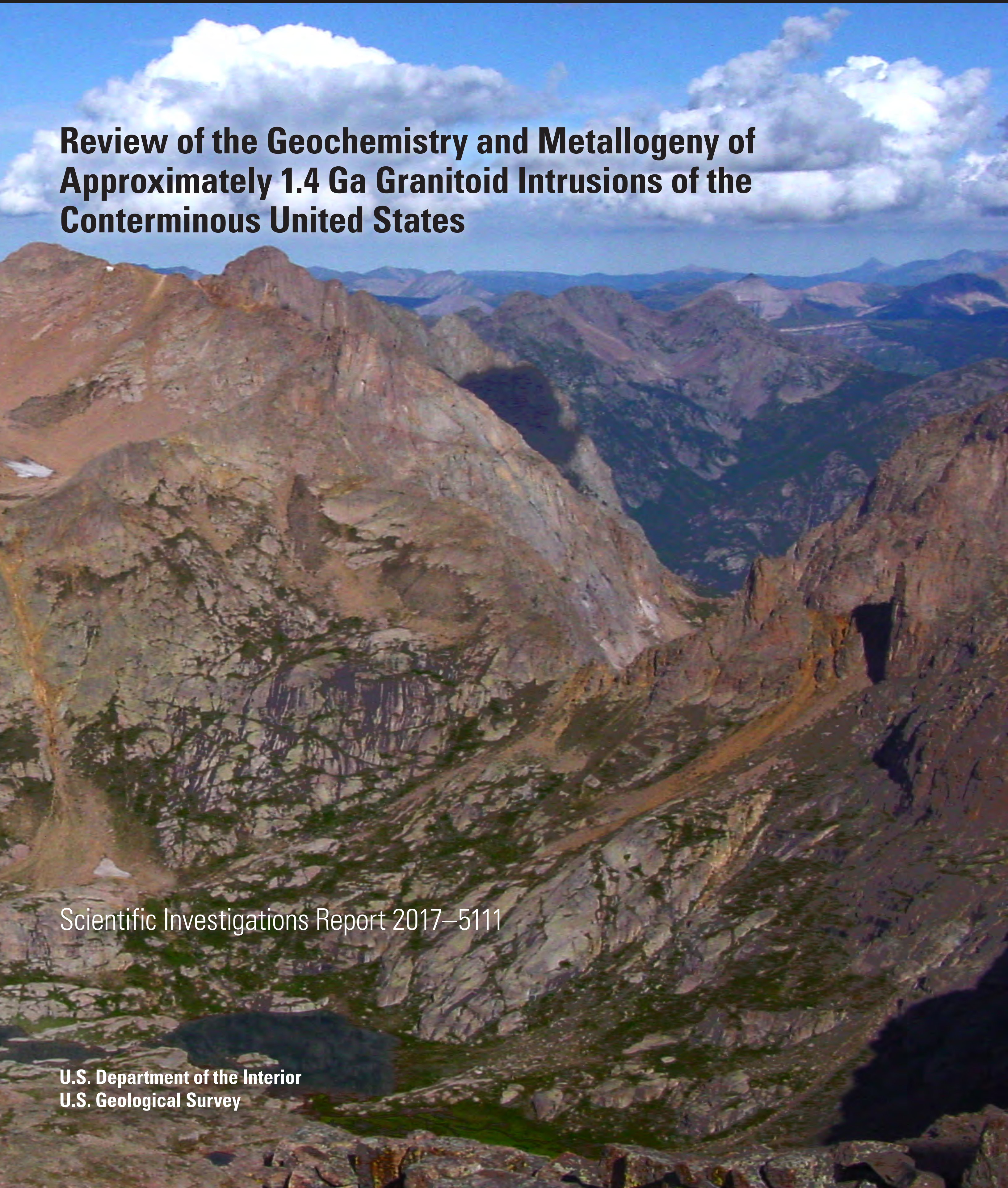
USGS
science for a changing world



Review of the Geochemistry and Metallogeny of Approximately 1.4 Ga Granitoid Intrusions of the Conterminous United States

Scientific Investigations Report 2017–5111

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

Cover. Mesoproterozoic Eolus Granite, Needle Mountains, Colorado. (Photograph by Edward A. du Bray, U.S. Geological Survey.)

Review of the Geochemistry and Metallogeny of Approximately 1.4 Ga Granitoid Intrusions of the Conterminous United States

By Edward A. du Bray, Christopher S. Holm-Denoma, Karen Lund, and Wayne R. Premo

Scientific Investigations Report 2017–5111

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Deputy Director
exercising the authority of the Director

U.S. Geological Survey, Reston, Virginia: 2018

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
du Bray, E.A., Holm-Denoma, C.S., Lund, Karen, and Premo, W.R., 2018, Review of the geochemistry and metallogeny of approximately 1.4 Ga granitoid intrusions of the conterminous United States: U.S. Geological Survey Scientific Investigations Report 2017–5111, 34 p., https://doi.org/sir20175111.

ISSN 2328-0328 (online)

Contents

Figures

Tables

Abbreviations

ASI	alumina saturation index
cm	centimeter
Ga	billion years before present
HREE	heavy rare-earth element
IOA	iron oxide-apatite
IOCG	iron oxide-copper-gold
kbar	kilobar
LILE	large-ion lithophile element
LREE	light rare-earth element
m.y.	million years
Ma	million years ago
MALI	modified alkali-lime index
ppm	part per million
REE	rare-earth element

Elements

Ba	barium
Ca	calcium
Ce	cerium
Cl	chlorine
Co	cobalt
Cr	chromium
Cs	cesium
Cu	copper
Eu	europium
F	fluorine
Fe	iron
Ga	gallium
Hf	hafnium
La	lanthanum
Li	lithium
Lu	lutetium
Mg	magnesium

Mo	molybdenum
Nb	niobium
Nd	neodymium
Ni	nickel
P	phosphorus
Pb	lead
Rb	rubidium
Sc	scandium
Sm	samarium
Sn	tin
Sr	strontium
Ta	tantalum
Th	thorium
Ti	titanium
U	uranium
V	vanadium
W	tungsten
Y	yttrium
Yb	ytterbium
Zn	zinc
Zr	zirconium

Chemical Compounds

Al_2O_3	aluminum oxide
CaO	calcium oxide
FeO*	iron oxide, total as ferrous iron
H_2O	water
K_2O	potassium oxide
MgO	magnesium oxide
MnO	manganese oxide
Na_2O	sodium oxide
P_2O_5	phosphorus pentoxide
SiO_2	silicon dioxide
TiO_2	titanium dioxide

Review of the Geochemistry and Metallogeny of Approximately 1.4 Ga Granitoid Intrusions of the Conterminous United States

By Edward A. du Bray, Christopher S. Holm-Denoma, Karen Lund, and Wayne R. Premo

Abstract

The conterminous United States hosts numerous volumetrically significant and geographically dispersed granitoid intrusions that range in age from 1.50 to 1.32 billion years before present (Ga). Although previously referred to as A-type granites, most are better described as ferroan granites. These granitoid intrusions are distributed in the northern and central Rocky Mountains, the Southwest, the northern midcontinent, and a swath largely buried beneath Phanerozoic cover across the Great Plains and into the southern midcontinent. These intrusions, with ages that are bimodally distributed between about 1.455–1.405 Ga and 1.405–1.320 Ga, are dispersed nonsystematically with respect to age across their spatial extents. Globally, although A-type or ferroan granites are genetically associated with rare-metal deposits, most U.S. 1.4 Ga granitoid intrusions do not contain significant deposits. Exceptions are the light rare-earth element deposit at Mountain Pass, California, and the iron oxide-apatite and iron oxide-copper-gold deposits in southeast Missouri.

Most of the U.S. 1.4 Ga granitoid intrusions are composed of hornblende ± biotite or biotite ± muscovite monzogranite, commonly with prominent alkali feldspar megacrysts; however, modal compositions vary widely. These intrusions include six of the eight commonly identified subtypes of ferroan granite: alkali-calcic and calc-alkalic peraluminous subtypes; alkalic, alkali-calcic, and calc-alkalic metaluminous subtypes; and the alkalic peralkaline subtype. The U.S. 1.4 Ga granitoid intrusions also include variants of these subtypes that have weakly magnesian compositions. Extreme large-ion lithophile element enrichments typical of ferroan granites elsewhere are absent among these intrusions. Chondrite-normalized rare-earth element patterns for these intrusions have modest negative slopes and moderately developed negative europium anomalies. Their radiogenic isotopic compositions are consistent with mixing involving primitive, mantle-derived components and evolved, crust-derived components.

Each compositional subtype can be ascribed to a relatively unique petrogenetic history. The numerically dominant ferroan, peraluminous granites probably represent low-degree, relatively high-pressure partial melting of preexisting, crust-derived, intermediate-composition granitoids. The moderately numerous, weakly magnesian, peraluminous granites probably reflect similar partial melting but at a higher degree and in a lower pressure environment. In contrast, the ferroan but metaluminous granites may be the result of extensive differentiation of tholeiitic basalt. Finally, the peralkaline igneous rocks at Mountain Pass have compositions potentially derived by differentiation of alkali basalt. The varying alkalic character of each subtype probably reflects polybaric petrogenesis and the corresponding effect of diverse mineral stabilities on ultimate melt compositions. Mantle-derived mafic magma and variably assimilated partial melts of mainly juvenile Paleoproterozoic crustal components are required to generate the relatively low initial strontium ($^{87}Sr/^{86}Sr$) and distinctive neodymium isotope compositions characteristic of the U.S. 1.4 Ga granitoid intrusions. The characteristics of these intrusions are consistent with crustal melting in an extensional/decompressional, intracratonic setting that was triggered by mantle upwelling and emplacement of tholeiitic basaltic magma at or near the base of the crust. Composite magmas, formed by mingling and mixing mantle components with partial melts of Paleoproterozoic crust, produced variably homogenized storage reservoirs that continued polybaric evolution as intrusions lodged at various crustal depths.

Introduction

The geology of the United States, exclusive of Alaska and Hawaii, includes an aerially extensive group of generally felsic plutonic rocks whose ages cluster between about 1.50 and 1.32 billion years before present (Ga) (fig. 1). Globally, these intrusions are an especially prominent component of the Earth's geologic history because plutonism immediately before or after 1.4 Ga is volumetrically minor. The majority of these intrusions have been identified as A-type granites (Anderson, 1983; Anderson and Bender, 1989). More recently, Frost and Frost (2011) suggested that the A-type granite nomenclature has become confused to the point of

Base from U. S. Geological Survey digital data, 2017
Albers Equal-Area Conic projection
Standard parallels 29°30′ N. and 45°30′ N.
Central meridian 96°00′ W.
North American Datum of 1983

Figure 1. Map showing the spatial distribution of 1.4 Ga granitoid intrusions in the conterminous United States (du Bray and others, 2015). Dotted lines and corresponding names identify the six physiographic regions within the conterminous United States in which 1.4 Ga granitoid intrusions are present. The 1.4 Ga rocks at Mountain Pass, California, are not shown because the corresponding intrusions are very small and were not delineated on the geologic map that was the source for this figure. (Ga, billion years before present)

non-usefulness by the inclusion of diverse igneous rocks that have varying compositional characteristics and petrogenetic histories. They proposed that many of the igneous rocks previously described as A-type, including many of the 1.4 Ga granitoid intrusions in the conterminous United States, are better referred to as ferroan granites. Diagnostically, relative to other granitic rocks, ferroan granites have high ratios of iron to iron + magnesium (Fe/(Fe+Mg)), they are metaluminous to weakly peraluminous, and most formed in an intracontinental setting (Frost and Frost, 2011; Bickford and others, 2015). Importantly, 1.4 Ga granitoid intrusions in the conterminous United States (hereafter referred to as the 1.4 Ga intrusions) also include some that are weakly magnesian; relative abundances of FeO* and MgO in these intrusions are part of the compositional continuum that includes those that are definitively ferroan and others that have compositions that are transitional from ferroan to magnesian.

The first synthesis of the compositions, ages, isotope geochemistry, and petrographic characteristics of these intrusions was completed by Anderson (1983). There was no other substantial synthesis of data pertaining to these rocks until du Bray and others (2015) compiled, from a diverse collection of sources, a database that includes geochemical, petrographic, and isotopic data for almost 1,200 samples of the 1.4 Ga intrusions. Data for these samples were synthesized to support interpretations concerning the petrogenetic processes and tectonic setting responsible for the magmatism described herein. The type and quantity of geochemical and geochronologic data available for each 1.4 Ga intrusion are documented in the compilation of du Bray and others (2015). The interpreted dataset includes analyses from all pertinent sources and may include biases introduced by more intense sampling in some areas and less complete sampling in others. All analyses were evaluated relative to standard geochemical metrics (du Bray and others, 2015), and altered samples were removed from the interpreted dataset.

The suite of 1.4 Ga intrusions identified in the compilation of du Bray and others (2015) was defined using a variety of spatial, compositional, and geochronologic criteria. Most of these 1.4 Ga intrusions are felsic, although a few have more intermediate compositions. They characteristically are composed of medium- to coarse-grained granite (Streckeisen, 1976), and many contain conspicuous alkali feldspar phenocrysts. In some parts of the conterminous United States, mafic to felsic volcanic rocks are temporally, spatially, and likely genetically associated with the 1.4 Ga intrusions (Kisvarsanyi, 1972; Day and others, 2016). Mafic intrusive rocks may also be coeval and cospatial with the 1.4 Ga intrusions (Anderson, 1983) elsewhere in the conterminous United States, but the petrogenesis of these mafic intrusive rocks is beyond the scope of this investigation.

Ages of most Proterozoic intrusions in North America range from about 1.8 to 1.0 Ga, although Anderson (1983) suggested that more than 70 percent (by volume) of this magmatism occurred between 1.49 and 1.41 Ga. In the conterminous United States, this magmatic episode is largely restricted to between about 1.5 and 1.32 Ga (Peterman and Hedge, 1968; Bickford and Mose, 1975; Van Schmus and others, 1975; Bickford and others, 1981; Van Schmus and Bickford, 1981; Anderson, 1983; Hoppe and others, 1983; Bickford and others, 1989; Bauer and Pollock, 1993; Dewane and Van Schmus, 2007; Bickford and others, 2015). A belt of Mesoproterozoic rocks (approx. 1.4–0.95 Ga) form inliers in the eastern United States from central Vermont to central Georgia. However, lead (Pb) and neodymium (Nd) isotopic investigations (Loewy and others, 2003; Tohver and others, 2004) suggest that the basement rocks of the central and southern Appalachians do not represent North American magmatism. These rocks have been interpreted as allochthonous, having been accreted to Laurentia between 1.25 and 1.0 Ga (Thomas and others, 2012), and are not further considered herein.

Some of the 1.4 Ga intrusions are spatially and perhaps genetically associated with mineral deposits. Common iron oxide-apatite (IOA) and rare iron oxide-copper-gold (IOCG) deposits hosted in felsic volcanic rocks in the St. Francois Mountains of southeastern Missouri may be petrogenetically related to the 1.4 Ga intrusions in that region (Kisvarsanyi, 1972; Day and others, 2016). Similarly, the light rare-earth element (LREE) deposit at Mountain Pass, Calif., is also broadly associated with the 1.4 Ga intrusions (Castor, 2008; Poletti and others, 2016). Dall'Agnol and others (2012) summarized important global associations between A-type rocks (and broadly synonymous ferroan granites) and a variety of important ore deposit types, particularly tin (Sn), high-field-strength elements (zirconium [Zr], hafnium [Hf], niobium [Nb], tantalum [Ta], and the rare-earth elements [REEs]), and IOCG deposits.

The significance of the 1.4 Ga intrusions relative to the geologic evolution of the conterminous United States remains uncertain despite previous petrogenetic studies (Anderson, 1983; Anderson and Bender, 1989; Bickford and others, 2015). They are exposed in the northern midcontinent, in the southwestern United States (New Mexico, Arizona, California, and southernmost Nevada), and throughout the Rocky Mountains (in a corridor that extends from New Mexico through Colorado and into southern Wyoming). A restricted area in central Idaho and (as indicated by drilling) a broad region beneath much of the Great Plains region also include 1.4 Ga intrusions. The broad distribution of the 1.4 Ga intrusions likely reflects province-scale tectonic and magmatic processes. In order to more fully comprehend the significance of the 1.4 Ga intrusions, our study explores their compositional systematics to constrain (1) prevailing tectonic setting, (2) petrogenesis, and (3) genetic associations with important mineral deposit types.

