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# Geochemical Database for the Boulder Batholith and Its Satellitic Plutons, Southwest Montana

## Data Series 454

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph:
Prominent outcrops of the Moose Creek pluton in the Humbug Spires area, southern Boulder batholith, Montana

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# Geochemical Database for the Boulder Batholith and Its Satellitic Plutons, Southwest Montana

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## Introduction

Data presented in this report pertain to Cretaceous igneous intrusions of the Boulder batholith and its satellitic plutons in southwest Montana. As summarized by Lund and others (2002), the Boulder batholith consists of the Butte Granite[1] and an array of satellitic plutons emplaced into Mesoproterozoic to Mesozoic sedimentary rocks and possibly cogenetic rocks of the Late Cretaceous Elkhorn Mountains Volcanics (Hamilton and Myers, 1967; Robinson and others, 1968; Klepper and others, 1971a, b; Tilling, 1974; Lambe, 1981; and Rutland and others, 1989). Data presented here were compiled during 2007 and 2008 as part of the updated National Mineral Resources—Planning Phase project conducted by the U.S. Geological Survey (USGS) in order to help place world-class mineral deposits of the Butte district into an appropriate framework relative to associated intrusive rocks. Although these deposits and their host rocks have been the subject of many investigations (Brown, 1894; Emmons and Tower, 1897; Weed, 1912; Knopf, 1913, 1950; Sales, 1913; Sales and Meyer, 1948, 1949; Meyer, 1965; Smedes, 1966; Meyer and others, 1968; Lange and Cheney, 1971; Brimhall, 1973, 1977, 1979, 1980; Miller, 1973; Proffett, 1973; Roberts, 1975; Rusk and others, 2008), the petrologic characteristics of associated intrusive rocks have not been systematically compiled, synthesized, or interpreted, with the exception of some analytical studies of rocks and (or) minerals of the Boulder batholith (Tilling, 1964, 1968, 1973, 1974, 1977; Doe and Tilling, 1967; Doe and others, 1968; Greenland and others, 1968, 1971, 1974; Tilling and Gottfried, 1969; Gottfried and others, 1972). The geographic area addressed in this compilation is approximately bounded by lats 45.6° and 46.7°N. and longs 112.75° and 111.5° W. (fig. 1). The area is dominated by the voluminous Butte Granite, but as many as a dozen other significant plutons surround this very large pluton. In addition, small stocks and plugs are numerous north and especially east of the Butte Granite, where they intruded the Elkhorn Mountains Volcanics. Abundant late Mesozoic intrusions in the study area are probably byproducts of subduction-related processes, including back-arc magmatism that prevailed along the west edge of the North American plate during this interval.

Lund and others (2002) and Rusk and others (2008), for example, have highlighted the association between magmatism and ore deposits in the area of the Boulder batholith. More than a century of geologic investigations in the study area demonstrate that many ore deposits, representing diverse deposit types, are spatially, and probably temporally and genetically, associated with igneous intrusions. Because of the significance of mineral deposits associated with the Boulder batholith, many investigations of these deposits have been completed, including those by Master's and Doctoral thesis students (particularly University of California, Berkeley, and both Oregon and Oregon State University students and associated faculty), economic geologists working on behalf of exploration and mining companies, and USGS earth scientists. These studies have produced many igneous rock geochemical analyses, but despite the number and importance of igneous intrusions in the study area, no complete synthesis of these data has been completed.

Starting in the 1950s, USGS personnel began a significant geologic mapping and geochemical analysis campaign in the Boulder batholith region (see references, especially sources of mapping, compiled by Smedes and others, 1988). The principal impetus for these investigations was U.S. Atomic Energy Commission funding dedicated to an assessment of uranium resource potential associated with these rocks. This first episode of study concluded about 1956 and was summarized in an unpublished report prepared by Randolph W. Chapman (Trinity College, Hartford, Conn.). Subsequently, geologic mapping continued, and in the early 1960s R.I. Tilling of the USGS initiated a second round of petrologic research, which included collecting and analyzing additional rock samples and mineral concentrates. This work culminated in two seminal papers about the Boulder batholith and associated rocks (Tilling, 1973, 1974). Unfortunately, much of the data synthesized and interpreted in these papers

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[1] See "lithology" section for rationale considered in changing the name of the Butte intrusion from quartz monzonite to granite.

