobacco Root batholith, which is more sodic than, but east of, the Boulder batholith, may represent a local reversal. A more comprehensive comparison of the Boulder batholith with its neighboring plutonic bodies is in progress (R. I. Tilling, 1973, unpub. data).

SOURCES OF THE BOULDER BATHOLITH MAGMAS

The data show that the Boulder batholith is formed of rocks representing two chemically distinct magma series. The distinction between these two series is also shown by differing lead isotope compositions with no overlap, but not by strontium isotope compositions. Because rocks of the two magma series were emplaced contemporaneously within a short time span (78 to 68 m.y.), models of petrogenesis involving a single source that changes character with time are implausible. Furthermore, as the rocks of the two series are juxtaposed in a rather small localized area of the crust, the problem of reasonably deducing possible sources and mechanisms becomes even more difficult.

Various conceptual models relating to possible sources for the Boulder batholith were considered in some detail by Doe and others (1968). They rejected all models involving complete melting of upper crustal sources (such as the pre-Belt crystalline rocks), mainly because these sources are too radiogenic to yield the relatively unradiogenic batholith rocks. Models involving partial melting of lower crustal or upper mantle material seemed to be more viable, especially if such materials had a mean age of 2,200 m.y. and were of basaltic or quartz dioritic composition. The observed isotopic compositions also could be produced by partial melting of basaltic-gabbroic material together with variable and large-scale assimilation of the more radiogenic upper crustal material.

Let us assume that rocks of the main series were derived by partial melting of lower crustal or upper mantle material of the requisite isotopic and chemical make-up (model II of Doe and others, 1968, p. 904). Because the lead and strontium isotope compositions for these rocks are relatively uniform despite differences in bulk rock chemistry, the observed chemical variation patterns can be readily interpreted in terms of magmatic differentiation of the derived silicate melt (Figs. 4, 5, 7, 13, 14, and 15). Accordingly, no signifi-