Tectonic Setting

Ferroan granitoid magmatism in the United States was most voluminous during the Mesoproterozoic, which corresponds to global peak volumes and distribution of ferroan granitoid magmatism (Dall'Agnol and others, 2012). The 1.4 Ga intrusions in the United States are interpreted to have been emplaced in an intracratonic setting within broad domains composed of Paleoproterozoic (1.9–1.6 Ga) juvenile continental crust fringing the southern and western boundaries of the older Laurentian craton (Condie, 1982). These domains, formed during the early and middle phases of supercontinent Columbia fragmentation, include the Wisconsin magmatic zone, Great Plains (Yavapai) domain, Great Falls domain, and Wallace domain, all of which formed at about 1.85–1.72 Ga; the Mojave domain, which formed at about 1.84 Ga; the Mazatzal domain, which formed at 1.72–1.65 Ga; and the most outboard Shawnee (granite-rhyolite) domain, which formed at about 1.6–1.55 Ga (Whitmeyer and Karlstrom, 2007; Lund and others, 2015; and references in both). Emplacement of the 1.4 Ga intrusions was coeval with the final stages of supercontinent Columbia (Nuna) fragmentation and was completed before the beginning of amalgamation of supercontinent Rodinia (Rogers and Santosh, 2002).

Paleogeographic locations and host rock characteristics suggest that ferroan magmatism was confined to intracontinental or intraplate settings (Loiselle and Wones, 1979). The 1.4 Ga intrusions were not deformed during emplacement, which reflects the absence of compressional tectonism. In addition, their particular geochemical characteristics are unlike those of intrusions generated in other tectonic environments, especially plutons associated with arc magmatism. Some of the 1.4 Ga intrusions are spatially associated with coeval mafic igneous rocks (Anderson, 1983). Together, these felsic and mafic igneous rocks form bimodal magmatic associations that are similar to those commonly identified in intracratonic settings; as such, the 1.4 Ga intrusions and the related mafic rocks are also consistent with magmatism in intracratonic settings. These settings, where regional extension (rifting) or transtension caused by oblique collision and related slab breakoff and foundering prevail (Dall'Agnol and others, 2012, and references therein), may reflect lower crustal melting due to basalt underplating (Frost and Frost, 2011). The tectonic processes responsible for juvenile, host-domain growth and the tectonic setting prevailing during bimodal magmatism may have been essential for the development of voluminous 1.4 Ga ferroan magmatism within broad zones of newly created Paleoproterozoic crust.

Petrographic Characteristics

Quartz-alkali feldspar-plagioclase modal data indicate that the 1.4 Ga intrusions are predominantly composed of monzogranite, although many are composed of granodiorite and syenogranite (fig. 2). Fewer are composed of quartz monzodiorite and quartz monzonite, and a very small subset is

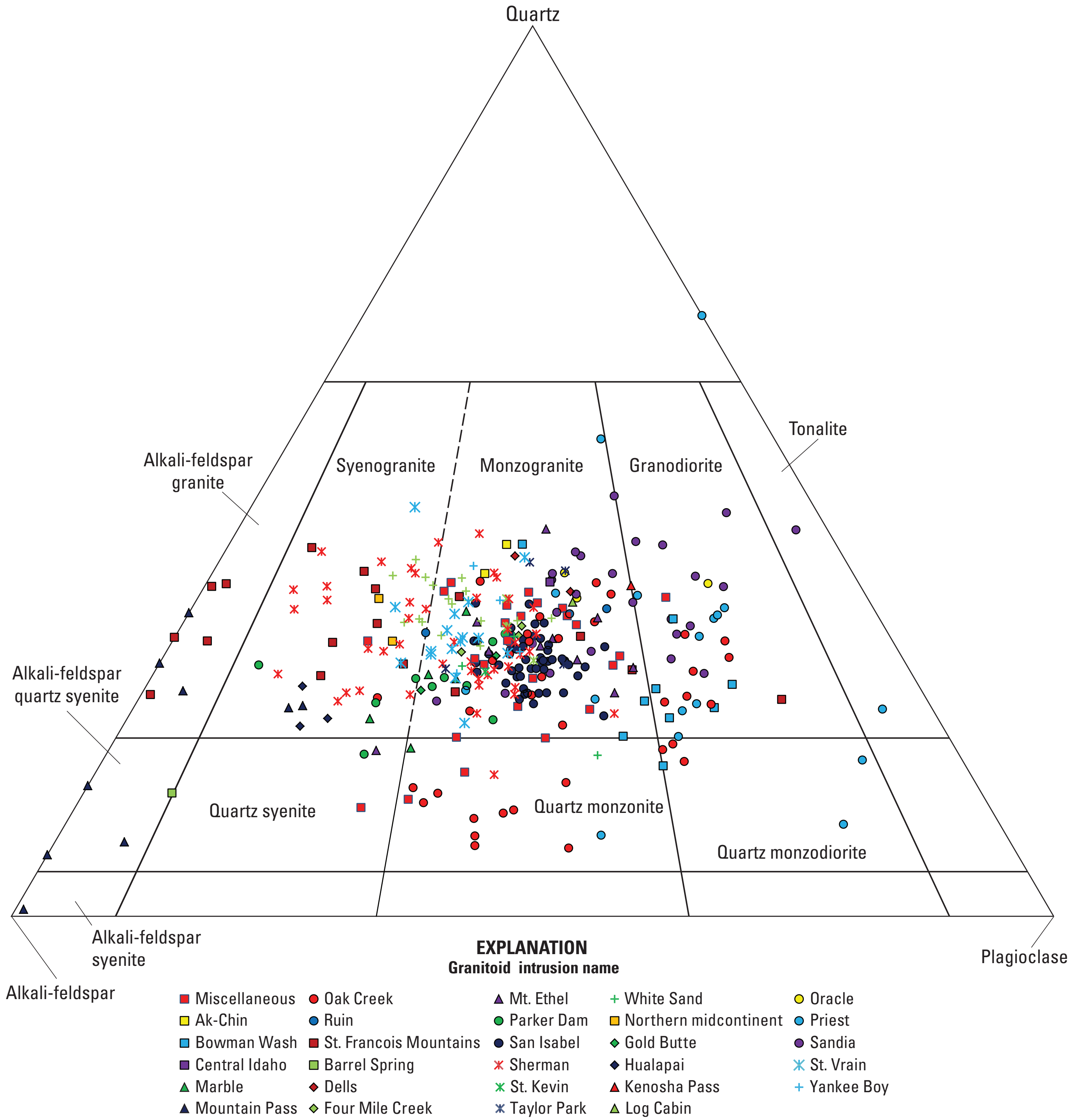


Figure 2. Quartz-alkali feldspar-plagioclase ternary diagram showing modal compositions of 1.4 Ga granitoid intrusions of the conterminous United States. Classification grid and rock names are from Streckeisen (1976). (Ga, billion years before present)

composed of alkali-feldspar granite, tonalite, quartz syenite, or alkali-feldspar quartz syenite (fig. 2). Most of the 1.4 Ga intrusions are medium- to coarse-grained, hypidiomorphic, and inequigranular. Many contain conspicuous, variably perthitic alkali feldspar phenocrysts or megacrysts (2–10 centimeters [cm]), commonly with rapakivi texture (Anderson and Cullers, 1978; Condie and Budding, 1979; Anderson, 1983; Anderson and Bender, 1989). Strongly exsolved alkali feldspar is common in many of these intrusions and is consistent with cooling and solidification in shallow, relatively dry crustal reservoirs favorable for hypersolvus alkali feldspar crystallization. Some of the most peraluminous 1.4 Ga intrusions contain small amounts of almandine-spessartine garnet.

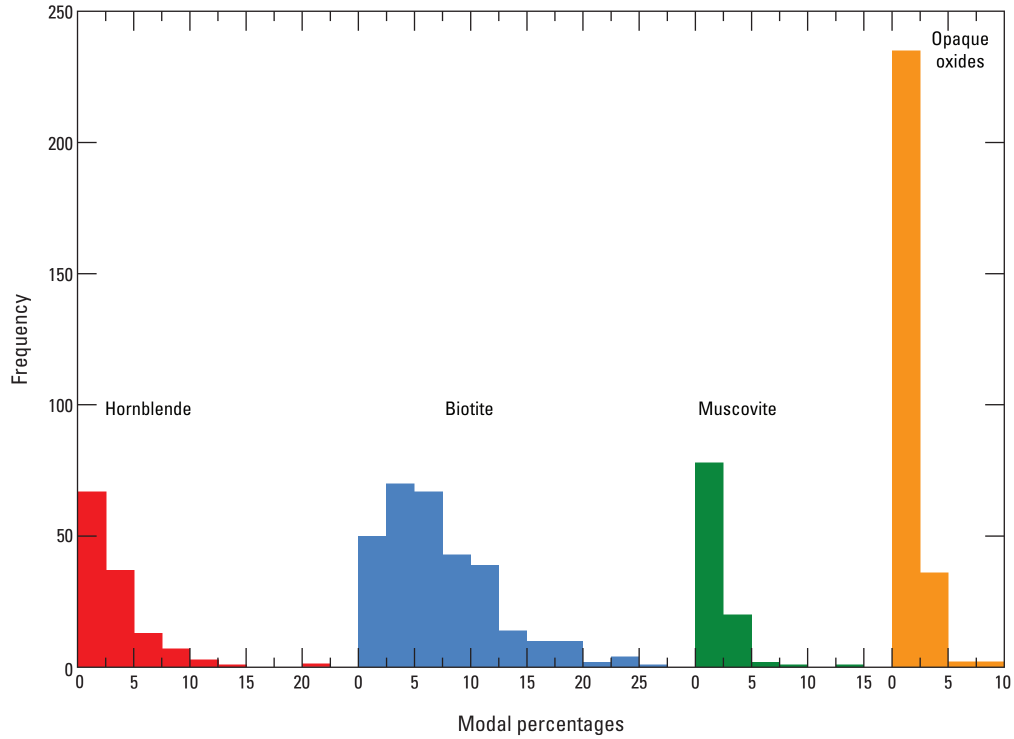


Figure 3. Frequency histogram showing the relative abundances of hornblende, biotite, muscovite, and opaque oxides in 1.4 Ga granitoid intrusions of the conterminous United States. Bins represent 2.5 percent modal abundance ranges, and numbers beneath each bin reflect the maximum modal abundance associated with each bar. (Ga, billion years before present)

The 1.4 Ga granitoids in the United States contain variable mafic silicate and opaque oxide mineral suites, have unusually elevated accessory mineral abundances, and commonly display the effects of weak deuteric alteration. Mafic silicate assemblages include variable amounts of biotite and hornblende or biotite and muscovite. Biotite/hornblende and biotite/muscovite (median 3.0, both ratios) are highly variable, but biotite is usually the predominant mafic silicate in most of the 1.4 Ga intrusions (fig. 3). Among samples in which hornblende, biotite, muscovite, or opaque oxides were identified, median quantities are 2.5, 6.5, 1.1, and 1.2 percent, respectively. A subset of 1.4 Ga granitoids that extends from central Arizona northward into the Colorado Rocky Mountains has been distinguished because of elevated muscovite content (Anderson and Bender, 1989). The compilation of du Bray and others (2015) confirms and refines this domain of biotite- and (or) muscovite-bearing 1.4 Ga granitoid intrusions. Paleoproterozoic rocks that host and probably contributed to the petrogenesis of the relatively muscovite-rich 1.4 Ga intrusions are characterized by greenschist facies mineral assemblages. Partial melting involving the low-grade mineral assemblages characteristic of these 1.4 Ga intrusions apparently fostered enhanced muscovite content of the 1.4 Ga intrusions contained therein. Pyroxene is absent in essentially all of the 1.4 Ga intrusions, although some silicate intrusive rocks associated with the REE-enriched carbonatite rocks at Mountain Pass, Calif., contain diopside (Castor, 2008). Magnetite is the predominant opaque iron-titanium (Fe-Ti) oxide mineral in most of the 1.4 Ga intrusions and is principally responsible for approximately circular magnetic anomalies associated with many of these intrusions (Bankey and others, 2002). The predominance of magnetite over ilmenite in these intrusions is consistent with their petrogenesis in characteristically oxidizing environments. The 1.4 Ga intrusions contain variable accessory mineral assemblages, commonly including apatite, zircon, allanite, and titanite; less common accessory minerals include monazite, thorite, tourmaline, cordierite, corundum, and sillimanite. Secondary epidote, chlorite, actinolite, and sericite reflect weak postmagmatic alteration of some of these intrusions.

Age Distribution

Ages of the 1.4 Ga intrusions span the 1.50–1.32 Ga interval. This period includes two, and perhaps as many as three, age populations, each representing a distinct magmatic pulse (fig. 4). The 1.455–1.405 Ga interval defines the period during which apparently the largest number of these intrusions were emplaced in the conterminous United States; within this interval, magmatism was most voluminous at about 1.440 Ga. The interval 1.405–1.320 Ga (peak magmatism at about 1.370 Ga) constitutes a second, somewhat less important age population. A third age population, about 1.500–1.455 Ga, overlaps in time with the beginning of the 1.455–1.405 Ga episode and may define a third, much less significant magmatic event in the conterminous United States. Whether this third population is distinct from the principal, slightly younger population or is simply an older subset of the principal population remains uncertain. However, 1.4 Ga magmatism in the United States seems to have been essentially continuous from 1.50 to 1.32 Ga; the 1.405–1.395 Ga interval constitutes the closest approximation to a magmatic hiatus during this almost 200-million-year (m.y.) magmatic episode.