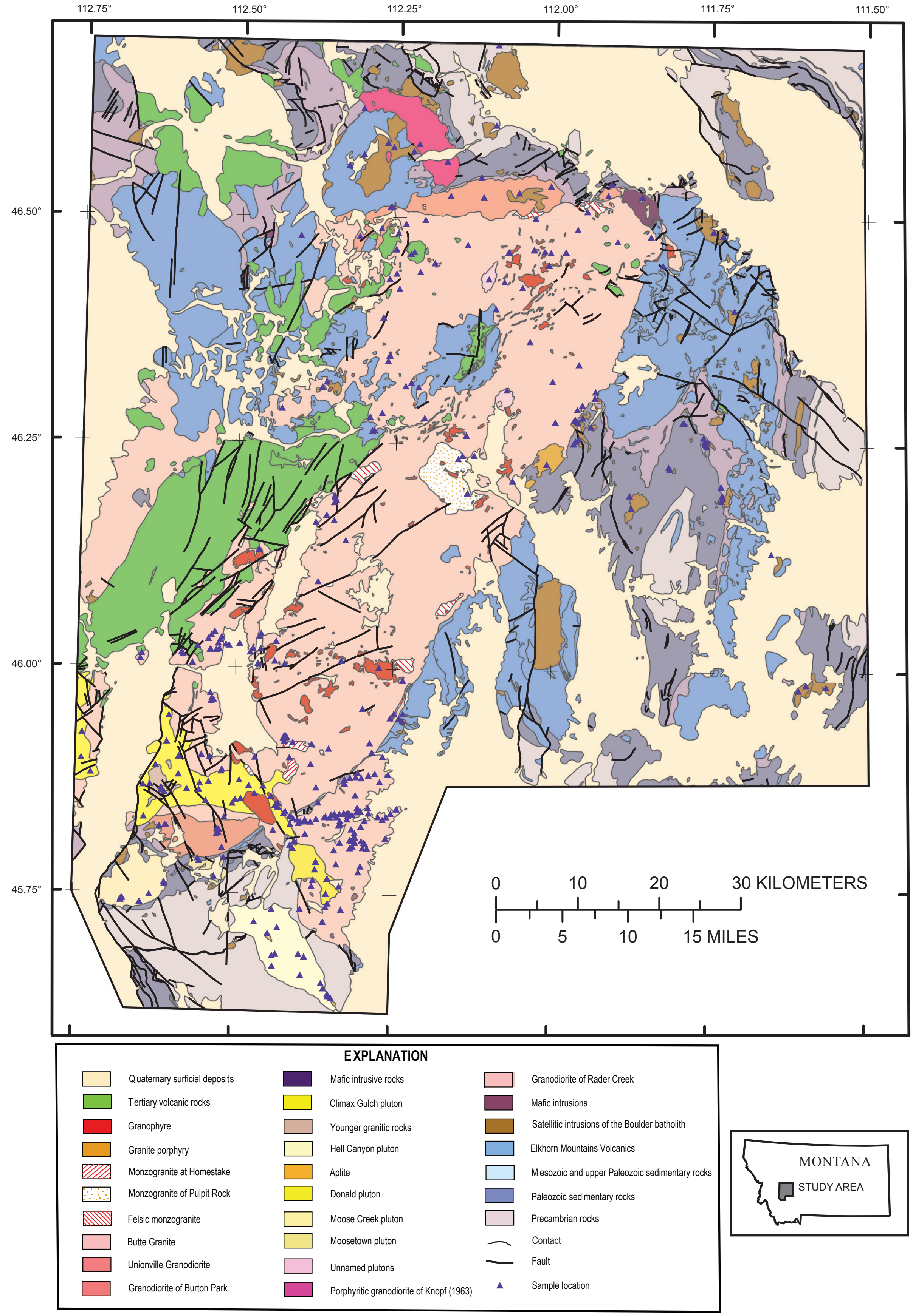

**Figure 1.** Index map showing the Boulder batholith and its satellitic plutons, southwest Montana (modified from Smedes and others, 1988).

remained unpublished (see fig. 4 caption in Tilling, 1973). Soon thereafter, L.K. McClain (Bauer), G.W. Matthews, and colleagues extensively sampled and analyzed rocks of the Boulder batholith as part of the National Uranium Resource Evaluation (NURE) conducted by the U.S. Department of Energy. The resulting, never-published data (analyses of nearly 100 samples) were preserved in a single paper copy of analytical results in the files of R.I. Tilling (L.K. McClain and G.W. Matthews, unpub. data, 1979). Lambe (1981) completed a Ph. D. thesis concerning the petrology of the Boulder batholith rocks but once again pertinent data remained unpublished. Subsequently, interest in Boulder batholith intrusive rocks waned, and significant additional research on these rocks did not recommence until about 10 years ago, during the USGS Headwaters Project (Lund and others, 2002; Lund, 2007) and with renewed academic interest, coordinated principally by J.H. Dilles (Oregon State University, Corvallis, Oreg.), M.H. Reed (University of Oregon, Eugene, Oreg.), and their students. Now, with the USGS about to initiate an updated National Mineral Resource Assessment (Johnson and others, 2008), it is important that the genetic understanding of giant deposits, such as those associated with the Boulder batholith, be refined to reduce uncertainties of mineral resource assessments. To fully understand the Boulder batholith and its associated deposits, it is essential to develop, synthesize, and interpret the magmatic framework within which these evolved. The text and data that follow contain a synthesis of available composition data for igneous rocks of the Boulder batholith area. The ultimate goal of this effort will be an evaluation of the time-space-compositional evolution of Mesozoic magmatism associated with the Boulder batholith and identification of genetic associations between magmatic and mineralizing processes in this region.

## Acknowledgments

We thank several individuals who helped make this effort possible. The staff of the USGS Denver library, who used the interlibrary loan process to obtain some of the geologic reports on which parts of this compilation are based, were critical to its success. R.N. Lambe helped establish location information for many samples included in his research. S.M. Smith and Matthew Granitto extracted geochemical data for samples of the Boulder batholith from the USGS National Geochemical Database (NGDB). Matthew Granitto was also instrumental in searching for Boulder batholith data in paper archives to find original laboratory reports that contained data for Boulder batholith samples that had never been entered into the NGDB. Finally, we gratefully acknowledge technical reviews by Mathew Granitto and R.M. O'Leary that helped to improve this report.

## The Boulder Batholith and Its Satellitic Intrusions—Constituents of the Database

The data compilation described here pertains to the very large Butte Granite pluton, approximately a dozen contiguous smaller plutons generally considered to be part of the Boulder batholith, and numerous isolated small stocks and plugs that are especially abundant north and east of the Butte Granite (fig. 1). The Elkhorn Mountains Volcanics also include many hypabyssal intrusions; however, compositional data for these rocks are not included in the compilation. These fine-grained to aphanitic basaltic and andesitic rocks form moderately large, concordant intrusions that are demonstrably associated with the Elkhorn Mountains Volcanics. In contrast, satellitic intrusions considered to be parts of the Boulder batholith form small, discordant, phaneritic intrusions. Applying the emerging K-Ar dating technique, Tilling and others (1968) estimated the time span of emplacement of the Boulder batholith to about 6 million years (≈78–72 Ma). Modern U-Pb zircon geochronologic investigations (Lund and others, 2002) have confirmed that all intrusions of the Boulder batholith are Cretaceous. Aside from the granodiorite of Rader Creek (80.7 Ma) and the Unionville Granodiorite (78.2 Ma), ages of Boulder batholith plutons are restricted to the 77.6–73.7 Ma interval; the age of the Butte Granite ranges from 76.5 to 74.5 Ma (Lund and others, 2002). However, early K-Ar age data (McDowell, 1966) suggest that one of the Boulder batholith intrusions, the Climax Gulch pluton, might be as young as ≈68 Ma. The Boulder batholith also includes quartz porphyry dikes and plugs that are distinctly younger than other batholith rocks. Most ages determined for these rocks are in the 70.0–67.6 Ma age interval, although zircon from a rhyolite dike and from the informal Modoc breccia quartz porphyry intrusion gives ages of 62.7 Ma and 77.3 Ma (J.N. Aleinikoff, USGS, unpub. data, 2009), respectively. Ages have not been determined for any of the small satellitic masses that discordantly intruded the Elkhorn Mountains Volcanics.

## Data Compilation Methods

The map compilation of Smedes and others (1988) was used as the geologic framework for our geochemical compilation. That map identifies the intrusions for which geochemical data were compiled. Intrusion names were gleaned from publications on which that compilation is based. The original, stable-base geologic compilation of Smedes and others (1988) was scanned and attributed to produce an ArcGIS rendition of the map; associated data are included with the data release described here. The locations of samples for which geochemical data were compiled as part of this endeavor were combined with the ArcGIS data to create a PDF file (file, DS454_Plate.pdf) to which all intrusion names were added (pl. 1). Metadata for the

ArcGIS files are embedded in the geospatial database and are also contained in a freestanding file (file, Metadata.txt).