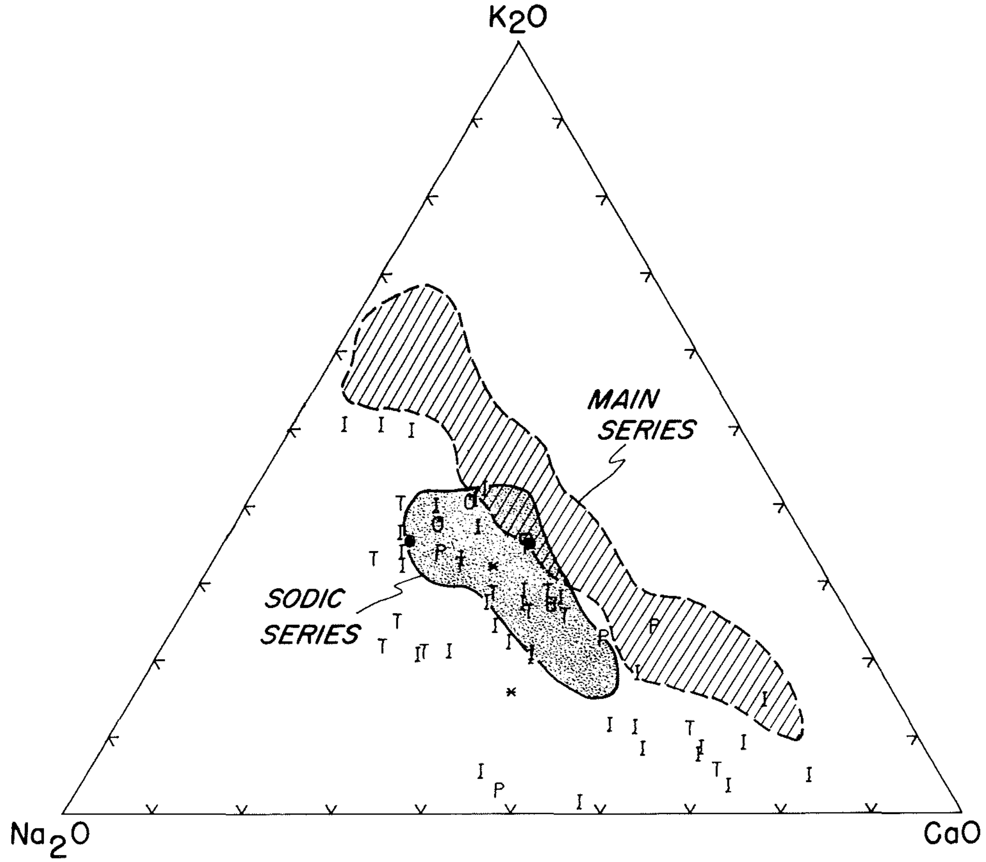

Figure 18. K_2O-Na_2O-CaO variations of rocks of nearby Montana batholiths (Tobacco Root, Philipsburg, and Pioneer) and of the Idaho batholith (see Fig. 1 for locations) compared with the variation patterns of the main and sodic series of the Boulder batholith as shown in Figure 10. Data sources: Idaho batholith: I, Larsen and Schmidt (1958) and Hietanen (1962, 1963), and dot, Tilling (1973, unpub. data); Tobacco Root batholith: T, Smith (1970), asterisk, Burger (1967), and O, Tilling (1973, unpub. data); Philipsburg batholith: P, Hyndman and others (1972) and Emmons and Calkins (1913), and square, Tilling (1973, unpub. data); Pioneer batholith: B, Zen (1973, unpub. data).

cant assimilation of upper crustal material is required to account for the chemical or isotopic differences. The level at which magmatic differentiation took place cannot be specified. Differentiation could have occurred in or near the source region (lower crust or upper mantle) and yielded a compositionally zoned body of magma, chemically different portions of which were then emplaced, with little or no further differentiation, to their present levels to form the constituent plutons of the main series. Or, the parent magma, once derived, could have ascended directly to near the present level and then differentiated to form the various magmas resulting in the rocks of the main series.

Alternatively, if the main-series rocks were from a parent magma derived by mixing of partially melted basaltic-gabbroic material with an isotope composition similar to that of present-day oceanic tholeiites and assimilated upper crustal material (model III of Doe and others, 1968, p. 905), the systemic variations in composition observed for the main series could then be taken as indirect evidence that magmatic differentiation probably occurred after the magma had ascended to a level at or near that of batholith emplacement.

Chemical and isotopic evidence (Figs. 5A and 7 through 15) strongly suggests that the rocks of the sodic series were derived from a source(s) different from that for the main series. However, the isotope variation patterns for the sodic series, particularly those for strontium, are not amenable to simple interpretation. One possible interpretation is that the rocks making up the Rader Creek, Donald, and Hell Canyon plutons were derived by partial melting of three discrete, isotopically different sources within the lower crust or upper mantle. Another and perhaps more plausible interpretation is that all the sodic-series rocks were derived from a source region of Precambrian age (a minimum age of 580 m.y.; see Doe and others, 1968, p. 903) that was highly variable with respect to Rb/Sr and initial Pb^{206}/Pb^{207} (Fig. 15). In this case, the Rader Creek, Donald, and Hell Canyon magmas are interpreted to come directly from that isotopically heterogeneous source with little differentiation. Variations in initial Sr^{87}/Sr^{86} ratios as great or greater than those observed for the sodic-series rocks have been reported for ash-flow sheets, and these have been interpreted in terms of models involving a single, but chemically and isotopically zoned, source (Noble and Hedge, 1969; Dickinson and Gibson, 1972).

Another possible interpretation of the isotopic differences between the various members of the sodic series is that all the magmas forming these rocks originated at one source (different from that which gave rise to the main-series rocks) and that the observed differences merely reflect the varying extent of contamination by the more radiogenic upper crustal materials. In this interpretation, for the sodic-series rocks for which isotopic data are available, the Rader Creek rocks (the least radiogenic) are assumed to be unaffected or least affected by high-level crustal contamination, and the Hell Canyon rocks the most affected. However, the low Rb/Sr ratios and high Sr contents of the rocks in the sodic series constitute a serious limitation in this interpretation.