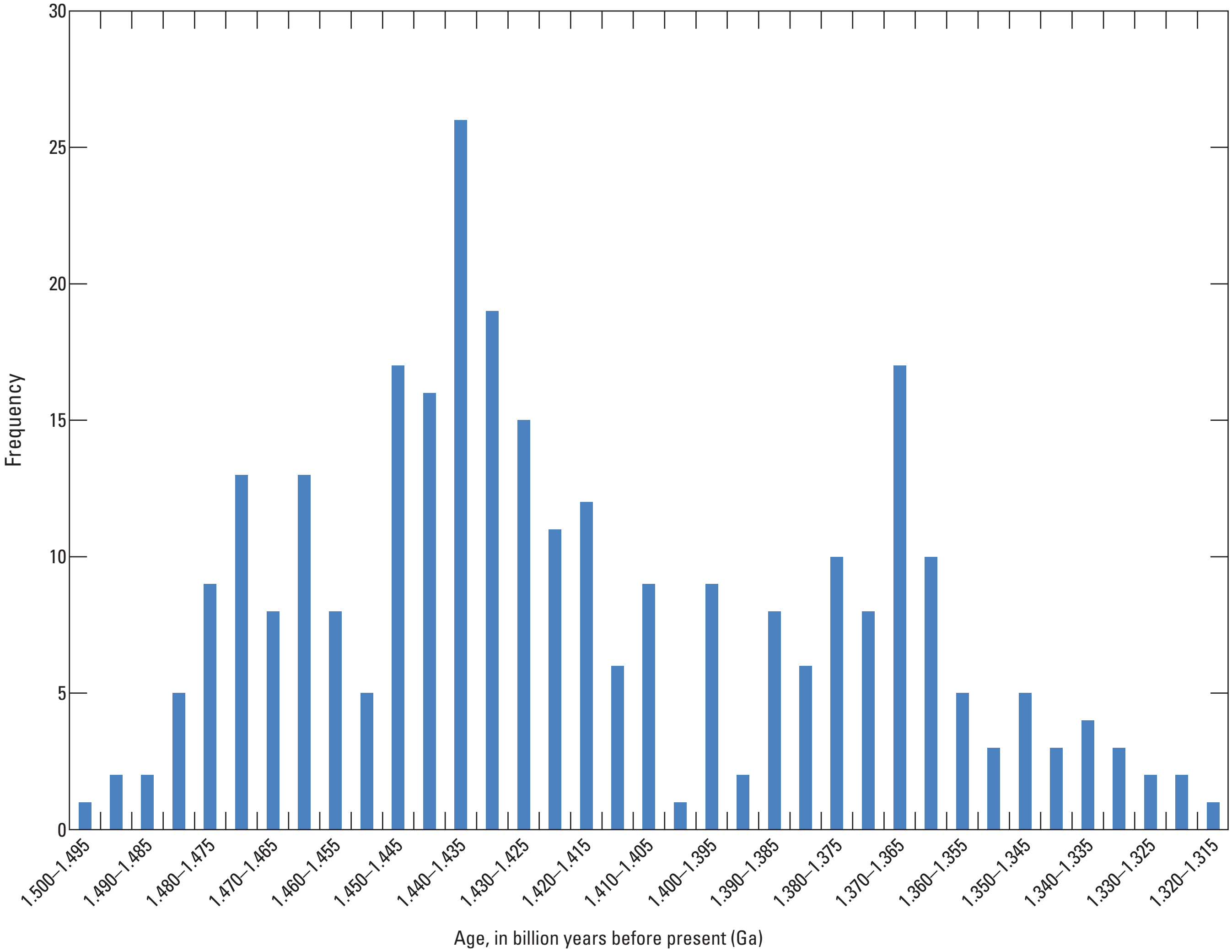


Figure 4. Histogram showing the temporal distribution of broadly 1.4 Ga granitoid intrusions of the conterminous United States (du Bray and others, 2015). (Ga, billion years before present)

Time-Space Relations

Broadly 1.4 Ga magmatism in the conterminous United States was neither continuous nor synchronous throughout the geographic extent of these intrusions. Rather, magmatism waxed and waned through this 200-m.y. interval, with different parts of the conterminous United States becoming predominant magmatic loci during specific age intervals. The large area within the United States that hosts the 1.4 Ga intrusions is divisible into half a dozen distinct physiographic domains. These include the northern Rocky Mountains, central Rocky Mountains, northern midcontinent, southern midcontinent, Great Plains, and Southwest provinces (fig. 1). Available age determinations (du Bray and others, 2015) were parsed to these six regions and binned in 10-m.y. increments (table 1); we assume that the number of age determinations in each 10-m.y. bin, for each of the physiographic provinces, constitutes a reasonably accurate representation of the age and spatial distribution of 1.4 Ga magmatism in the conterminous United States. Accordingly, about a third of the age determinations, and presumably therefore about a third of the broadly 1.4 Ga magmatism known in the conterminous United States, occurred in the central Rocky Mountains physiographic province (table 1). Known 1.4 Ga intrusions in the Great Plains and Southwest physiographic provinces are about half as numerous as those in the central Rocky Mountains region. Significantly fewer 1.4 Ga intrusions are known to have been emplaced in the northern and southern midcontinent regions and especially in the northern Rocky Mountain province than in the central Rocky Mountains. As the distribution of the 1.4 Ga intrusions becomes better established beneath covered areas, especially those in the midcontinent region that are covered by Paleozoic sedimentary rocks, these relations may evolve.

Table 1. Numbers of age determinations by age in billion years before present (Ga), in 10-million-year increments (age bins), for 1.4 Ga granitoid intrusions of the conterminous United States, by region.

[Data from du Bray and others (2015). Ga, billion years before present]

Region	<1.50 Ga	<1.49 Ga	<1.48 Ga	<1.47 Ga	<1.46 Ga	<1.45 Ga	<1.44 Ga	<1.43 Ga	<1.42 Ga	<1.41 Ga	<1.4 Ga	<1.39 Ga	<1.38 Ga	<1.37 Ga	<1.36 Ga	<1.35 Ga	<1.34 Ga	<1.33 Ga	Totals
Northern Rocky Mountains	0	0	0	0	0	0	0	0	0	0	0	0	4	3	1	0	0	0	8
Central Rocky Mountains	0	3	4	3	5	24	31	15	4	2	7	1	1	1	1	1	1	0	104
Northern midcontinent	0	2	10	6	3	1	1	0	0	1	0	0	0	0	0	0	0	0	24
Southern midcontinent	2	5	4	7	3	1	0	0	0	1	0	1	4	4	1	2	0	2	37
Southwest	0	0	1	5	8	3	3	10	12	5	2	0	0	1	3	0	2	3	58
Great Plains	0	0	1	2	2	2	5	2	1	1	4	10	16	6	4	3	4	0	63
Totals	2	10	20	23	21	31	40	27	17	10	13	12	25	15	10	6	7	5	294

The distribution of ages for broadly 1.4 Ga intrusions within particular regions of the conterminous United States, when considered in 10-m.y. increments, confirms the variability of magmatism in time and space (fig. 5). For instance, 1.4 Ga magmatism in the northern Rocky Mountains is confined to a relatively small area in central Idaho and to a brief interval, between about 1.38 and 1.36 Ga. In contrast, 1.4 Ga magmatism in the central Rocky Mountains was essentially continuous in this large area between about 1.5 and 1.34 Ga, but magmatic activity was greatest during the 1.45–1.42 Ga interval. The central Rocky Mountain region was the locus of a second, less significant magmatic pulse at about 1.40 Ga. In the northern midcontinent region, magmatism was largely restricted to the 1.48–1.45 Ga interval. In the southern midcontinent region, magmatism is temporally bimodal. The older magmatic phase is largely limited to the 1.49–1.45 Ga interval. Following a magmatic hiatus of about 60 m.y., magmatism in the southern midcontinent region resumed and peaked between 1.38 and 1.36 Ga. In the Southwest province, protracted magmatism between 1.47 and 1.40 Ga, with a peak between about 1.43 and 1.41 Ga, was continuous across the southern midcontinent magmatic hiatus. The Southwest region also hosted a second, temporally more diffuse magmatic episode between about 1.37 and 1.32 Ga. In the Great Plains region, like in the central Rocky Mountains region, magmatism was apparently continuous between about 1.48 and 1.30 Ga and peaked between about 1.39 and 1.36 Ga. Accordingly, the overall distribution of felsic 1.4 Ga magmatism in the conterminous United States seems to vary in a nonsystematic fashion with respect to time and space (fig. 6). A robust analysis of the distribution of magmatism in time and space is impeded by discontinuous exposure of Mesoproterozoic rocks across the United States, particularly in the midcontinent region where exposures are especially scarce.

Whole Rock Geochemistry

Major Oxide Data

The 1.4 Ga intrusions have felsic through intermediate compositions. The range of SiO_2 contents varies continuously from 56 to almost 78 weight percent; about 69 percent of the analyzed samples contain greater than 70 weight percent SiO_2, and median and mean SiO_2 contents are 72.0 and 71.1 weight percent, respectively. The majority of these intrusions are subalkaline (Irvine and Baragar, 1971), although samples of the Mountain Pass and Barrel Springs intrusions have consistently alkaline compositions (fig. 7). The median Na_2O/K_2O value for the 1.4 Ga intrusions is 0.64, and relative K_2O enrichment is essentially invariant with respect to SiO_2 content. Alumina saturation indices (ASIs, molar $Al_2O_3/(Na_2O+K_2O+CaO)$) of these intrusions (fig. 8) straddle the metaluminous-peraluminous boundary (median ASI=1.03), but at least 65 percent of analyzed samples are weakly peraluminous (Shand, 1951), and 23 percent are strongly peraluminous (ASI>1.1). In contrast, the Mountain Pass rocks are distinctly peralkaline (Shand, 1951) (molar $(Na_2O+K_2O)/Al_2O_3$ >1). Relative to the modified alkali-lime index (MALI; Frost and others, 2001), compositions of most 1.4 Ga granitoids are calc-alkalic to alkali-calcic (fig. 9); a small number of samples are calcic, whereas about half of all Mountain Pass and Oak Creek samples and all Barrel Springs samples are alkalic.

Traditionally (Anderson, 1983), the 1.4 Ga intrusions were identified as having A-type (Loiselle and Wones, 1979) compositions, which are broadly synonymous with "ferroan" (tholeiitic) granites (Frost and Frost, 2011). Indeed, most of the 1.4 Ga intrusions are ferroan, although about a third of the analyzed samples are weakly magnesian (calc-alkaline), most having compositions within 0.05 FeO*/(FeO*+MgO) units of the magnesian-ferroan boundary (fig. 10). Notably, the transition

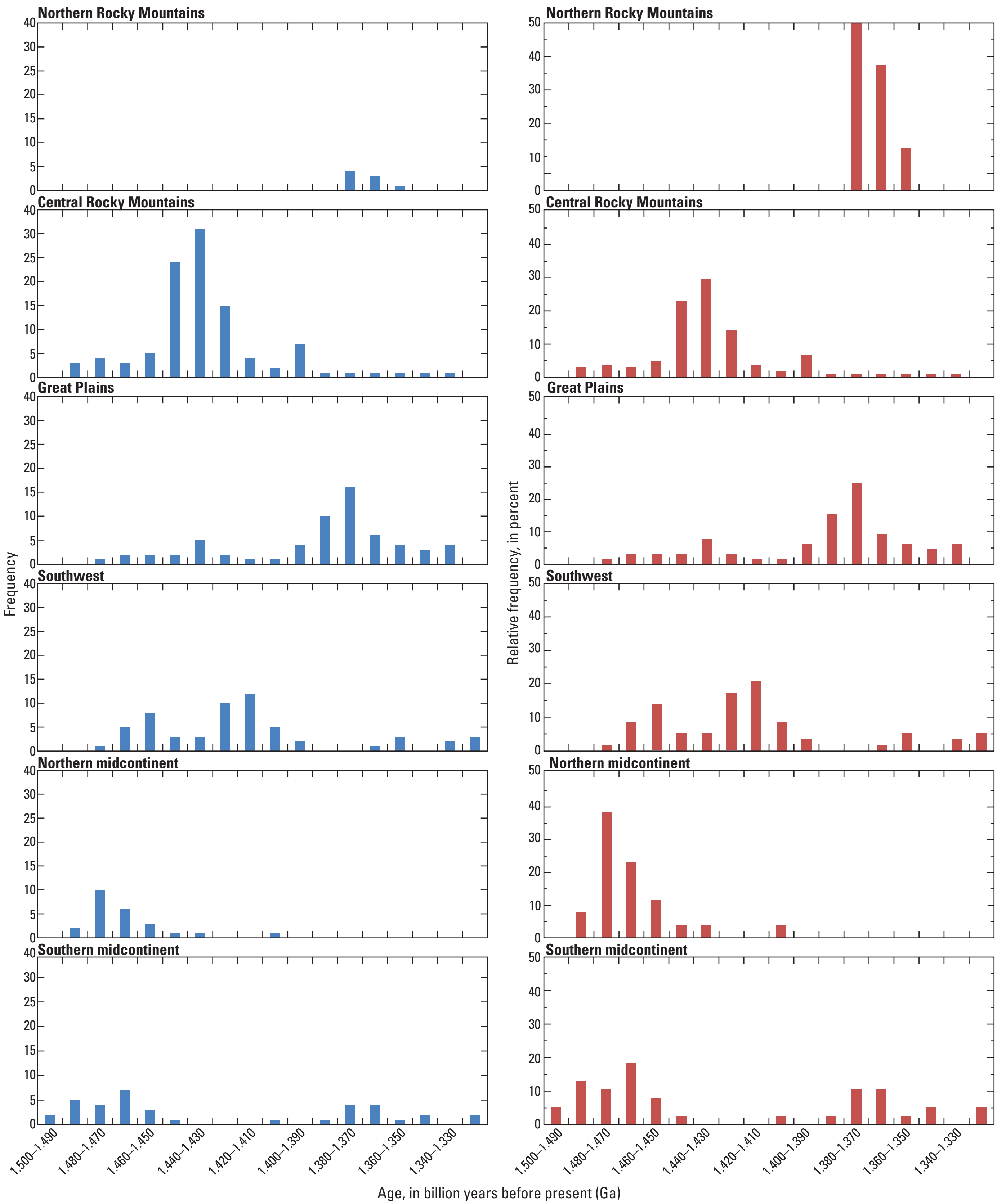


Figure 5. Histograms showing the temporal distribution, by region, of broadly 1.4 Ga granitoid intrusions of the conterminous United States (du Bray and others, 2015). (Ga, billion years before present)

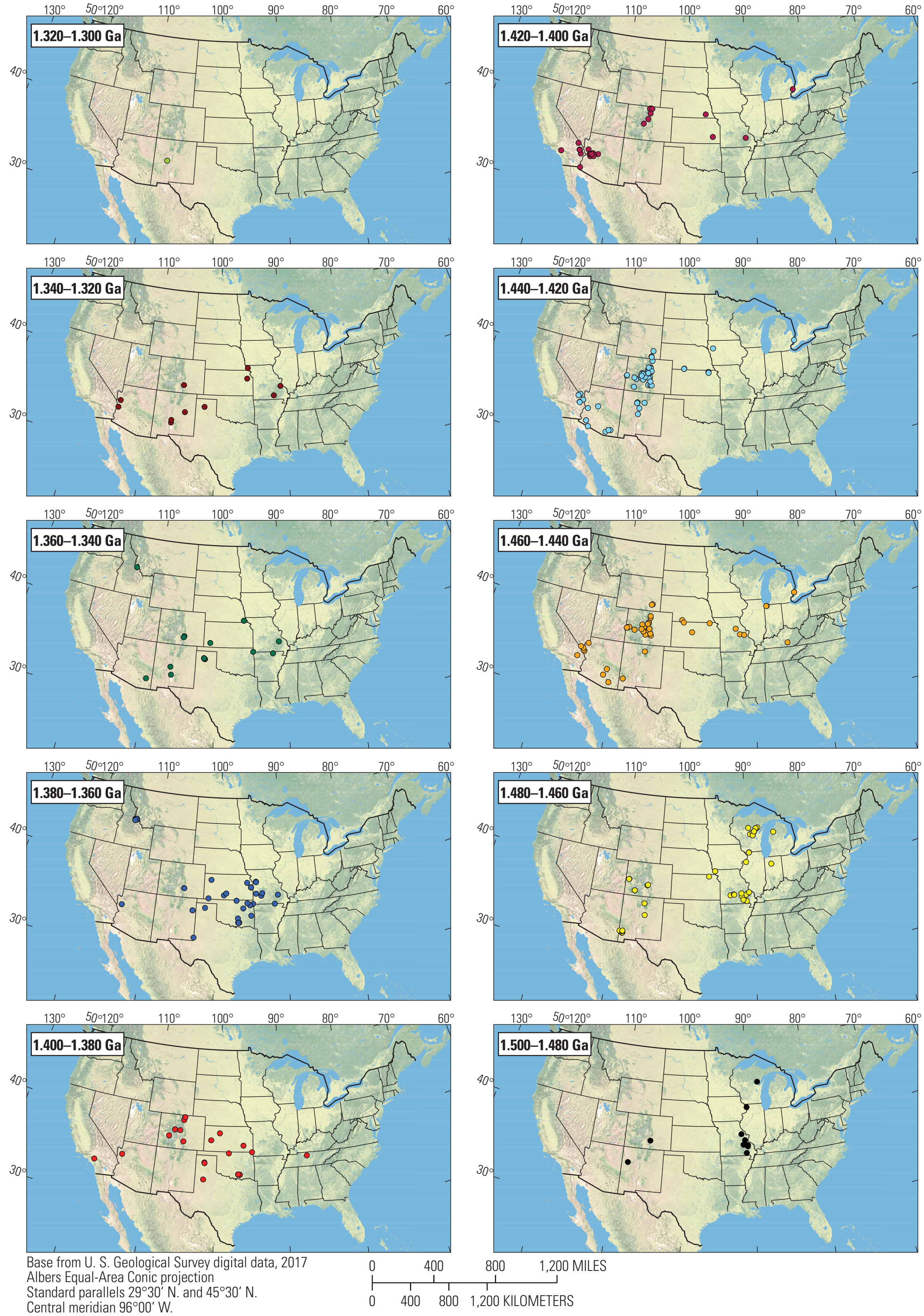


Figure 6. Maps showing the geographic distribution of broadly 1.4 Ga granitoid intrusions of the conterminous United States with respect to time. (Ga, billion years before present)