Several significant efforts to acquire and compile compositional data for Boulder batholith intrusions preceded and served as a starting point for the effort documented here. Compilations by R.W. Chapman (Trinity College, Hartford, Conn., unpub. data, 1956), Tilling (1973), L.K. McClain and G.W. Matthews (NURE, unpub. data, 1979), and Lambe (1981) constitute the majority of the compiled data; all other data were compiled from published sources. Much of the data compiled, plotted, and interpreted by Tilling (1973) have never been published and were recently recovered from original paper copies of lab analysis reports. The McClain and Matthews data are essentially undocumented; original lab reports are unavailable.

Original data source materials (subsequently referred to as sources), including published reports and theses, were used to add information to the database. Compiling analytical methods and associated estimates of precision and accuracy associated with the reported data was beyond the scope of this effort. Analytical protocols, precision, and accuracy were highly variable among sources. Fortunately, most sources document these parameters so that associated questions can be resolved by referring to the appropriate data source. Reference lists contained in the data sources were examined and used to identify additional potential data sources. In this way, data for 435 samples from 22 sources were identified and incorporated in the database. We believe that this process has probably resulted in identification and incorporation of most of the compositional data that have been produced for samples of Boulder batholith intrusions. For a sample to be included in the database, at least a sample number and major oxide analysis were required. Additional trace element and (or) isotopic data may be available for some samples (Doe and Tilling, 1967; Doe and others, 1968; Greenland and others, 1968, 1971, 1974), but because the number of these samples is very small, these data were not included in the database. Small amounts of additional data can be gleaned by consulting the appropriate data sources. Data were compiled using Microsoft Excel and can be accessed using software compatible with .xls files. The database release file is titled ButteChem.xls. The database release also includes a tab-delimited, text file version of the database (file, ButteChem.txt).

No effort was made to exclude hydrothermally altered samples from the compilation. Rather, all intrusive rock compositional data were compiled, and samples identified by the sources as altered were coded accordingly. Additional altered samples were identified using standard geochemical criteria. Specifically, for the purposes of this compilation, hydrothermally altered samples are those with any of the following characteristics: $SiO_2$ abundances greater than 78 percent, $Al_2O_3$ abundances less than 10 percent or greater than 20 percent, total volatile concentrations greater than 3 percent, $CO_2$ concentrations greater than 0.35 percent, S concentrations greater than 0.2 percent, or Total_oth_sulf concentrations greater than 0.2 percent; samples with any of these characteristics probably do not preserve primary igneous rock compositions. In addition, samples with initial analytic totals greater than 103 percent or initial analytic totals less than 95 percent were identified; samples with these characteristics probably indicate unusable, inaccurate analyses.

Starting with data contained in the principal compilation (accessed via the “Butte DB” tab; file, ButteChem.xls), data winnowing and processing resulted in two derivative databases, accessed via the “Nml db no alt cens Fe2” and “Alt” tabs (file, ButteChem.xls), that were both processed (to enhance their ready usability) from the principal compilation (as described in the following). First, all censored values were replaced by blank cells. Next, because different sources report iron concentrations determined by different analytical protocols, the mode of iron abundance data presentation required standardization. For most samples, abundances of both ferric and ferrous iron (compiled in the $Fe_2O_3$ and FeO data columns, respectively) are reported in the sources. Some compiled analyses report only total iron abundances (compiled in the $FeTO_3$ column) as ferric iron, and analyses of a few samples contain data for ferrous iron only. Reported ferrous and ferric iron abundances in many of these rocks are unlikely to represent magmatic values because of oxidation during late- to post-magmatic processes. Interaction with post-magmatic fluids caused compositions of many Boulder batholith intrusive rocks to change in other ways as well. In particular, many of these rocks were hydrothermally altered (as indicated by secondary clay minerals, sericite, and (or) chlorite). Late magmatic processes and alteration caused volatile concentrations of the affected samples to increase, and correspondingly caused relative abundances of all other constituents to decrease. Therefore, to facilitate meaningful comparison of oxide abundances between variably altered samples, all iron abundances were converted to ferrous iron (compiled in the FeO* column) and each major oxide analysis was recalculated to 100 percent on a volatile-free basis. The derivative database for essentially unaltered intrusive samples accessed via the “Nml db no alt cens Fe2” tab can be used to evaluate time-space-compositional relations between magmatism and ore genesis. The associated spreadsheet includes data for unaltered samples only and no censored data; portrays total iron concentrations as ferrous iron; and presents major oxide analyses recalculated to 100 percent on a volatile-free basis. The derivative database containing information for altered rocks can be accessed via the tab labeled “Alt” and can be used to evaluate the effects of hydrothermal alteration on primary rock compositions. The associated spreadsheet includes data for all altered samples and no censored data, and also presents total iron concentrations as ferrous iron and major oxide analyses recalculated to 100 percent on a volatile-free basis. Row entries in the data accessed via the “Alt” tab are sorted into subsets of samples that share the same alteration characteristic (in red, at the top of each subset of data rows).

Data presented in source materials were included in the database, without modification, and all input subsequently verified. Background documentation for some analytical data presented in this report is incomplete and (or) may be misleading or incorrect, any of which could cause inclusion of inappropriate information in the database. Every effort has been made to preclude inclusion of misleading data; the amount of this type of data inadvertently included in the database is probably small and should not significantly affect data interpretation.

# Data Fields

Data fields presented and described herein represent those considered most critical to addressing questions concerning tectonic, petrologic, and metallogenic relations. Data for each of these fields constitute a column, or set of related columns, in the database. Data in these columns can be sorted, queried, and interpreted to address questions concerning the history, development, and implications of magmatic activity. Sample records are aggregated in blocks of data that share a primary geochemical data source.

Blank cells in the main "Butte DB" database indicate that no data are available for the corresponding column. Some sources report values of zero for some database fields. These values indicate that an abundance determination was attempted but that the constituent was not detected in the sample. Similarly, some sources present qualified data. In particular, records for some samples include less than (<) symbols. These data indicate that the constituent was detected but that its concentration was unquantifiable beyond the fact that its concentration is less than the indicated value. Analytical precision varies within individual columns in accordance with specific analytical protocols and the way data are reported in individual sources.

## sample_number

Identifiers for analyzed samples were compiled from sources and presented, without modification.