Whatever model is invoked for the sources of the Boulder batholith magmas, the problem of specific mechanisms to accommodate the derivation and(or) contamination of magmas within an extremely limited amount of time and space still must be resolved. This problem would be greatly alleviated, if not obviated, if the crust in the Boulder batholith region were heterogeneous *prior* to the Mesozoic and Cenozoic igneous activity, that is, with the abundances of U, Th, Pb, K, Rb, and Rb/Sr varying spatially. Kistler and Peterman (1972), in their recent study of the Sierra Nevada batholith, concluded that the observed differences in initial Sr^{87}/Sr^{86} and in abundances of Sr, Rb, K, and Na reflected lateral compositional variation in the magma source region. Although the possibility of a laterally variable source region for the Boulder batholith magmas cannot be disregarded, the much smaller areal extent of the Boulder batholith (relative to the Sierra Nevada batholith) does not favor large-scale lateral variation, unless the present-day outcrop area of the batholith bears no relation to the site or size of the source region(s). On the other hand, the space problem would be eliminated if the crust were differentiated vertically with the abundances of U, Th, Pb, K, Rb, and the ratio Rb/Sr decreasing with increasing depth. Such an assumed vertical differentiation is not incompatible with results of limited geochemical and geothermal studies that suggest a decrease of these elements with increasing metamorphic grade or with depth (Lambert and Heier, 1967, 1968; Hyndman and others, 1968; Roy and others, 1968, 1972; Lachenbruch, 1968; Zartman and Wasserburg, 1969; Tilling and others, 1970; Lachenbruch and Bunker, 1971; Swanberg, 1972; and Swanberg and Blackwell, 1973). If such vertical variation did exist, then it could be speculated that the rocks of the sodic series were derived from a source or sources at a level(s) deeper than that for the main series. Of course, a more definitive assessment of lateral versus vertical variation in the source region for the Boulder batholith magmas must await chemical and isotopic data for adjoining regions.

Figure 19 summarizes the available lead and strontium data for the rocks of the two proposed magma series. The main series, which makes up 80 percent or more of the exposed batholith, could have originated from a single source that was relatively well mixed isotopically; the field shown in Figure 19 for the main series encompasses the isotopic variation for all the rocks of that series. The sodic-series rocks were derived from another source with different Pb^{206}/Pb^{207} compositions but similar Sr^{87}/Sr^{86} compositions, or from three localized sources, each having a different isotopic makeup. The postbatholith Lowland Creek Volcanics are chemically more similar to rocks of the sodic series than to rocks of the main series (Figs. 6, 7, and 9), but isotopically they more closely resemble the main series, even though they are slightly more radiogenic. Thus, although the specifics relating to the derivation and chemical evolution of the Boulder batholith magmas are sketchy or still unknown, the available field, chemical, and isotopic evidence collectively indicates that the observed compositional variations seem best interpreted in terms of two magma series originating from two or more sources.

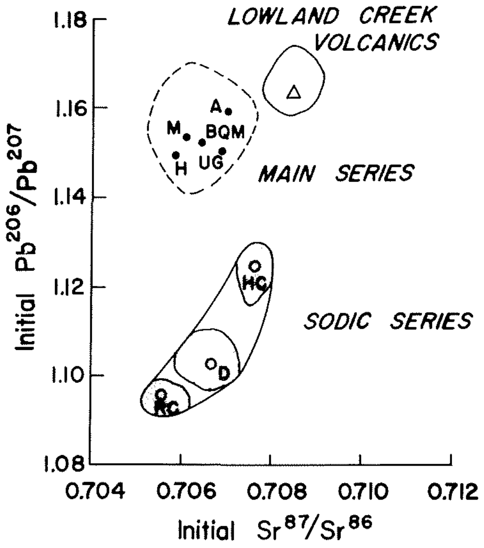

Figure 19. Composite diagram of mean initial Pb^{206}/Pb^{207} ratios plotted against mean initial Sr^{87}/Sr^{86} ratios of the Boulder batholith rocks and the postbatholith Lowland Creek Volcanics. Symbols and notation are as given in previous figures. The field for the main series, outlined by a dashed line, encompasses the total variation in isotopic composition. The compositional field for the sodic series is outlined by a solid line; shaded smaller fields give the isotopic variation for the individual plutons of this series for which isotope data exist. Summarized from data plotted in Figures 13 and 14.