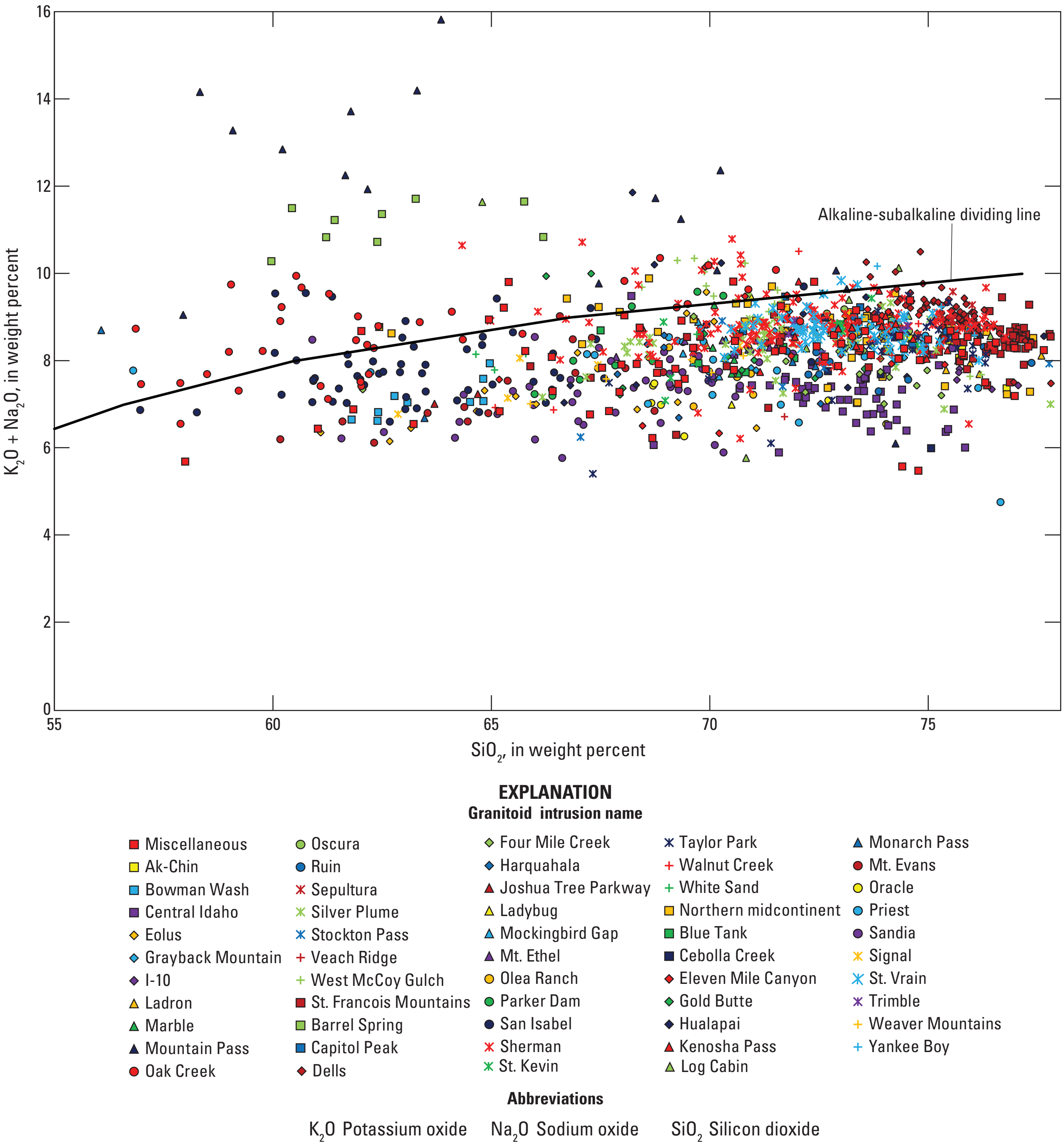


Figure 7. Total alkali-silica variation diagram showing compositions of 1.4 Ga granitoid intrusions of the conterminous United States. Alkaline-subalkaline dividing line from Irvine and Baragar (1971). (Ga, billion years before present)

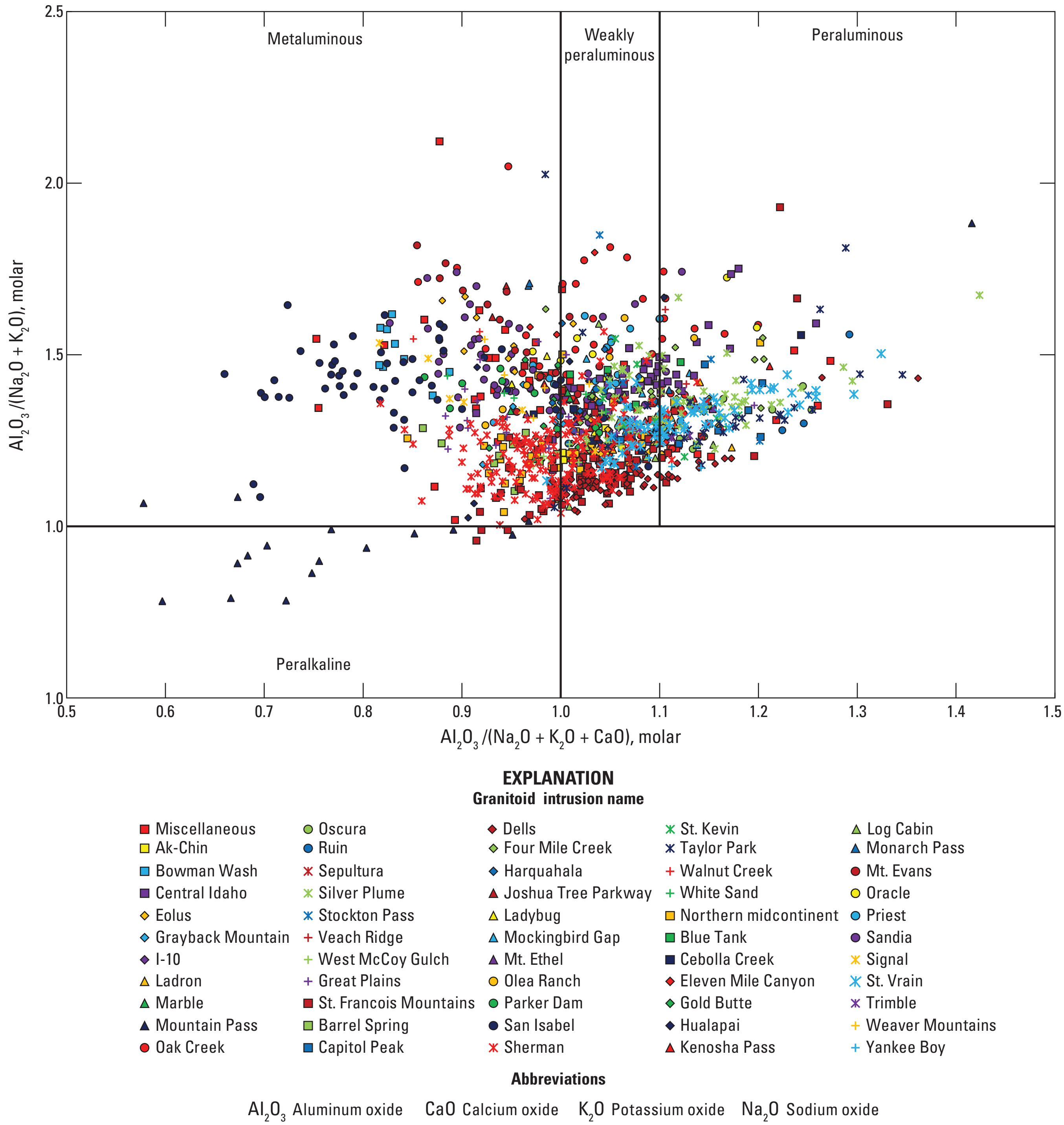


Figure 8. Variation diagram showing molar major-oxide compositions of 1.4 Ga granitoid intrusions of the conterminous United States as a function of relative alumina and alkali saturation. (Ga, billion years before present)

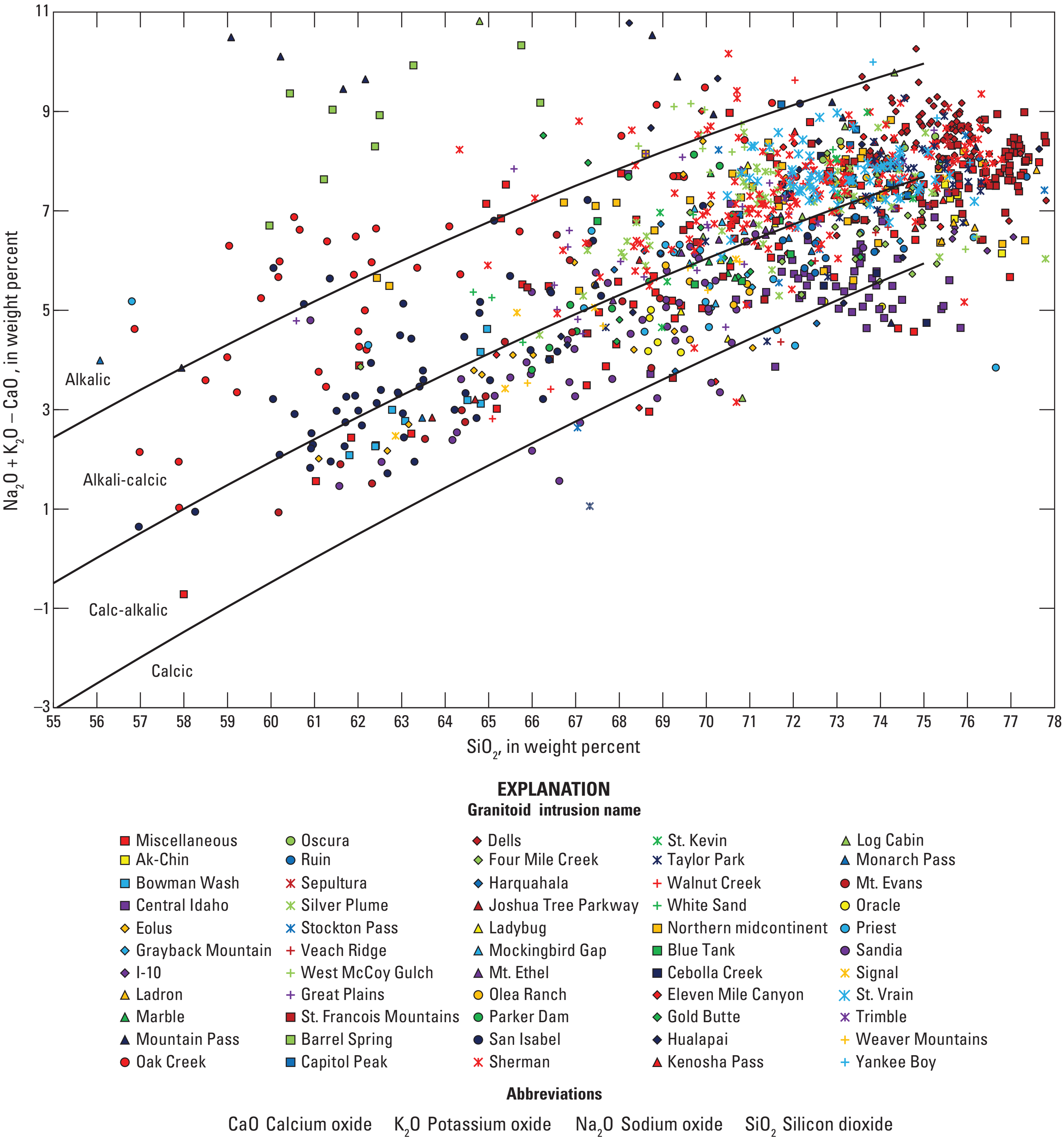


Figure 9. $Na_2O+K_2O–CaO$ versus SiO_2 variation diagram showing the compositions of 1.4 Ga granitoid intrusions of the conterminous United States relative to boundaries between alkalic, alkali-calcic, calc-alkalic, and calcic rock series. Boundaries between rock series from Frost and others (2001). (Ga, billion years before present)

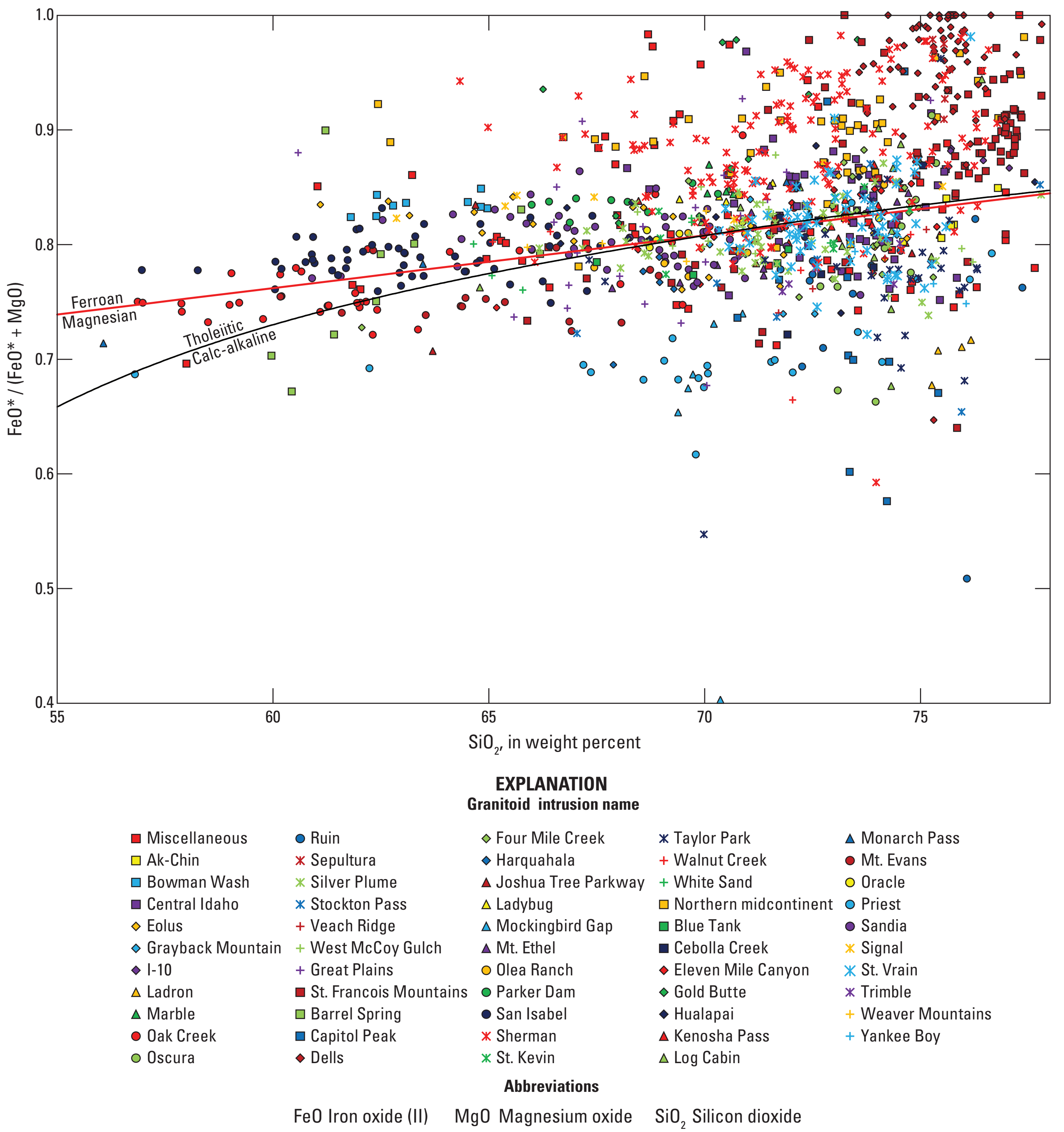


Figure 10. FeO*/(FeO*+MgO) variation diagram showing the composition of 1.4 Ga granitoid intrusions of the conterminous United States relative to boundaries between ferroan and magnesian rocks as well as between tholeiitic and calc-alkaline rocks. Ferroan versus magnesian boundary (red line) from Frost and others (2001); tholeiitic versus calc-alkaline boundary (black line) from Miyashiro (1974). (Ga, billion years before present)