## modal_lithology

Lithologic names of analyzed samples were derived from information contained in sources. In accordance with procedures defined by the International Union of Geological Sciences (IUGS), lithologic/composition names for intrusive rocks are best defined using the relative modal proportions of quartz, alkali feldspar, and plagioclase relative to the classification scheme of Streckeisen (1976). However, many publications that serve as sources for our compilation predate the classification recommendations of Streckeisen (1976); most of these used the classification of Johannsen (1931) to define sample lithology. Using modal data available for each sample, lithologic sample designations in the "modal_lithology" column have been verified, corrected, and converted from the nomenclature of Johannsen (1931) to that of Streckeisen (1976). As discussed by Lund and others (2002), the Butte pluton is actually composed (Streckeisen, 1976) of granite (more specifically, monzogranite). As such we refer to this intrusion as the Butte Granite, using the original nomenclature of Emmons (1888). For the same reason, we refer to the informal Homestake, Pulpit Rock, and felsic quartz monzonites of Smedes and others (1988) as the Homestake, Pulpit Rock, and felsic monzogranites. Modal data for samples of the Boulder batholith and its surrounding satellitic intrusions are summarized on a ternary quartz–alkali feldspar–plagioclase diagram (fig. 2). In recognition of the distinctive cuneiform textures characteristic of many of the aplite-alaskite-pegmatite bodies, we refer to intrusions whose lithologies are coded as aplite, alaskite, or alaskite-aplite as "granophyre."

## lithology

Modal data are not available for many samples included in the database. Lacking this data, original lithologic names (entries in the "lithology" column) designated in the sources were retained; these are approximate lithologic designations not supported by available modal data.

## ign_form

The form of the igneous intrusion represented by each sample is given where known. Samples coded as representing dikes, sills, or dike/sill represent thin tabular bodies that are discordant and concordant with enclosing rocks, respectively. Larger intrusive bodies, generally discordant to enclosing rocks, are coded as plutons and stocks. "Pluton" entries in the "ign_form" column identify intrusions that cooled slowly, at least several kilometers below the surface, and are phaneritic, whereas "Stock" entries designate smaller intrusions, many of which cooled relatively quickly at shallow levels in a subvolcanic environment, and may have a quenched groundmass. Smedes and others (1988) suggested that the aplite-alaskite-pegmatite bodies (granophyre) form gently dipping sheets; "ign_form" entries for samples of these units are coded as "Dike" or "Sill" depending on field relations or left blank if not known. They also suggest that the Moose Creek intrusion is a moderately inclined, irregular-shaped laccolith; "ign_form" entries for samples of this unit are coded "Laccolith."

## alteration

Some sources explicitly indicate that some analyzed samples are altered. Other sources provide sufficient descriptive information about samples that alteration can be inferred. Some sources simply indicate that samples are altered; these samples are simply coded as "Yes" in the "alteration" column. Other alteration terms used to code altered samples include argillic, propylitic, and sericitic. Each of these terms is applied in accordance with their standard usage as defined by Guilbert and Park (1986).

## longitude and latitude

An effort was made to obtain location data for all samples with composition data. Most sources contain some form of location information. Missing sample location data were requested from authors, most of whom were able to provide missing information. Accordingly, location data are available for all but a few samples. Latitude and longitude data are reported as decimal degrees (relative to the 1927 North American Datum). In the study area, longitude is reported as a negative value (western hemisphere) and latitude as a positive value (northern hemisphere).

Location data are of variable quality as a consequence of the manner in which they were initially acquired and subsequently reported. The number of significant figures presented as part of location data in the "longitude" and "latitude" columns defines relative levels of sample location precision, as follows:

- four significant figures indicate that the given location is accurate within tens of meters,
- three significant figures indicate that the given location is accurate within hundreds of meters, and
- two significant figures indicate that the given location is accurate within thousands of meters.

Some sources report sample location in terms of Township, Range, and section values, usually to the closest quarter section. Township-Range-section data were digitized to obtain decimal degree locations; within the appropriate quarter section quadrilaterals, digitized points were usually selected to coincide with a road, trail, stream bottom, quarry, or natural cliff, any of which might represent a likely sampling location. Some sources do not include numerical sample location data