ACKNOWLEDGMENTS

I thank all my colleagues of the U.S. Geological Survey and others who have worked in the Boulder batholith region, shared with me their geologic knowledge and insight, collected samples and (or) obtained analytical data, allowed me to cite unpublished data, or have otherwise kindly helped me throughout the course of this study. In particular, I thank D. E. Appleman, R. W. Chapman, B. R. Doe, John Forbes, David Gottfried, W. F. Hanna, C. E. Hedge, M. R. Klepper, the late Adolph Knopf, E. B. Knopf, Richard Marvin, J. D. Obradovich, Marie Onouye, H. J. Prostka, G. D. Robinson, E. T. Ruppel, Maurice Sako, R. G. Schmidt, H. W. Smedes, R. A. Weeks, T. L. Wright, and E-an Zen. I greatly appreciate the thoughtful and constructive reviews of earlier versions of this paper by David Gottfried, R. W. Kistler, M. R. Klepper, and H. W. Smedes. Igor Effimoff, presently of Shell Oil Company, kindly provided some rock powders used in this study.

Added in proof. The originally reported low value of 1.5 wt percent K_2O for the sample of the Hell Canyon pluton referred to in the text and in the captions for Figures 5A and 10 is due to a calculation error; the corrected value for this sample is 2.9 wt percent K_2O.

REFERENCES CITED

Al-Hashimi, A.R.K., and Brownlow, A. H., 1970, Copper content of biotites from the Boulder batholith, Montana: Econ. Geology, v. 65, p. 985–992.

Barrell, Joseph, 1907, Geology of the Marysville mining district, Montana: U.S. Geol. Survey

Prof. Paper 57, 178 p.

Bateman, P. C., and Dodge, F.C.W., 1970, Variations of major chemical constituents across the central Sierra Nevada batholith: Geol. Soc. America Bull., v. 81, p. 409–420.

Bateman, P. C., Clark, L. D., Huber, N. K., Moore, J. G., and Reinhart, C. D., 1963, The Sierra Nevada batholith—A synthesis of recent work across the central part: U.S. Geol. Survey Prof. Paper 414–D, 46 p.

Becraft, G. E., Pinckney, D. M., and Rosenblum, Sam, 1963, Geology and mineral deposits of the Jefferson City quadrangle, Jefferson and Lewis and Clark Counties, Montana: U.S. Geol. Survey Prof. Paper 428, 101 p.

Biehler, Shawn, and Bonini, W. E., 1969, A regional gravity study of the Boulder batholith, Montana, *in* Larsen and others, eds., Igneous and metamorphic geology (Poldervaart volume): Geol. Soc. America Mem. 115, p. 401–421.

Billingsley, Paul, 1915, The Boulder batholith of Montana: Am. Inst. Mining Engineers Trans., v. 51, p. 31–47.

Burger, R. H., III, 1967, Bedrock geology of the Sheridan district, Madison County, Montana: Montana Bur. Mines and Geology Mem. 41, 22 p.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate-tectonic evolution of the Western United States. II. Late Cenozoic: Royal Soc. London Philos. Trans., v. 271, p. 249–284.

Dickinson, D. R., and Gibson, I. L., 1972, Feldspar fractionation and anomalous Sr^{87}/Sr^{86} ratios in a suite of peralkaline silicic rocks: Geol. Soc. America Bull., v. 83, p. 231–240.

Doe, B. R., 1967, The bearing of lead isotopes on the source of granitic magma: Jour. Petrology, v. 8, no. 1, p. 51–83.

Doe, B. R., Tilling, R. I., Hedge, C. R., and Klepper, M. R., 1968, Lead and strontium isotope studies of the Boulder batholith, southwestern Montana: Econ. Geology, v. 63, p. 884–906.

Effimoff, Igor, 1972, The chemical and morphological variations of zircons from the Boulder batholith, Montana [Ph.D. thesis]: Cincinnati, Ohio, Univ. Cincinnati, 136 p.

Emmons, W. H., and Calkins, F. C., 1913, Geology and ore deposits of the Philipsburg quadrangle, Montana: U.S. Geol. Survey Prof. Paper 78, 271 p.

Evernden, J. F., and Kistler, R. W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geol. Survey Prof. Paper 623, 42 p.

Giletti, B. J., 1966, Isotopic ages from southwestern Montana: Jour. Geophys. Research, v. 71, p. 4029–4036.

Hanna, W. F., 1967, Paleomagnetism of Upper Cretaceous volcanic rocks of southwestern Montana: Jour. Geophys. Research, v. 72, p. 595–610.

—— 1973, Paleomagnetism of the Late Cretaceous Boulder batholith, Montana: Am. Jour. Sci. (in press).