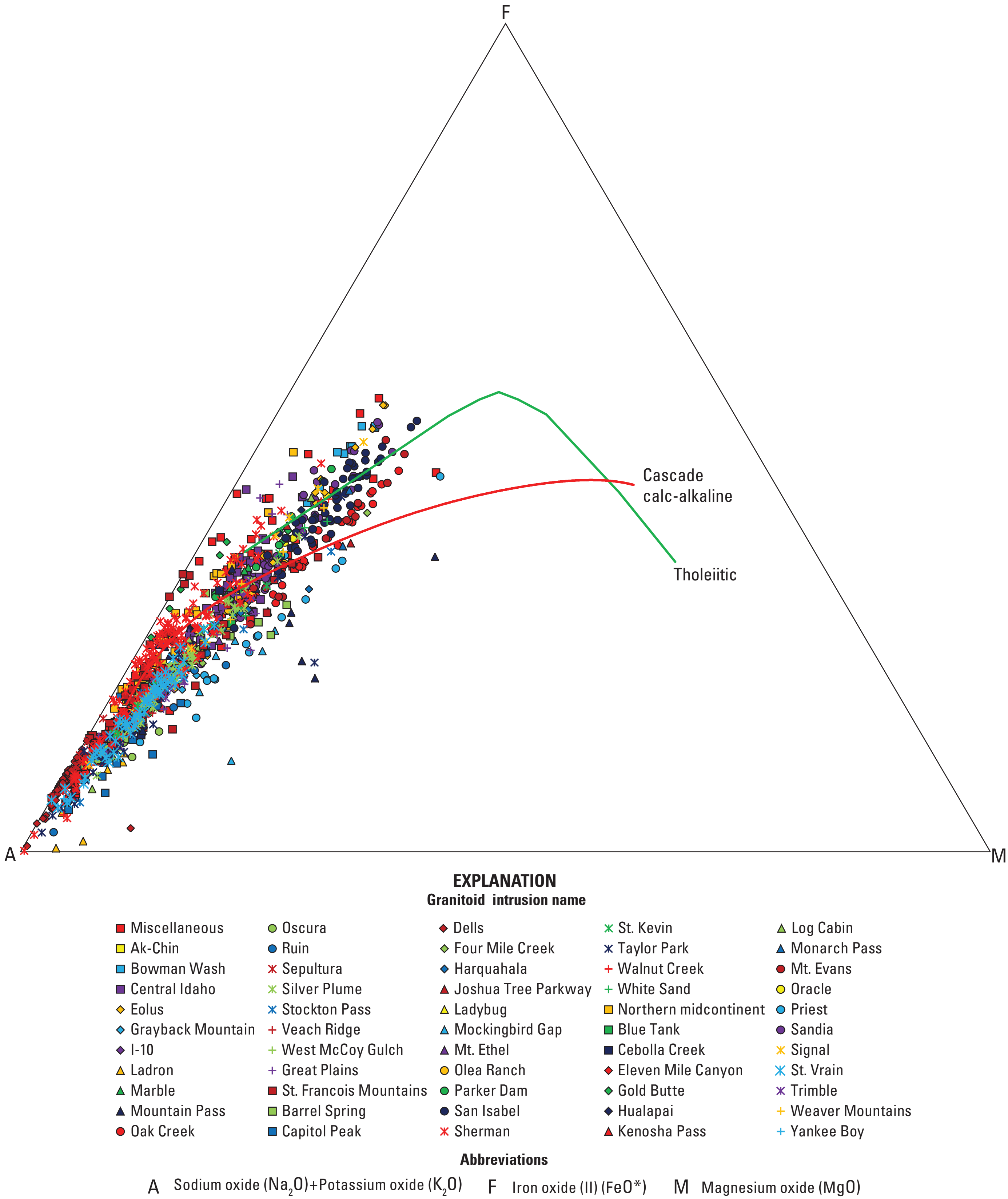


Figure 11. Ternary AFM diagram showing compositions of 1.4 Ga granitoid intrusions of the conterminous United States. Cascade calc-alkaline (red) and tholeiitic (green) trend lines from Irvine and Baragar (1971). (Ga, billion years before present)

Table 2. Chemical classification of 1.4 Ga granitoid intrusions of the conterminous United States.

[From Frost and Frost (2011). Ga, billion years before present]

Ferroan							
Peraluminous		Metaluminous				Peralkaline	
Alkali-calcic	Calc-alkalic	Alkalic	Alkali-calcic	Calc-alkalic	Calcic	Alkalic	Alkali-calcic
West McCoy Gulch	St. Francois Mountains	Barrel Spring	Sherman	Sandia		Mountain Pass	
Dells	I-10		Parker Dam	Gold Butte			
Log Cabin	Oracle		San Isabel	Signal			
Mt. Ethel	Marble		Great Plains	Weaver Mountains			
Sepultura	Monarch Pass			Ladybug			
White Sand	Central Idaho			Bowman Wash			
Kenosha Pass	Four Mile Creek						
Silver Plume	Miscellaneous						
St. Vrain							
Northern midcontinent							
Eleven Mile Canyon							
St. Kevin							
Hualapai							
Eolus							
Walnut Creek							

Magnesian					
Peraluminous		Metaluminous			
Alkali-calcic	Calc-alkalic	Alkalic	Alkali-calcic	Calc-alkalic	Calcic
Oak Creek	Blue Tank			Grayback Mountain	
Capitol Peak	Olea Ranch			Mt. Evans	
Mockingbird Gap	Ak-Chin				
Oscura	Ladron				
Trimble	Ruin				
Yankee Boy	Veach Ridge				
Harquahala	Joshua Tree Parkway				
Taylor Park	Priest				
Cebolla Creek	Stockton Pass				

from ferroan to magnesian compositions among the 1.4 Ga granitoids is continuous; although samples can be classified as either ferroan or magnesian, the data define a single diverse population with no compositionally distinct outliers. Correspondingly, compositions of the 1.4 Ga granitoids, especially those with the least evolved compositions, follow the iron-enrichment differentiation trend (fig. 11) defined by Irvine and Baragar (1971) for tholeiitic magmatic systems, which confirms the intrinsically ferroan character of most of the 1.4 Ga intrusions. However, thorough consideration of all geochemical data for 1.4 Ga granitoid samples demonstrates that the geochemical characteristics of the ferroan and magnesian groups are essentially indistinguishable; no additional compositional features discriminate these two groups.

About 75 percent of the ferroan 1.4 Ga granitoids are peraluminous (table 2). Within that subset, rocks of the alkali-calcic subtype (Frost and Frost, 2011) are about twice as abundant as rocks of the calc-alkalic subtype. Among the metaluminous ferroan 1.4 Ga granitoids, representatives of the alkali-calcic and calc-alkalic subtypes are about equally numerous. Among magnesian 1.4 Ga granitoids, almost all are peraluminous, and the alkali-calcic and calc-alkalic subtypes are about equally abundant. In contrast to all of the other 1.4 Ga intrusions, which are alkali-calcic to calc-alkalic and metaluminous to peraluminous, compositions of the 1.4 Ga intrusions at Mountain Pass are alkalic and peralkaline, and those at Barrel Springs are alkalic and metaluminous.

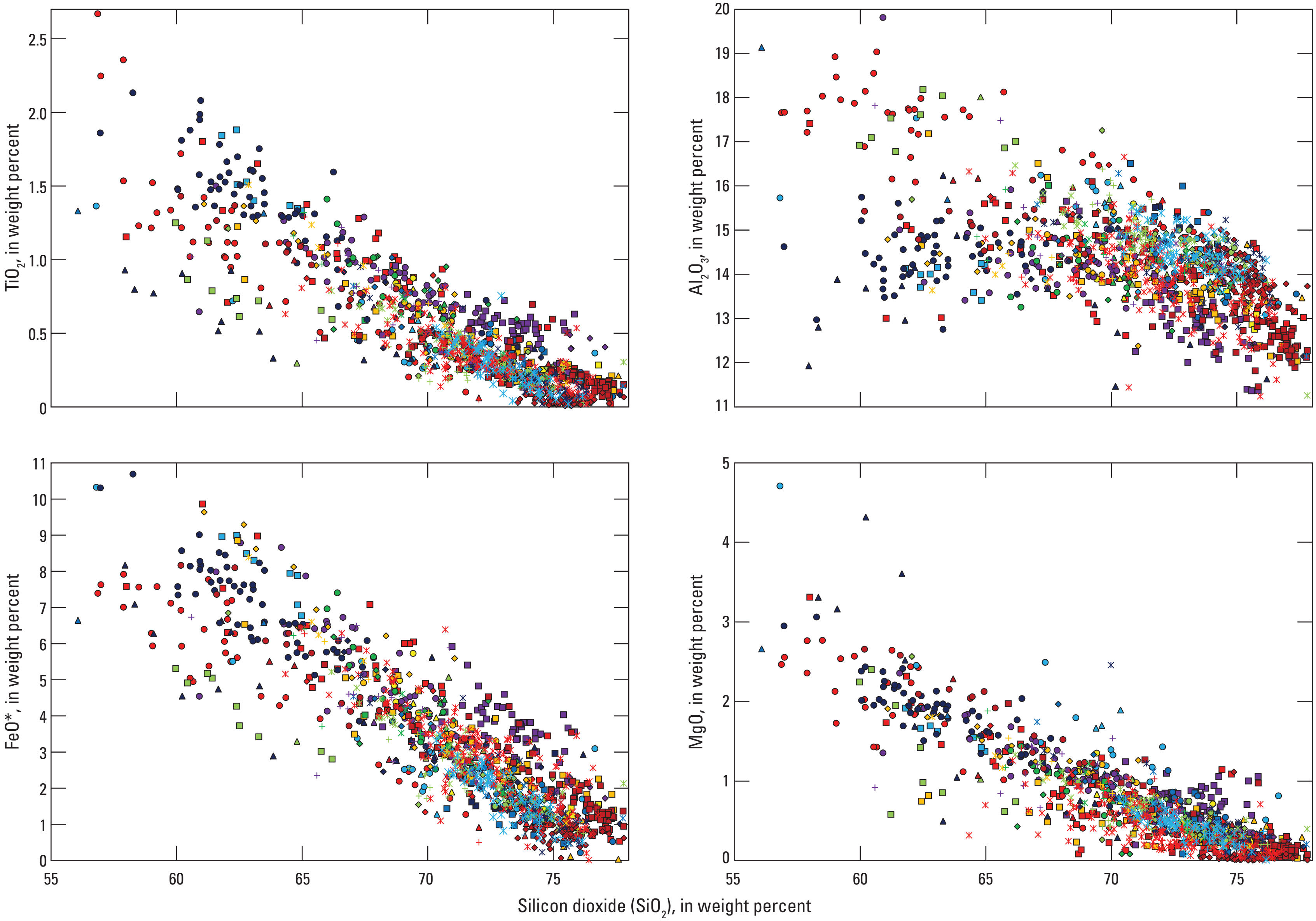
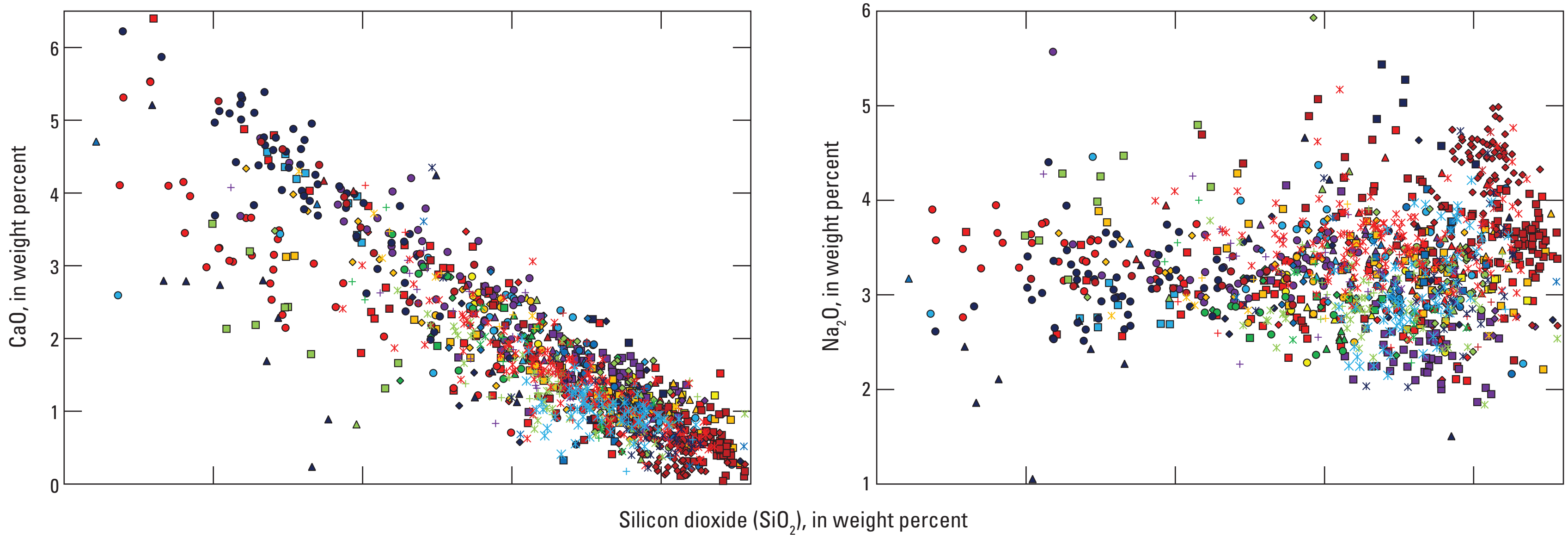


Figure 12. Variation diagrams showing abundances of major oxides (weight percent) in 1.4 Ga granitoid intrusions of the conterminous United States. Field boundaries on K_2O versus SiO_2 diagram from Le Maitre (1989); high potassium (K)-shoshonitic dividing line from Ewart (1982). (Ga, billion years before present)



EXPLANATION

Granitoid intrusion name

Miscellaneous	Oscura	Dells	St. Kevin	Log Cabin
Ak-Chin	Ruin	Four Mile Creek	Taylor Park	Monarch Pass
Bowman Wash	Sepultura	Harquahala	Walnut Creek	Mt. Evans
Central Idaho	Silver Plume	Joshua Tree Parkway	White Sand	Oracle
Eolus	Stockton Pass	Ladybug	Northern midcontinent	Priest
Grayback Mountain	Veach Ridge	Mockingbird Gap	Blue Tank	Sandia
I-10	West McCoy Gulch	Mt. Ethel	Cebolla Creek	Signal
Ladron	Great Plains	Olea Ranch	Eleven Mile Canyon	St. Vrain
Marble	St. Francois Mountains	Parker Dam	Gold Butte	Trimble
Mountain Pass	Barrel Spring	San Isabel	Hualapai	Weaver Mountains
Oak Creek	Capitol Peak	Sherman	Kenosha Pass	Yankee Boy

Abbreviations

Al_2O_3	aluminum oxide	MgO	magnesium oxide	TiO_2	titanium dioxide	FeO*	iron oxide (II)
Na_2O	sodium oxide	CaO	calcium oxide	K_2O	potassium oxide	P_2O_5	diphosphorus pentoxide

Figure 12. Variation diagrams showing abundances of major oxides (weight percent) in 1.4 Ga granitoid intrusions of the conterminous United States. Field boundaries on K_2O versus SiO_2 diagram from Le Maitre (1989); high potassium (K)-shoshonitic dividing line from Ewart (1982). (Ga, billion years before present)—Continued