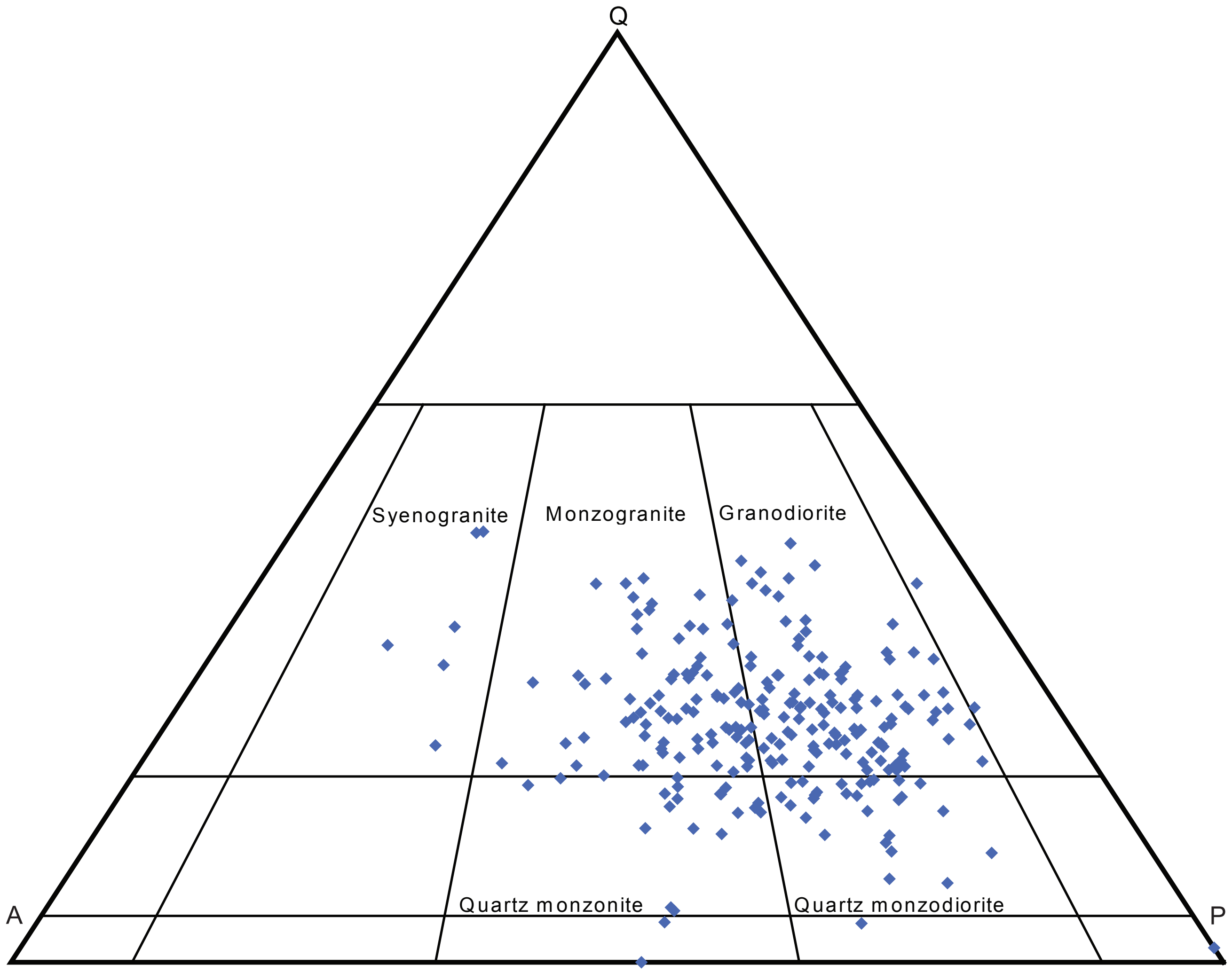

**Figure 2.** Quartz (Q)-alkali feldspar (A)-plagioclase (P) ternary diagram showing modal compositions of Boulder batholith samples. Classification grid and rock names are those of Streckeisen (1976).

but do contain sample maps. Location data for these samples were obtained by digitizing sample sites. A very few sources merely describe sample locations; these were used to estimate a sample location, which was then digitized.

## SiO2, TiO2, Al2O3, Fe2O3, FeTO3, FeO, MnO, MgO, CaO, Na2O, K2O, and P2O5

Sources report whole rock, major oxide data in a variety of formats. The database includes columns for the abundances (in weight percent) of $SiO_2$, $TiO_2$, $Al_2O_3$, $Fe_2O_3$, $FeTO_3$, FeO, MnO, MgO, CaO, $Na_2O$, $K_2O$, and $P_2O_5$. However, because diverse analytical protocols, each with its own associated analytical precision and accuracy, were used to analyze samples, not all sources contain data for each of these constituents. Data in the "Fe2O3" and "FeO" columns are abundances of ferric and ferrous iron, respectively. Data in the "FeTO3" column represent total iron reported as ferric iron. To facilitate comparison of major oxide data for the Boulder batholith and its surrounding satellitic intrusions to those for other plutonic rocks, the compiled data are presented on several standard variation diagrams (figs. 3, 4, 5).

## LOI, H2O+, H2O-, Tot_H2O, CO2, Cl, F, S, SO3, FeS2, and Tot_oth_sulf

Data sources report volatile constituent concentrations for Boulder batholith samples in widely disparate ways. In order to capture important information concerning the volatile concentrations of these rocks, an array of data columns was designated to account for various analytical protocols and data reporting formats. Volatile constituents whose abundances were commonly determined include LOI (loss on ignition), $H_2O$+ (bound), $H_2O$- (nonessential, moisture), and $CO_2$. Several sources present data for total $H_2O$ without regard for species; these data are compiled in the "Tot_H2O" database column. Few sources contain Cl, F, S, or $SO_3$ abundance data. Several sources present iron and sulfur abundances for mineralized samples as $FeS_2$. Finally, one source presents abundances of several sulfide species in moderately mineralized samples. These abundances were added and compiled in the "Tot_oth_sulf" column. All data are reported in weight percent.

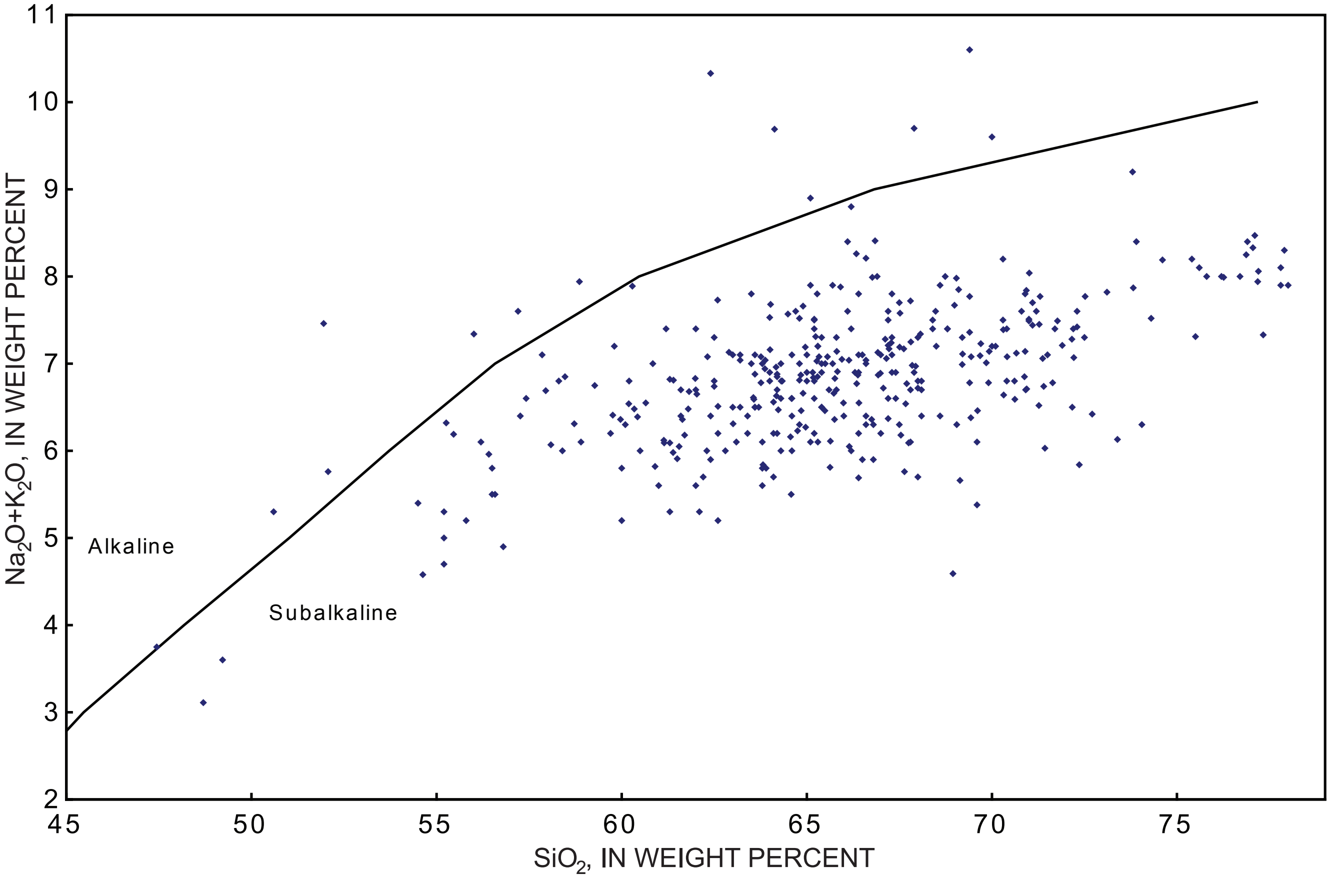

**Figure 3.** Total alkali-silica variation diagram showing compositions of the Boulder batholith and its satellitic plutons, southwest Montana. Alkaline and subalkaline fields defined by Irvine and Baragar (1971).