Hedge, C. E., 1966, Variations in radiogenic strontium found in volcanic rocks: Jour. Geophys. Research, v. 71, no. 24, p. 6119–6126.

Hedge, C. E., and Walthall, F. G., 1963, Radiogenic strontium-87 as an index of geologic processes: Science, v. 140, p. 1214–1217.

Hedge, C. E., Peterman, Z. E., and Dickinson, W. R., 1972, Petrogenesis of lava from Western Samoa: Geol. Soc. America Bull., v. 83, p. 2709–2714.

Hietanen, Anna, 1962, Metasomatic metamorphism in western Clearwater County, Idaho: U.S. Geol. Survey Prof. Paper 344–A, 116 p.

—— 1963, Idaho batholith near Pierce and Bungalow, Clearwater County, Idaho: U.S. Geol. Survey Prof. Paper 344–D, 42 p.

Hyndman, R. D., Lambert, I. B., Heier, K. S., Jaeger, J. C., and Ringwood, A. E., 1968, Heat flow and surface radioactivity measurements in the Precambrian shield of western Australia: Physics Earth and Planetary Interiors, v. 1, p. 129–135.

Hyndman, D. W., Obradovich, J. D., and Ehinger, Robert, 1972, Potassium argon age determinations of the Philipsburg batholith: Geol. Soc. America Bull., v. 83, p. 473–474.

Kistler, R. W., and Peterman, Z. E., 1972, Variations in Sr, Rb, K, Na and initial Sr^{87}/Sr^{86} in Mesozoic granitic rocks in California: Geol. Soc. America, Abs. with Programs (Ann. Mtg.), v. 4, no. 7, p. 562.

Kistler, R. W., Evernden, J. F., and Shaw, H. R., 1971, Sierra Nevada plutonic cycle: Pt. I, Origin of composite granitic batholiths: Geol. Soc. America Bull., v. 82, p. 853–868.

Klepper, M. R., and Smedes, H. W., 1959, Elkhorn Mountains volcanic field, western Montana [abs.]: Geol. Soc. America Bull., v. 70, p. 1631.

Klepper, M. R., Weeks, R. A., and Ruppel, E. T., 1957, Geology of the southern Elkhorn Mountains, Montana: U.S. Geol. Survey Prof. Paper, 292, 82 p.

Klepper, M. R., Ruppel, E. T., Freeman, V. L., and Weeks, R. A., 1971, Geology and mineral deposits, east flank of the Elkhorn Mountains, Broadwater County, Montana: U.S. Geol. Survey Prof. Paper 665, 66 p.

Knopf, Adolph, 1913, Ore deposits of the Helena mining region, Montana: U.S. Geol. Survey Bull. 527, 143 p.

—— 1950, The Marysville granodiorite stock, Montana: Am. Mineralogist, v. 35, no. 9–10, p. 834–844.

—— 1957, The Boulder bathylith of Montana: Am. Jour. Sci., v. 255, p. 81–103.

—— 1963, Geology of the northern part of the Boulder bathylith and adjacent area, Lewis and Clark and Jefferson Counties, Montana: U.S. Geol. Survey Misc. Geol. Inv. Map I–381, scale 1:48,000.

Lachenbruch, A. H., 1968, Preliminary geothermal model of the Sierra Nevada: Jour. Geophys. Research, v. 73, p. 6977–6989.

Lachenbruch, A. H., and Bunker, C. M., 1971, Vertical gradients of heat production in the continental crust; 2, Some estimates from borehole data: Jour. Geophys. Research, v. 76, p. 3852–3860.

Lambert, I. B., and Heier, K. S., 1967, The vertical distribution of uranium, thorium, and potassium in the continental crust: Geochim. et Cosmochim. Acta, v. 31, p. 377–390.

—— 1968, Geochemical investigations of deep-seated rocks in the Australian shield: Lithos, v. 1, no. 1, p. 30–53.

Larsen, E. S., Jr., 1948, Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California: Geol. Soc. America Mem. 29, 182 p.

Larsen, E. S., Jr., and Schmidt, R. G., 1958, A reconnaissance of the Idaho batholith and comparison with the southern California batholith: U.S. Geol. Survey Bull. 1070–A, p. 1–33.