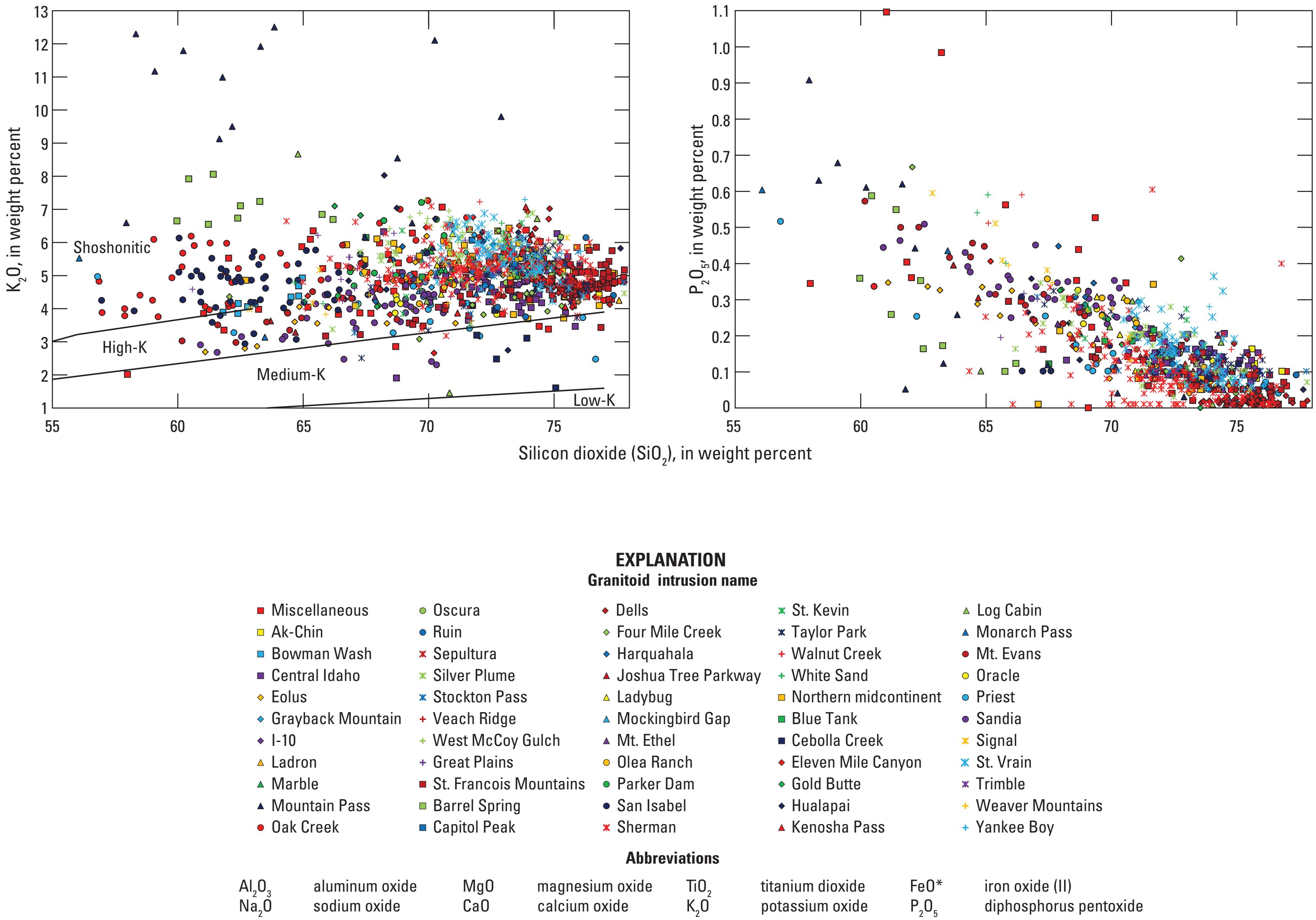


Figure 12. Variation diagrams showing abundances of major oxides (weight percent) in 1.4 Ga granitoid intrusions of the conterminous United States. Field boundaries on K_2O versus SiO_2 diagram from Le Maitre (1989); high potassium (K)-shoshonitic dividing line from Ewart (1982). (Ga, billion years before present)—Continued

Major oxide compositions of individual 1.4 Ga intrusions form diffuse clusters or irregular arrays, each somewhat distinctive (fig. 12). Combined, these overlapping clusters and arrays define the full compositional spectrum characteristic of the 1.4 Ga intrusions. Although individual intrusions have somewhat distinct compositions, only the Mountain Pass, Barrel Springs, and Oak Creek intrusions have compositions that are clearly distinct from those of all the remaining intrusions. These three intrusions have low TiO_2, FeO*, CaO, and MnO abundances relative to the remaining 1.4 Ga intrusions. In addition, the Barrel Springs rocks have distinctly high Al_2O_3, Na_2O, and K_2O and low MgO abundances; the Mountain Pass rocks have low Na_2O and unusually elevated K_2O abundances; and the Oak Creek rocks have high Al_2O_3 abundances. Among the 1.4 Ga intrusions, TiO_2 and P_2O_5 abundances vary considerably at lower SiO_2 abundances but scatter less and decrease with increasing SiO_2 abundances. Concentrations of FeO* (total iron expressed as ferrous oxide), MgO, CaO, and MnO decrease linearly with increasing SiO_2. Like TiO_2 and P_2O_5 abundances, Al_2O_3 abundances vary considerably at lower SiO_2 abundances; Al_2O_3 abundances vary unsystematically in samples with less than about 65 weight percent SiO_2 and then decrease significantly and consistently, forming a concave downward data array. Relative to the other major oxides, Na_2O and K_2O abundances vary considerably (fig. 12). At any silica content, Na_2O abundances vary by as much as about 3 weight percent, whereas K_2O abundances vary by as much as 4.5 weight percent. However, these highly variable Na_2O and K_2O abundances do not systematically correlate with SiO_2 content. K_2O abundances of the 1.4 Ga granitoids are broadly coincident with the high-K (potassium; Le Maitre, 1989) and shoshonitic (Ewart, 1982) fields.

Volatile component abundances of the 1.4 Ga intrusions provide another important point of comparison with globally distributed ferroan, A-type granites, which are anhydrous, as initially defined by Loiselle and Wones (1979). Similar median total volatile and bound H_2O contents (0.73 and 0.67 weight percent, respectively) among the 1.4 Ga intrusions indicate that H_2O is their principal volatile constituent. H_2O abundances, ranging from 0.1 to about 2 weight percent and symmetrically and unimodally distributed about a maximum frequency value of about 0.7 weight percent, are similar to abundances in subalkalic silicic obsidians (Macdonald and others, 1992), which are compositionally akin to 1.4 Ga granitoids. Although H_2O contents of the 1.4 Ga intrusions are not especially low relative to the obsidians, they are significantly lower than the >4 weight percent H_2O required to stabilize hornblende in andesitic arc magmas (Rutherford and Hill, 1993). Data synthesized by Anderson (1983) suggest that the 1.4 Ga intrusions are distinctly enriched in fluorine (F). Our larger dataset confirms that F contents, which are not well correlated with host-rock silica content, are also essentially symmetrically and unimodally distributed around a maximum frequency value of 0.07 weight percent (700 parts per million [ppm]). The median F content of these intrusions, 1,000 ppm, is elevated relative to the average value for low-calcium granites (850 ppm; Turekian and Wedepohl, 1961), distinctly elevated relative to average abundances in silicic obsidians associated with magmatic arcs (500 ppm), and low relative to average abundances in intracontinental silicic obsidians (1,500 ppm) (Macdonald and others, 1992). Chlorine (Cl) abundances of the 1.4 Ga intrusions range from 0.01 to about 0.07 weight percent and are strongly skewed to values between 0.01 and 0.02 weight percent. The maximum frequency value is 0.02 weight percent (200 ppm), and the median Cl abundance of these intrusions, 170 ppm, is similar to the average Cl content of low-calcium granite (200 ppm; Turekian and Wedepohl, 1961) and low relative to abundances in most silicic obsidians (Macdonald and others, 1992).

Trace-Element Data

Trace-element abundances among the 1.4 Ga intrusions vary widely, but some of these are distinct and diagnostic. Relative to the average low-calcium (Ca) granite (Turekian and Wedepohl, 1961), essentially all of the 1.4 Ga intrusions contain elevated Hf, Pb, Y (yttrium), and Zr and low Cu (copper), Sc (scandium), Ta, and V (vanadium). Abundances of Rb (rubidium), Th (thorium), and U (uranium) increase slightly with increasing silica content; those for Ba (barium), Co (cobalt), Cr (chromium), Hf, La (lanthanum; slightly), Ni (nickel), Sc, Sr (strontium), V, Zn (zinc), and Zr decrease with increasing silica content; and abundances of Cs (cesium), Cu, Ga (gallium), Pb, Nb, Ta, and Y display no consistent covariation with silica content. Trace-element abundances for several intrusions are distinct relative to those of all of the other 1.4 Ga intrusions. At any particular SiO_2 content, the Barrel Springs rocks have relatively elevated Ba, Hf, Rb, Sr, and Zr abundances and low Sc and V abundances; the Mountain Pass rocks have relatively high Ba, Rb, Sr and Th abundances; the Oak Creek rocks have relatively high Ba contents; the Eolus rocks have distinctly high Cr contents; and the Silver Plume rocks have distinctly elevated Th contents. These trace-element abundances and variation patterns probably reflect compositionally diverse magma sources and variable petrologic processes operating within the representative magma reservoirs.

Among the 1.4 Ga intrusions, average REE abundances range over an order of magnitude, but their average chondrite-normalized REE patterns are essentially parallel (fig. 13). Importantly, although absolute REE contents of particular 1.4 Ga intrusions vary significantly, as a group, their REE characteristics are relatively similar (table 3), but many of the metaluminous 1.4 Ga intrusions have higher overall REE contents and less-well-developed negative europium (Eu) anomalies (fig. 13). The extent of single-intrusion REE abundance variation (chondrite-normalized pattern dispersion) is conveyed by standard deviation values calculated from the REE data for each 1.4 Ga intrusion. For any given 1.4 Ga intrusion, standard deviations calculated for each of the REEs vary within relatively narrow ranges, suggesting that the standard deviation for any

Table 3. Rare-earth element (REE) characteristics of 1.4 Ga granitoid intrusions of the conterminous United States.

[Dispersion is the calculated lanthanum (La) standard deviation divided by the calculated La average. Ga, billion years before present; Eu, europium; Yb, ytterbium; blank, no data available; Misc., miscellaneous]

Intrusion name	Eu/Eu*	$(La/Yb)_N$	Total REE	Dispersion
Mountain Pass	0.783	–	1181.6	0.430
Barrel Spring	0.896	56.9	150.0	0.374
Gold Butte	–	11.0	187.3	0.184
St. Francois Mountains	0.306	5.2	144.7	0.342
Central Idaho	0.399	6.9	149.2	0.336
Signal	0.563	12.2	96.1	0.100
Ruin	0.495	10.6	159.5	0.146
Misc. central Arizona	0.615	13.2	177.4	0.343
Eleven Mile Canyon	0.431	34.0	125.5	0.863
Bear Basin	0.419	12.6	168.9	0.334
Eolus	0.465	18.7	131.2	0.409
San Isabel	0.581	10.5	133.0	0.268
Yankee Boy	0.369	30.0	91.1	0.318
Firefly	0.382	8.3	144.2	0.171
Four Mile Creek	0.472	15.4	155.0	0.349
Oak Creek	0.642	55.1	161.7	0.869
West McCoy Gulch	0.283	16.1	156.2	0.347
Misc. central Colorado	0.456	34.3	117.4	0.493
Sherman	0.430	14.4	128.9	0.361
Misc. New Mexico	0.644	5.4	157.8	0.177
Priest	0.574	14.9	135.4	0.489
Sandia	0.657	6.5	95.1	0.148
White Sands	0.364	7.5	110.1	0.108
Wisconsin	0.519	11.1	129.5	0.415

particular REE (such as La, which is abundant and easily determined with high precision) depicts REE abundance dispersion for each 1.4 Ga intrusion. The standard deviation of La abundance calculated for each 1.4 Ga intrusion was divided by its associated average La abundance to yield a consistent, normalized REE dispersion metric (La STD/AVE) (table 3). Calculated REE dispersion values exhibit no systematic variation with respect to SiO_2 content. The Signal, White Sand, Ruin, Sandia, Firefly, Gold Butte, and miscellaneous New Mexico 1.4 Ga intrusions have low REE dispersion values (<0.20), which reflect relatively homogeneous within-intrusion REE contents. In contrast, the Eleven Mile Canyon and Oak Creek 1.4 Ga intrusions have very large REE dispersion values (>0.85); these intrusions have very inhomogeneous REE contents. The remaining 1.4 Ga intrusions have intermediate, although somewhat elevated, REE dispersion values consistent with somewhat inhomogeneous REE contents. Among the 1.4 Ga intrusions, total REE abundances increase slightly with increasing SiO_2 content, whereas moderate negative Eu anomalies are weakly negatively correlated and $(La/Yb)_N$ uncorrelated with increasing SiO_2 content. La/Yb (ytterbium) is distinctly elevated in samples of the Mountain Pass and Barrel Springs intrusions, which is in accord with other compositional distinctions characteristic of these intrusions.

Essential characteristics of average primitive-mantle-normalized patterns for the 1.4 Ga intrusions are relatively similar (fig. 14). These patterns are gently negatively sloping and include several superimposed abundance anomalies, including negative Ba, Sr, P (phosphorus), and Ti anomalies. These patterns also include moderately well developed negative Nb (and less pronounced Ta) anomalies, generally considered characteristic of subduction-related magmas (Wood and others, 1979; Gill, 1981; Pearce and others, 1984). Average primitive-mantle-normalized patterns for the 1.4 Ga intrusions also include prominent positive Th and Pb anomalies. Trace-element abundance variations also result in considerable primitive-mantle-normalized pattern dispersion within individual intrusions.