## total

One measure of major oxide analytical accuracy is how nearly the sum of the determined constituents approaches 100 percent. Consequently, the database includes a column that reports analytical totals (in weight percent) as reported by the source. Some sources do not include totals; totals for these samples were computed and added to the database. Initial analytical totals reported in the sources were spot checked for accuracy; discrepancies were noted and corrected in a number of cases.

## vol_sum

The total volatile concentration of Boulder batholith samples provides some insight concerning whether abundances of other constituents accurately represent primary magmatic values. Samples with elevated volatile concentrations, for example greater than 3 weight percent, are likely to have experienced some fluid-mediated, post-magmatic chemical modification. Given the wide range of analytical protocols used in analysis of these samples, the best possible measure of sample volatile concentration is total volatile concentration. For the purposes of the compilation, if LOI data are the only information contained in source data compilations concerning volatile concentration, LOI values were designated as total volatile concentration. Alternatively, if the source includes data for any combination of $H_2O+$, $H_2O-$, Tot_$H_2O$, $CO_2$, Cl, F, S, $SO_3$, $FeS_2$, or Tot_oth_sulf, these data were summed to yield total volatile concentration. All data are presented in weight percent.

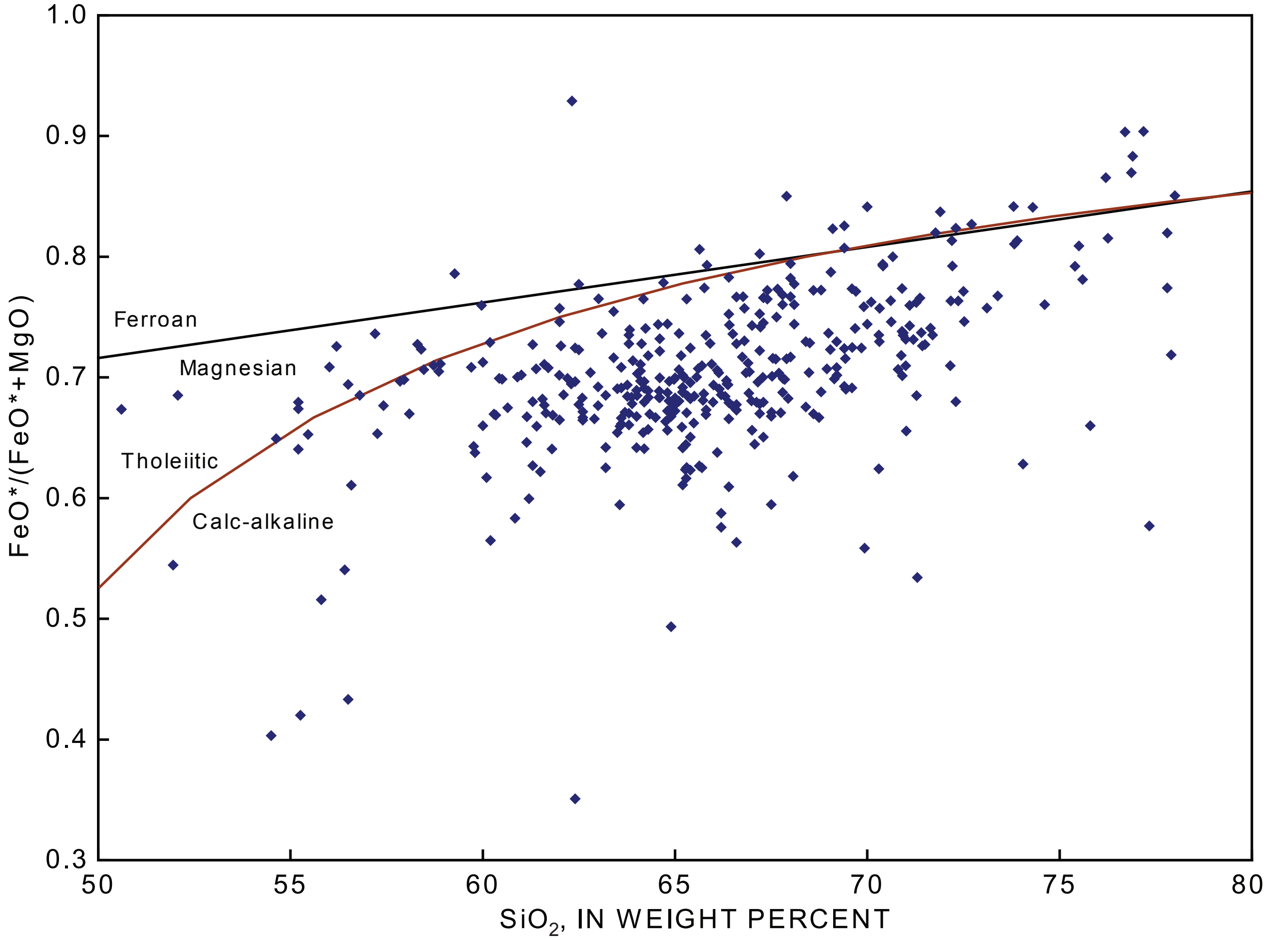

**Figure 4.** FeO*/(FeO*+MgO) versus $SiO_2$ variation diagram showing compositions of the Boulder batholith and its satellitic plutons, southwest Montana. FeO*, total iron expressed as ferrous iron. Ferroan versus magnesian boundary (black line) from Frost and others (2001); tholeiitic versus calc-alkaline boundary (red line) from Miyashiro (1974).