Lee, D. E., and Van Loenen, R. E., 1971, Hybrid granitoid rocks of the southern Snake Range, Nevada: U. S. Geol. Survey Prof. Paper 668, 48 p.

Lindgren, Waldemar, 1915, The igneous geology of the Cordilleras and its problems, *in* Problems of American geology: New Haven, Conn., Yale Univ., Silliman Found., p. 234–286.

Lipman, P. W., Prostka, H. J., and Christiansen, R. L., 1972, Cenozoic volcanism and plate-tectonic evolution of the Western United States. I. Early and middle Cenozoic: Royal Soc. London Philos. Trans., v. 271, p. 217–248.

McDowell, F. W., and Kulp, J. L., 1969, Potassium-argon dating of the Idaho batholith: Geol. Soc. America Bull., v. 80, p. 2379–2382.

Moore, J. G., 1959, The quartz diorite boundary line in the Western United States: Jour. Geology, v. 67, p. 198–210.

—— 1962, K/Na ratio of Cenozoic igneous rocks of the Western United States: Geochim. et Cosmochim. Acta, v. 26, p. 101–130.

Noble, D. C., and Hedge, C. E., 1969, Sr^{87}/Sr^{86} variations within individual ash-flow sheets: U.S. Geol. Survey Prof. Paper 650–C, p. 133–139.

Pardee, J. T., and Schrader, F. C., 1933, Metalliferous deposits of the Greater Helena mining region, Montana: U.S. Geol. Survey Bull. 842, 318 p.

Patterson, Claire, Silver, Leon, and McKinney, Charles, 1956, Lead isotopes and magmatic differentiation, *in* Resumenes de los trabajos presentados: Internat. Geol. Cong., 20th, Mexico City 1956, p. 221–222.

Peterman, Z. E., and Hedge, C. E., 1971, Related strontium isotopic and chemical variations in oceanic basalts: Geol. Soc. America Bull., v. 82, p. 493–500.

Robertson, F. S., 1953, Notes on the chemical petrology of the Boulder batholith and related igneous rocks: Montana Acad. Sci. Proc., v. 13, p. 67–76.

Robinson, G. D., 1963, Geology of the Three Forks quadrangle, Montana, with descriptions of igneous rocks by H. Frank Barnett: U.S. Geol. Survey Prof. Paper 370, 143 p.

Robinson, G. D., Klepper, M. R., and Obradovich, J. D., 1968, Overlapping plutonism, volcanism, and tectonism in the Boulder batholith region, western Montana, *in* Coats and others, eds., Geol. Soc. America Mem. 116, p. 557–576.

Ross, D. C., 1969, Descriptive petrography of three large granitic bodies in the Inyo Mountains, California: U.S. Geol. Survey Prof. Paper 607, 47 p.

Roy, R. F., Blackwell, D. D., and Birch, Francis, 1968, Heat generation of plutonic rocks and continental heat-flow provinces: Earth and Planetary Sci. Letters, v. 5, p. 1–12.

Roy, R. F., Blackwell, D. D., and Decker, E. R., 1972, Continental heat flow, *in* Robertson, E. C., ed., The nature of the solid Earth: New York, McGraw-Hill, p. 506–543.

Ruppel, E. T., 1963, Geology of the Basin quadrangle, Jefferson, Lewis and Clark, and Powell Counties, Montana: U.S. Geol. Survey Bull. 1151, 121 p.

Scott, R. B., Nesbitt, R. W., Dasch, E. J., and Armstrong, R. L., 1971, A strontium isotope evolution model for Cenozoic magma genesis, eastern Great Basin, U.S.A.: Bull. Volcanol., tome 35, p. 1–26.

Shenon, P. J., 1931, Geology and ore deposits of Bannack and Argenta, Montana: Montana Bur. Mines and Geology Bull. 6, 77 p.

Smedes, H. W., 1958, Interpretation of geologic structure of western Montana and northern Idaho [abs.]: Geol. Soc. America Bull., v. 69, no. 12, pt. 2, p. 1745.

—— 1962, Lowland Creek Volcanics, an upper Oligocene formation near Butte, Montana: Jour. Geology, v. 70, p. 255–266.

—— 1966, Geology and igneous petrology of the northern Elkhorn Mountains, Jefferson, and Broadwater Counties, Montana: U.S. Geol. Survey Prof. Paper 510, 116 p.