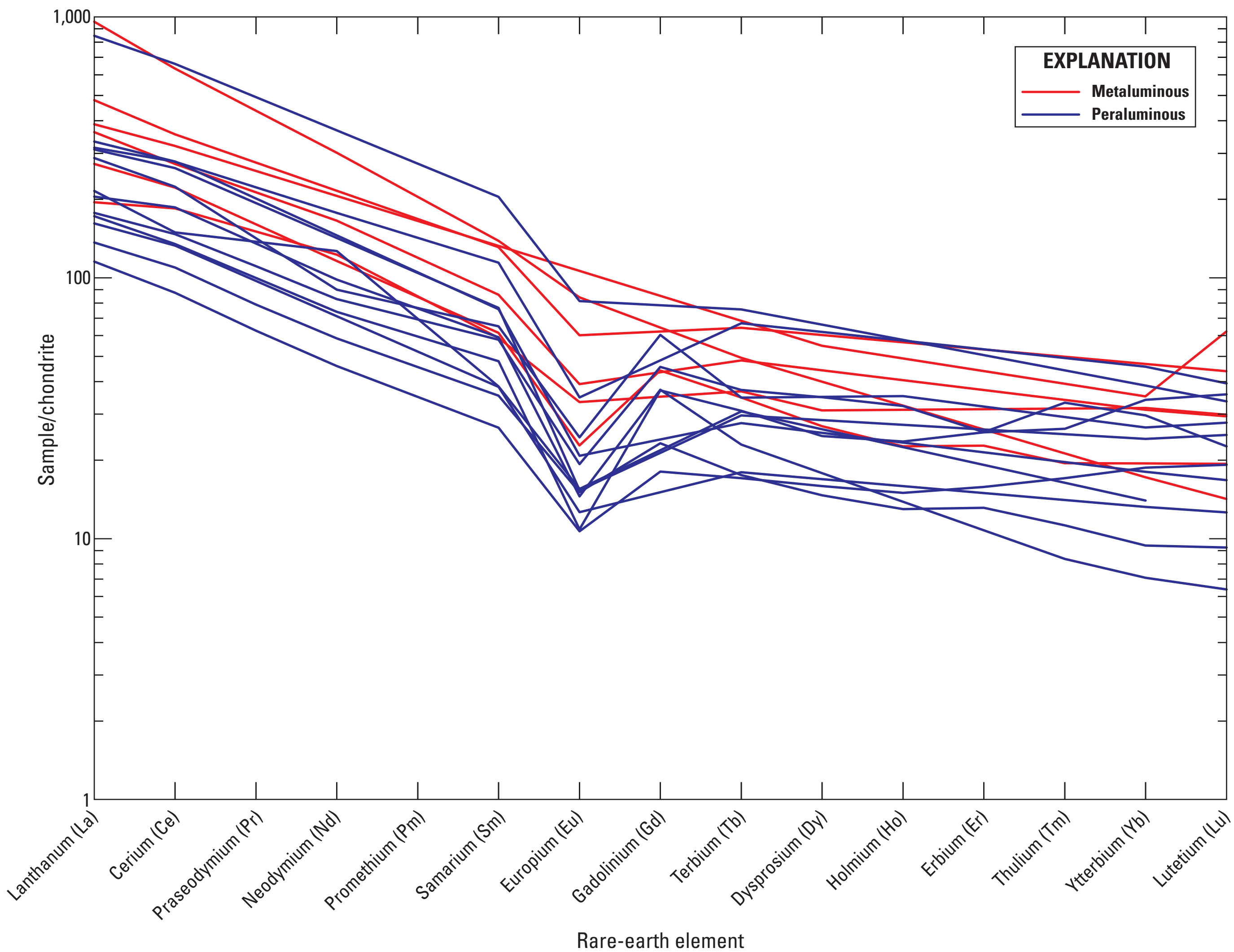


Figure 13. Average chondrite-normalized rare-earth element patterns for 1.4 Ga granitoid intrusions of the conterminous United States. Chondrite abundances from Anders and Ebihara (1982). Truncated segments indicate missing data. (Ga, billion years before present)

Radiogenic Isotope Data

Radiogenic isotope data for the 1.4 Ga intrusions are consistent with derivation from diverse-composition sources. Hf isotope data for zircon, available for a relatively limited subset of the 1.4 Ga intrusions, suggest magma involving extensive partial melting of lower crustal sources (Goodge and Vervoort, 2006; Bickford and others, 2015). Further, distinct ages and isotopic compositions of crustal sources result in well-developed region-scale, basement-derived Hf isotopic variations among the 1.4 Ga intrusions. Synthesis of whole-rock Sm (samarium)-Nd and zircon Lu (lutetium)-Hf isotopic data (Bickford and others, 2015) suggests that the petrogenesis of the 1.4 Ga intrusions involved crustal underplating by mantle-derived basalt and associated crustal partial melting. Similarly, the majority of initial strontium isotope ratio ($^{87}Sr/^{86}Sr$; Sr_i) values for the 1.4 Ga intrusions range from about 0.700 to about 0.707, although another, much smaller population has initial Sr_i values that range from 0.709 to 0.712, and a group of four samples have Sr_i values greater than 0.712 (fig. 15). The maximum frequency value for all of these Sr_i data is between 0.704 and 0.705, and the median value is 0.704; Sr_i values are uncorrelated with varying SiO_2 content. Although these Sr_i characteristics are consistent with primarily mantle sources, Anderson (1983) suggested that these relatively primitive values may instead reflect short residence times and minimally radiogenic lower crustal sources. Additional Sr and Nd isotopic data (Frost and others, 2001, 2002; Anderson and others, 2003) are consistent with a dominant role for mantle sources in the petrogenesis of at least some of the 1.4 Ga intrusions. Cumulatively, these radiogenic isotope data suggest that the petrogenesis of the 1.4 Ga intrusions involved a combination of mantle-derived and isotopically juvenile crust-derived components.

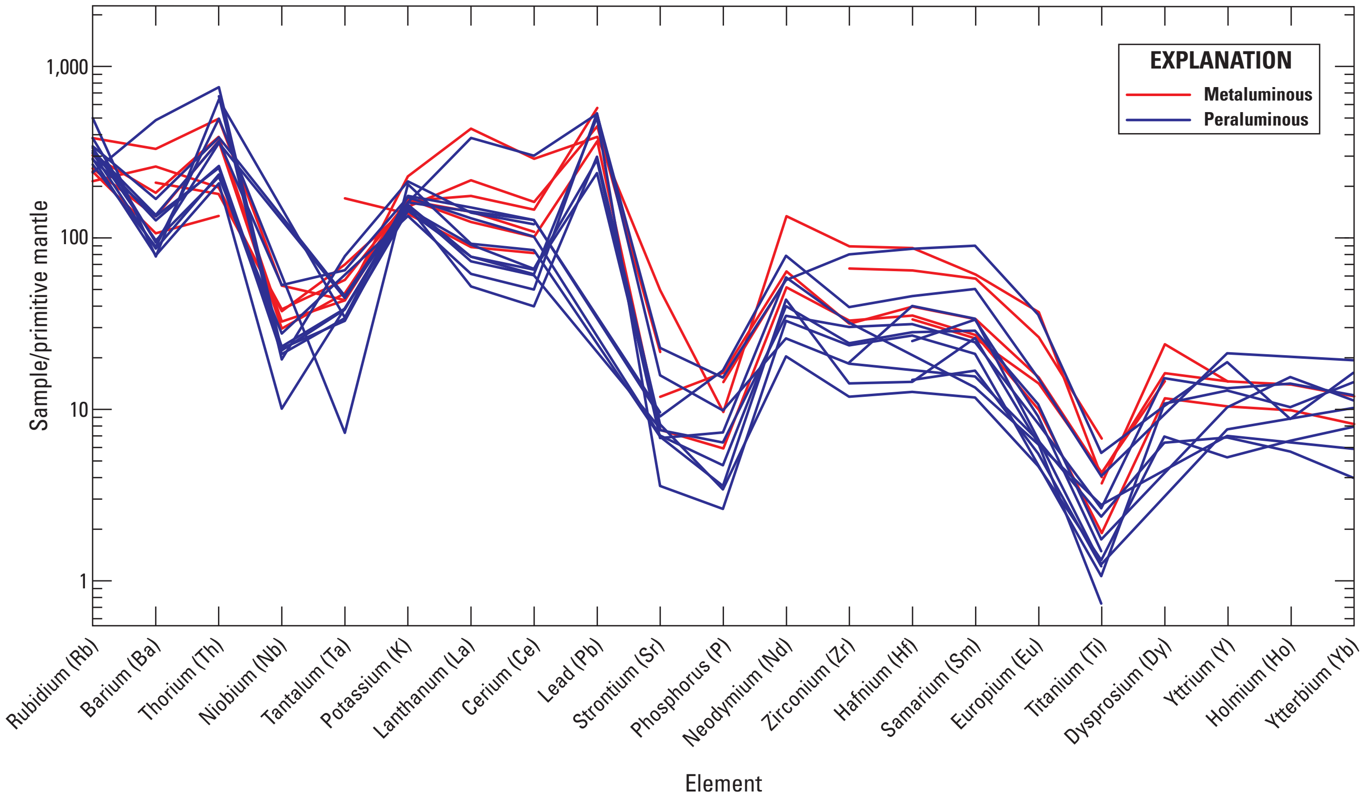


Figure 14. Primitive-mantle-normalized (Sun and McDonough, 1989) trace-element diagrams for 1.4 Ga granitoid intrusions of the conterminous United States. Truncated segments indicate missing data. (Ga, billion years before present)

Petrogenesis of 1.4 Ga intrusions in the Conterminous United States

Frost and Frost (2011) used major oxide compositions to subdivide ferroan granitoids into eight subtypes. The first four subtypes include the alkali-calcic and calc-alkalic variants of both ferroan peraluminous and ferroan peralkaline granitoids. The remaining four subtypes are the alkalic, alkali-calcic, calc-alkalic, and calcic variants of the ferroan metaluminous granitoids. Importantly, although the subtypes imply the potential for discrete compositional classification, available data (du Bray and others, 2015) demonstrate that many of the 1.4 Ga intrusions have composition ranges that extend across subtype boundaries. For instance, compositions of many of the 1.4 Ga intrusions span the boundary between peraluminous and metaluminous compositions and the boundary between alkali-calcic and calc-alkalic compositions (figs. 8, 9). These compositional variations reflect continuous variation of petrologic processes responsible for magmatism. Classification of 1.4 Ga intrusions using the schema of Frost and Frost (2011) constrains the relevant petrogenetic parameters because each compositional subtype can be compared to the results of experimental petrologic investigations, for which pressure, temperature, and compositional characteristics are known. The diverse processes prevailing during magma genesis and evolution can be directly identified from the geochemical diversity (table 2) of ferroan 1.4 Ga intrusions.

Experimental investigations (Skjerlie and Johnston, 1993; Patiño Douce, 1997) demonstrate that low-degree dehydration partial melting of granodiorite or magnesian tonalite gneiss yields ferroan, strongly peraluminous, calc-alkalic melts. With more advanced partial melting, the resultant magmas are instead increasingly magnesian, metaluminous, and alkali-calcic. At lower experimental pressures, derivative partial melts are more magnesian, metaluminous, and instead, calc-alkalic. Accordingly, the large group of 1.4 Ga intrusions in the conterminous United States (table 2) having ferroan, peraluminous, and calc-alkalic to alkali-calcic compositions are consistent with high-pressure (8–10 kilobars [kbar]), low-degree partial melting; members of the alkali-calcic subtype probably represent partial melting at higher pressure conditions than those prevailing during genesis of the calc-alkalic subtype (Patiño Douce, 1997).

A sizable group of the 1.4 Ga intrusions (table 2) have alkali-calcic and calc-alkalic peraluminous compositions that are magnesian, not ferroan. Although magnesian calc-alkaline magmas are the hallmark of subduction-related magmatic arcs, the geologic setting in which the 1.4 Ga intrusions formed is likely intracratonic (Bickford and others, 2015) and therefore inconsistent with arc magmatism. The transition from ferroan to magnesian compositions is continuous, which suggests that petrogenesis of the magnesian variants reflects variations of

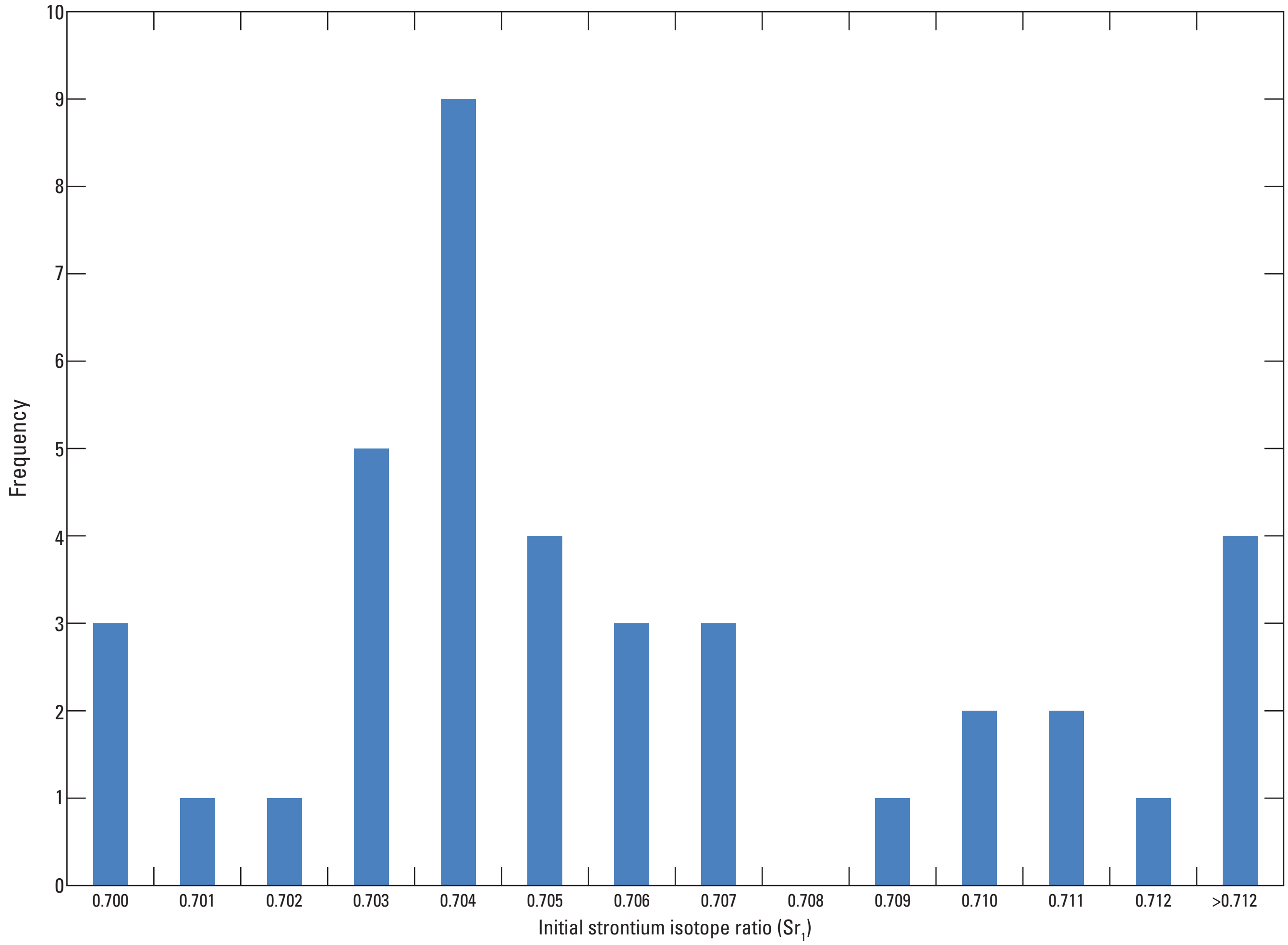


Figure 15. Frequency histogram showing the relative numbers of samples of 1.4 Ga granitoid intrusions of the conterminous United States having the indicated Sr_i values. (Ga, billion years before present; Sr_i, initial strontium isotope ratio)

processes not entirely different from those responsible for ferroan granitoid petrogenesis. Skjerlie and Johnston (1993) demonstrated that higher degree partial melting results in weakly magnesian but peraluminous compositions. Lower pressure partial melting may also contribute to weakly magnesian compositions (Skjerlie and Johnston, 1993). Consequently, the large group of 1.4 Ga intrusions that are magnesian and peraluminous likely reflect relatively advanced partial melting of a granodioritic to tonalitic protolith in the upper crust. Compositions of the alkali-calcic subtype are consistent with genesis under the lowest pressure conditions, whereas those of the calc-alkalic subtype reflect somewhat higher pressures (Patiño Douce, 1997). Among the 1.4 Ga intrusions, rare magnesian, metaluminous, and calc-alkalic granitoids probably represent the highest pressure (Patiño Douce, 1997), highest degree partial melting (Skjerlie and Johnston, 1993) of crustal protoliths.

In contrast, Frost and Frost (2011) concluded that metaluminous ferroan granites can be derived by differentiation of tholeiitic basalt. Whether these partial melts are alkali-calcic or calc-alkalic, or even alkalic, depends on the balance of plagioclase versus clinopyroxene crystallization and fractionation. Specifically, tholeiitic magma compositions become increasingly alkalic with clinopyroxene crystallization; accordingly, the onset of plagioclase crystallization limits residual liquid alkalinity variation (Frost and Frost, 2011). Consequently, (1) the alkalic composition of the 1.4 Ga Barrel Spring intrusion represents extensive clinopyroxene fractionation, (2) the alkali-calcic metaluminous 1.4 Ga intrusions reflect more limited clinopyroxene fractionation, and (3) the calc-alkalic subtype manifests the dominance of plagioclase fractionation. As summarized by Frost and Frost (2011), clinopyroxene stability reflects crystallization at a higher pressure than that accompanying plagioclase crystallization; as such, the most alkalic of the metaluminous 1.4 Ga intrusions probably evolved in environments with systematically higher pressures than those characteristic of the calc-alkalic subtype.