## Ba, Be, Cs, Rb, Sr, Y, Zr, Hf, Nb, Th, U, Ga, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ag, Au, Co, Cr, Ni, Sc, V, Cu, Mo, Pb, Zn, Sn, W, Ta, As, Sb, and B

The sources present data for inconsistent sets of trace elements. Of these, data for Ba, Be, Cs, Rb, Sr, Y, Zr, Hf, Nb, Th, U, Ga, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ag, Au, Co, Cr, Ni, Sc, V, Cu, Mo, Pb, Zn, Sn, W, Ta, As, Sb, and B were compiled; all data are in parts per million. These constituents are among those for which sources most often contain data and also are considered sufficient to address many petrologic, tectonic, and metallogenic questions. To facilitate comparison of trace element data and their tectonic implications for the Boulder batholith and its surrounding satellitic intrusions to those for other magmatic arc rocks, the compiled data are plotted on a Rb versus Y + Nb variation diagram (fig. 6).

## data_src

Chemical, petrographic, and location data for each sample included in the database were compiled from primary data sources, in most cases a single source. For a few samples, data were culled from two or more sources; for example, major oxide data may have been compiled from one source and trace element data from another. Sources of geochemical information include publications of the USGS, unpublished USGS data, Master's and Doctoral theses, and published articles. Entries in the "data_src" column of the database are keyed numerically to sources identified in the following list:

1. Knopf (1957)
2. Ruppel (1963)

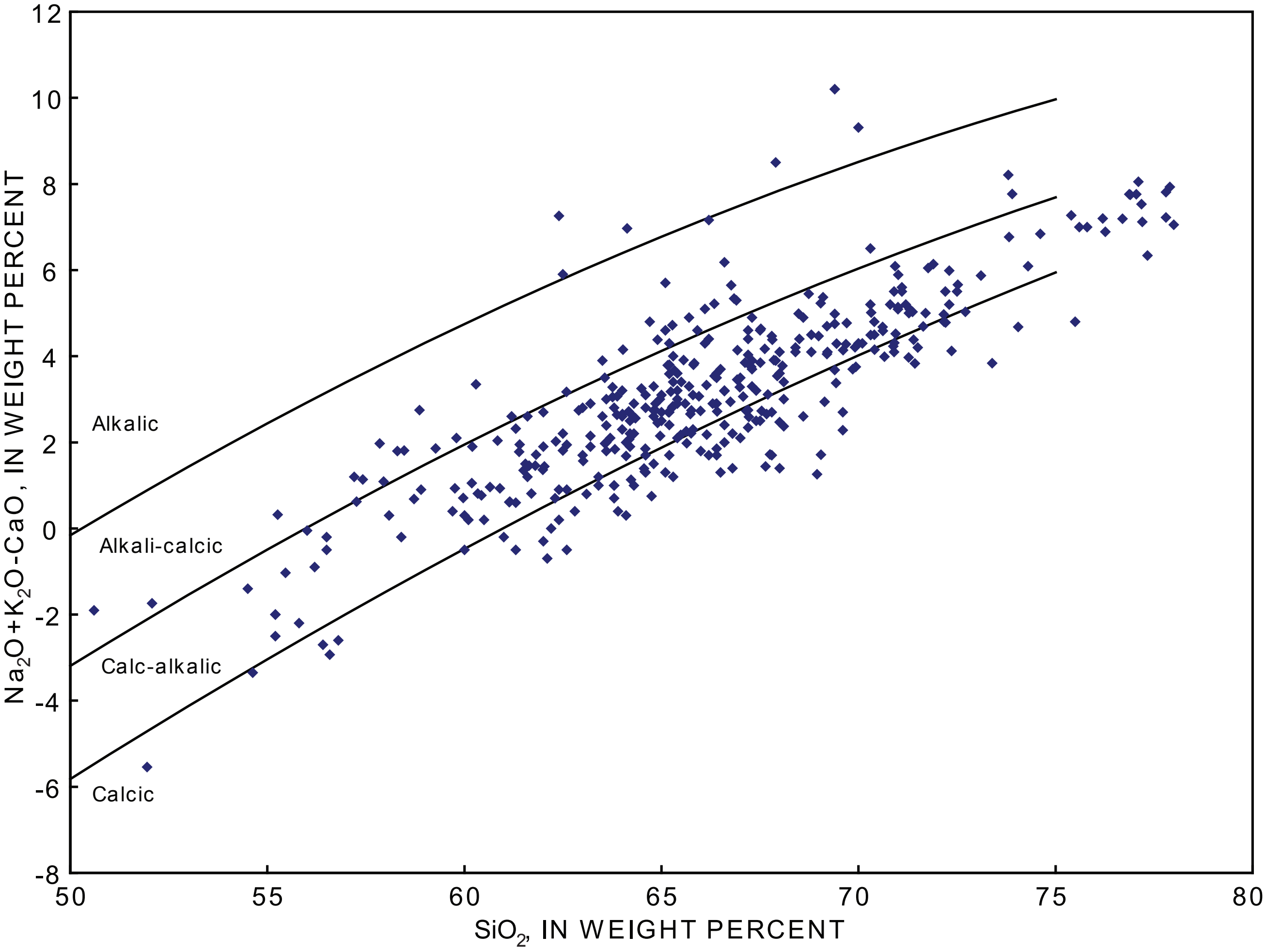

**Figure 5.** $Na_2O+K_2O-CaO$ versus $SiO_2$ variation diagram showing composition of the Boulder batholith and its satellitic plutons, southwest Montana. Boundaries between various rock series from Frost and others (2001).

3. Tilling (1968)
4. Lambe (1981)
5. Weed (1912)
6. Weed (1901)
7. Becraft and others (1963)
8. Barrell (1907)
9. Klepper and others (1957)
10. Smedes (1966)
11. Shenon (1931)
12. Knopf (1913)
13. Tilling and Gottfried (1969)
14. Robinson and Barnett (1963)
15. Klepper and others (1971b)
16. U.S. Geological Survey, National Geochemical Database, 2008
17. Tilling, R.I., U.S. Geological Survey, unpub. data, 2008
18. Smedes and others (1973)
19. Lund, Karen, U.S. Geological Survey, unpub. data, 2008
20. Chapman, R.W., Trinity College, unpub. data, 1956
21. Castor and Robins (1978)
22. McClain, L.K., and Matthews, G.W., Bendix Corp., unpub. data, 1979

## rad_age

The ages of several samples representative of Boulder batholith intrusions have been determined by U-Pb geochronology (Lund and others, 2002); these ages are compiled, in millions of years, in the database column titled “rad_age.” Although numerous K-Ar age determinations of Boulder batholith samples have been made (McDowell, 1966; Tilling and others, 1968), these data were not included in the compilation because K-Ar geochronologic systems in the dated minerals (principally biotite and hornblende) were easily perturbed during the complex and protracted thermal history characteristic of an intrusion as large as the Boulder batholith.