—— 1973, Regional geologic setting of the Boulder batholith, Montana [abs.]: Program, Butte Field Mtg., Soc. Econ. Geologists, p. A.

Smedes, H. W., and Thomas, H. H., 1965, Reassignment of the Lowland Creek Volcanics to

Eocene age: Jour. Geology, v. 73, no. 3, p. 508–510.

Smedes, H. W., Klepper, M. R., and Tilling, R. I., 1968, Boulder batholith—A description of geology and road log: Geol. Soc. America (Rocky Mtn. Sec., Bozeman, Montana), Field Trip 3, 21 p.

Smith, J. L., 1970, Petrology, mineralogy, and chemistry of the Tobacco Root batholith Madison County, Montana [Ph.D., thesis]: Bloomington, Indiana Univ., 198 p.

Suttner, L. J., and Leininger, R. K., 1972, Comparison of the trace element content of plutonic, volcanic, and metamorphic quartz from southwestern Montana: Geol. Soc. America Bull., v. 83, p. 1855–1862.

Swanberg, C. A., 1972, Vertical distribution of heat generation in the Idaho batholith: Jour. Geophys. Research, v. 77, no. 14, p. 2508–2513.

Swanberg, C. A., and Blackwell, D. D., 1973, Areal distribution and geophysical significance of heat generation in the Idaho batholith and adjacent intrusions in eastern Oregon and western Montana: Geol. Soc. America Bull., v. 84, p. 1261–1282.

Tatsumoto, M., 1966a, Isotopic composition of lead in volcanic rocks from Hawaii, Iwo Jima and Japan: Jour. Geophys. Research, v. 71, no. 6, p. 1721–1733.

—— 1966b, Genetic relations of oceanic basalts as indicated by lead isotopes: Science, v. 153, no. 3740, p. 1094–1101.

Tilling, R. I., 1964, Variation in modes and norms of a "homogeneous" pluton of the Boulder batholith, Montana, in Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501–D, p. D8–D13.

—— 1968, Zonal distribution of variations in structural state of alkali feldspar within the Rader Creek pluton, Boulder batholith, Montana: Jour. Petrology, v. 9, p. 331–357.

Tilling, R. I., and Gottfried, David, 1969, Distribution of thorium, uranium, and potassium in igneous rocks of the Boulder batholith region, Montana, and its bearing on radiogenic heat production and heat flow: U.S. Geol. Survey Prof. Paper 614–E, 29 p.

Tilling, R. I., Klepper, M. R., and Obradovich, J. D., 1968, K-Ar ages and time span of emplacement of the Boulder batholith, Montana: Am. Jour. Sci., v. 266, p. 671–689.

Tilling, R. I., Gottfried, David, and Dodge, F.C.W., 1970, Radiogenic heat production of contrasting magma series: Bearing on interpretation of heat flow: Geol. Soc. America Bull., v. 81, p. 1447–1462.

Weed, W. H., 1899, Granite rocks of Butte, Montana, and vicinity: Jour. Geology, v. 7, p. 737–750.

—— 1901, Geology and ore deposits of the Elkhorn mining district, Jefferson County, Montana: U.S. Geol. Survey 22d Ann. Rept., pt. 2, p. 399–550.

—— 1912, Geology and ore deposits of the Butte district, Montana: U.S. Geol. Survey Prof. Paper 74, p. 262.

Winchell, A. N., 1914, Mining districts of the Dillon quadrangle, Mont.: U.S. Geol. Survey Bull. 574, 191 p.

Zartman, R. E., and Wasserburg, G. J., 1969, The isotopic composition of lead in potassium feldspars from some 1.0 b.y. old North American rocks: Geochim. et Cosmochim. Acta, v. 33, p. 901–942.

Zietz, Isidore, Hearn, B. C., Jr., Higgins, M. W., Robinson, G. D., and Swanson, D. A., 1971, Interpretation of an aeromagnetic strip across the northwestern United States: Geol. Soc. America Bull., v. 82, p. 3347–3372.

MANUSCRIPT RECEIVED BY THE SOCIETY MARCH 5, 1973

REVISED MANUSCRIPT RECEIVED JUNE 18, 1973

PUBLICATION AUTHORIZED BY THE DIRECTOR, U.S. GEOLOGICAL SURVEY

PRINTED IN U.S.A.