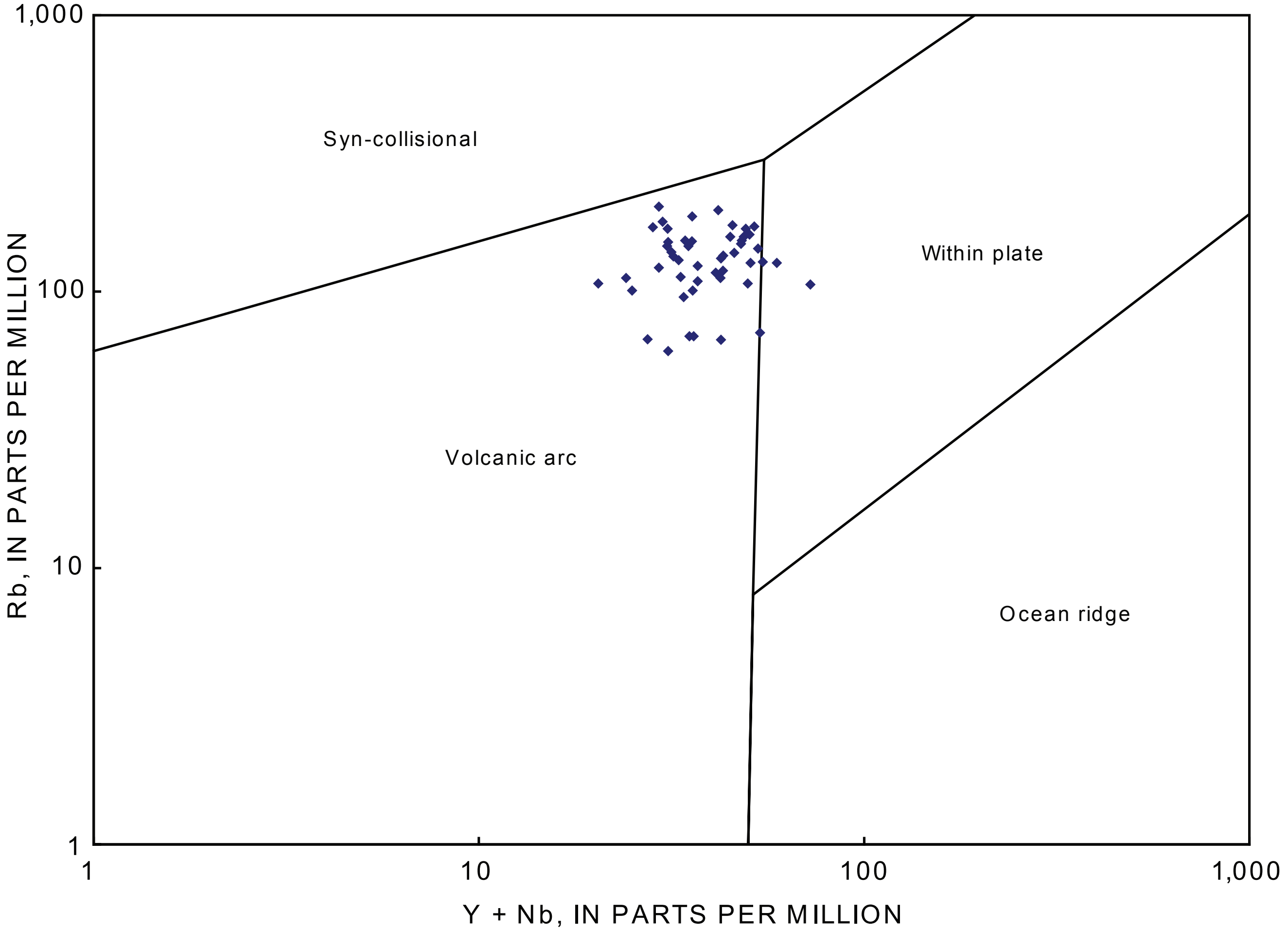

**Figure 6.** Trace-element, tectonic-setting–discrimination variation diagram showing composition of the Boulder batholith and its satellitic plutons, southwest Montana. Tectonic setting-composition boundaries from Pearce and others (1984).

## uncert

The database column titled "uncert" contains data, in millions of years, for the analytical uncertainties (as presented in the source) associated with each of the age determinations reported in the "rad_age" column.

## intrs_name

Most intrusions of the Boulder batholith, especially the largest, are named, either formally or informally; intrusion names are summarized by Smedes and others (1988). Many of the small satellitic plutons are named as well. Sources of names for these intrusions are summarized in the index to source data presented by Smedes and others (1988).

## Plag, Kspar, Qtz, Hb, Pyx, Opx, Cpx, Ol, Bi, Opq, Acc, Acces(incl opq), and Alt

In addition to their geochemical characteristics, the composition of intrusive rocks can be quantified in terms of the relative abundances of the minerals they contain. This type of characterization, modal analysis, is accomplished by point counting either thin sections using a petrographic microscope or stained slabs using a low magnification binocular microscope. The effort involved in conducting these types of modal analyses is time consuming and difficult, with the consequence that this type of data is rarely collected. However, because modal data are precisely the type of information required to classify the composition of phaneritic intrusive rocks (Streckeisen, 1976), these data were compiled as well. This section of the database contains columns for the relative abundances (summing to about 100 percent) in volume percent of plagioclase (Plag), alkali-feldspar (Kspar), quartz (Qtz), hornblende (Hb), pyroxene (Pyx), orthopyroxene (Opx), clinopyroxene (Cpx), olivine (Ol), biotite (Bi), opaque iron-titanium oxide minerals (Opq), accessory minerals, including zircon, titanite, apatite, allanite, and fluorite (Acc), accessory minerals plus opaque minerals (because some sources do not distinguish accessory from opaque minerals) (Acces(incl opq)), and alteration minerals, including epidote, sericite, carbonate minerals, chlorite, clay minerals, zeolite, and anhydrite (Alt). In some cases, sources do not separately quantify opaque mineral abundances; in these instances, opaque mineral abundances are presumed to be components of given accessory mineral abundances. An entry of "tr" in these columns signifies a trace amount, generally less than 0.1 percent, of the indicated constituent; and blank cells indicate that the constituent is not present.

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For more information concerning this publication, contact
Science Center Chief Scientist, USGS Central Region Mineral Resources
Box 25046, Mail Stop 973
Denver, CO 80225
(303) 236-1562

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