Peralkaline igneous rocks at Mountain Pass are unique among ferroan 1.4 Ga intrusions. Frost and Frost (2008) established that most ferroan peralkaline granitoids are generated by differentiation of transitional or alkali basalt magmas. The controlling differentiation trend reflects calcium-rich plagioclase fractionation, which preferentially removes aluminum relative to sodium, resulting in peralkaline magmas characterized by lower alkalinity indices. Consequently, the alkalic and peralkaline ferroan granitoids at Mountain Pass probably reflect magma genesis from an alkali basalt progenitor, involving processes similar to those described by Frost and Frost (2008) and subsequent fractionation.

Major oxide compositions of 1.4 Ga intrusions are similar to those of ferroan granites throughout the world (Dall'Agnol and others, 2012). Most of the 1.4 Ga intrusions are subalkaline, weakly to moderately peraluminous, alkali-calcic to calc-alkalic, and iron-enriched and have moderately evolved compositions. Major oxide abundance variations for these intrusions are consistent with crystallization and fractionation involving observed mineral assemblages. Among the 1.4 Ga intrusions, the onset of plagioclase crystallization and its fractionation is denoted by decreasing Al_2O_3, which pertains only to the 1.4 Ga intrusion with ≥67 weight percent SiO_2 (fig. 12). Similarly, moderate negative Eu anomalies among the 1.4 Ga intrusions confirm that plagioclase fractionation was important to their petrogenesis. Systematic decreases in the abundances of TiO_2, FeO*, MnO, MgO, and CaO with increasing SiO_2 content (fig. 12) are consistent with hornblende, biotite, and lesser Fe-Ti oxide crystallization and fractionation. Systematically lower P_2O_5 and TiO_2 abundances with increasing SiO_2 content reflect apatite and Fe-Ti oxide crystallization and fractionation. Progressively larger negative P and Ti anomalies (fig. 14) are also diagnostic of apatite and Fe-Ti oxide mineral crystallization and fractionation among increasingly evolved 1.4 Ga intrusions.

Systematically lower Zr concentrations with increasing SiO_2 content reflects zircon crystallization and fractionation throughout the compositional spectrum represented by the 1.4 Ga intrusions. Zr abundances among the 1.4 Ga intrusions, as high as 2,540 ppm, are remarkable; fully two thirds of analyzed samples contain more than 200 ppm, which is significantly greater than the 140–175 ppm range characteristic of granitoid rocks (Turekian and Wedepohl, 1961). Although the 1.4 Ga intrusions with the very highest Zr content are alkaline, most of them, including those with moderately elevated Zr contents, are subalkaline. Watson (1979) suggested that subalkaline granitoid melts with Zr contents greater than about 100 ppm become zircon saturated. Consequently, consistently elevated Zr abundances, greater than 200 ppm in subalkaline 1.4 Ga intrusions, are poorly reconciled with experimental results and represent an unexplained petrogenetic characteristic of these intrusions.

By comparison, abundances of Sr in the 1.4 Ga intrusions are lower than those characteristic of continental magmatic arc rocks (Hildreth and Moorbath, 1988; du Bray and others, 2015). These relatively low Sr abundances likely reflect petrogenetic conditions in which plagioclase, the principal residence of Sr, was retained in the source residuum during partial melting and (or) was crystallized and removed from evolving, residual silicate liquids. Plagioclase stability in the source region implies magma genesis in a relatively low-pressure (<20 kbar) environment (Green, 1982), likely beneath continental crust substantially thinner than that prevailing in continental magmatic arc environments. Moderately well developed negative Eu anomalies characteristic of the 1.4 Ga intrusions are also consistent with source-region plagioclase retention.

Most of the 1.4 Ga intrusions have Rb and Y+Nb concentrations consistent with a within-plate tectonic setting (fig. 16). However, several of these intrusions have compositions that straddle the boundary between the within-plate and volcanic arc fields. Paradoxically, primitive-mantle-normalized trace-element plots for most 1.4 Ga intrusions include negative Nb-Ta anomalies that are typical of subduction-related arc magmas but are only slightly enriched with large-ion lithophile elements (LILEs). Some of these geochemical signatures, suggestive of arc magmatism, were probably inherited from the crustal rocks that contributed to the petrogenesis of the 1.4 Ga intrusions because their other geologic characteristics are inconsistent with arc affiliations or emplacement in a suprasubduction zone setting. Accordingly, some calc-alkaline granodioritic to tonalitic rocks in the lower crust that were partially melted during 1.4 Ga granitoid magma genesis may have developed in preexisting magmatic arc settings; upon subsequent partial melting, these calc-alkaline granodioritic to tonalitic rocks appear to have contributed an inherited, arc-like geochemical signature to magmas represented by the 1.4 Ga intrusions.

Several additional geochemical parameters suggest that the 1.4 Ga intrusions represent mantle-derived magmas that were variably contaminated by crustal assimilants, thereby contributing to the compositional diversity characteristic of these intrusions (fig. 17). In particular, among the 1.4 Ga intrusions, P_2O_5/K_2O decreases with increasing SiO_2 content, which is consistent with progressive mafic magma contamination by crustal assimilation because crustal materials generally have P_2O_5/K_2O values of <0.1 (Farmer and others, 2002). Similarly, among the 1.4 Ga intrusions, CaO/Al_2O_3 systematically decreases with increasing SiO_2 content, which is consistent with magma composition modification by crustal contamination (Cousens and others, 2008). Finally, Pb/Ce (cerium) increases from about 0.05 to about 0.35 among intermediate through felsic 1.4 Ga intrusions because higher Pb/Ce values with increasing SiO_2 content reflect enhanced assimilation of Pb-rich crustal rocks (Hildreth and Moorbath, 1988). These processes confirm the importance of primary basaltic magma involvement in the genesis of the 1.4 Ga intrusions and their evolution to more felsic compositions by variable assimilation of crust-derived contaminants.

Relative REE abundances further constrain the petrogenetic history of the 1.4 Ga intrusions. Chondrite-normalized REE patterns for these intrusions have moderately steep, negative slopes (table 3); values of $(La/Yb)_N$ range from about 5 to 57 but cluster at about 20. Correspondingly, the 1.4 Ga intrusions have characteristically lower Zr concentrations with increasing silica content, which suggests that zircon was a liquidus phase and therefore was likely fractionated from essentially all of the magmas they represent.

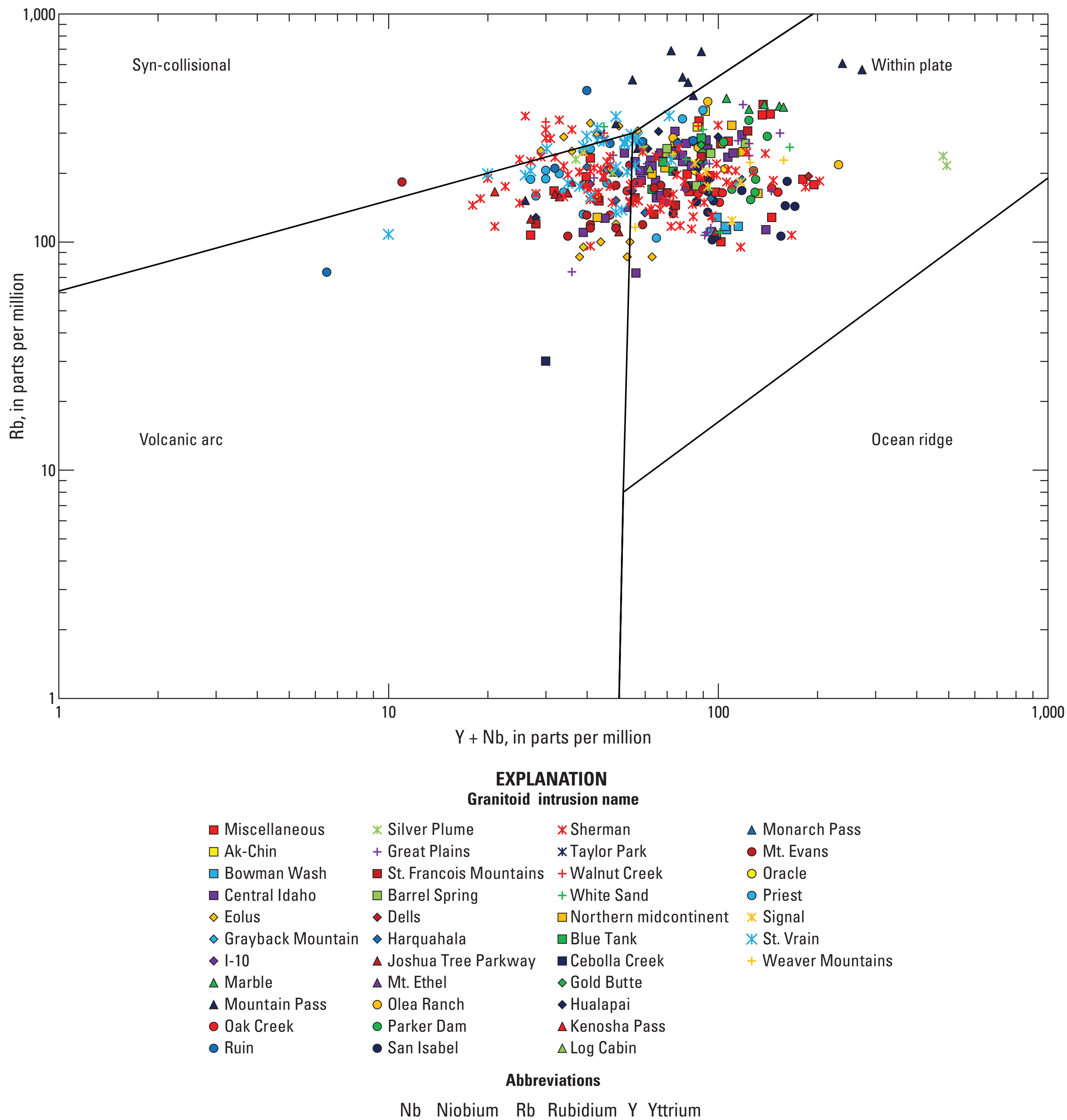


Figure 16. Trace-element, tectonic-setting discrimination variation diagram showing the composition of 1.4 Ga granitoid intrusions of the conterminous United States. Tectonic setting–composition boundaries from Pearce and others (1984). (Ga, billion years before present; Rb, rubidium; Y, yttrium; Nb, niobium)

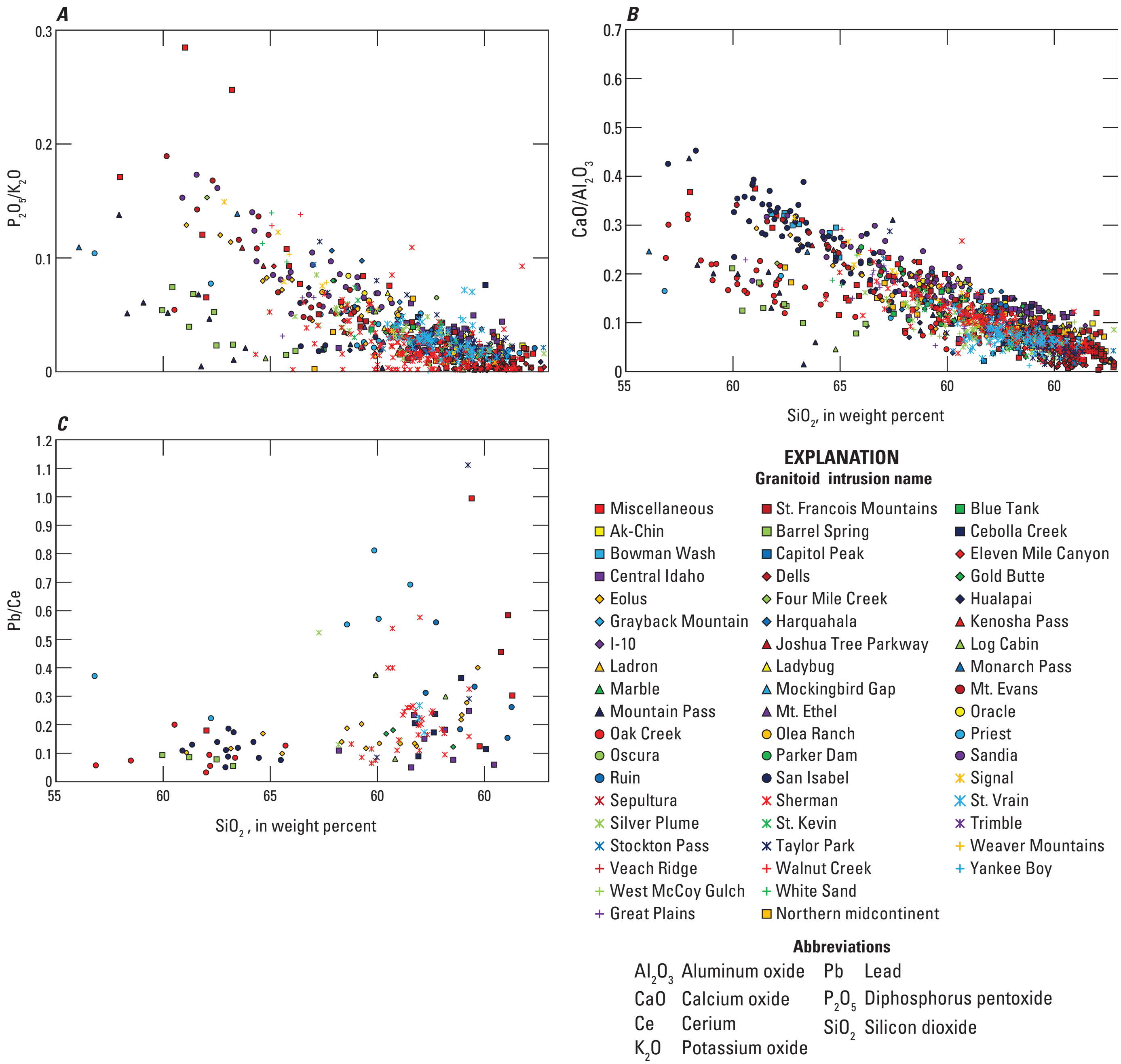


Figure 17. Variation diagrams showing that compositions of 1.4 Ga granitoid intrusions of the conterminous United States are consistent with primary magmas being variably contaminated by crustal assimilants. *A*, P_2O_5/K_2O versus SiO_2. *B*, CaO/Al_2O_3 versus SiO_2. *C*, Pb/Ce versus SiO_2. (Ga, billion years before present; Pb, lead; Ce, cerium)

Accordingly, heavy rare-earth element (HREE) depletion among these magmas likely reflects, in part, zircon fractionation because zircon preferentially incorporates HREEs versus LREEs (Hanson, 1980). Additional relative HREE depletion may also reflect retention of HREE-enriched garnet in lower to middle crustal rocks from which assimilated crustal melts were derived. Average chondrite-normalized patterns for the 1.4 Ga intrusions are essentially parallel (fig. 13), which suggests that petrogenetic processes responsible for magma genesis and subsequent evolution were similar; crystalized and fractionated mineral assemblages, as well as their REE mineral-melt distribution coefficients, did not vary significantly among these intrusions. Moderately well developed negative Eu anomalies (fig. 13, table 3), characteristic of most of the 1.4 Ga intrusions, are consistent with significant plagioclase fractionation from the magmas they represent. In contrast, the Mountain Pass and Barrel Springs intrusions have small negative Eu anomalies—Eu/Eu* of 0.783 and 0.896, respectively—that are consistent with minor plagioclase fractionation from the representative magmas. Among most of the 1.4 Ga intrusions, Eu/Eu* is weakly correlated with SiO_2 content (table 3); the most silica-rich samples generally have the lowest values of Eu/Eu* (and therefore the largest negative Eu anomaly), which is consistent with peak plagioclase fractionation from the most evolved magmas. In contrast, neither $(La/Yb)_N$ nor total REE content of the 1.4 Ga intrusions are correlated with SiO_2 content (table 3).

Within-unit REE dispersion (table 3) for each of the 1.4 Ga intrusions is somewhat variable and reflects the extent of compositional evolution and homogenization within each of the magma reservoirs they represent. REE dispersion values of ≤0.4 (table 3) represent reasonably homogenous intrusions; many have dispersion values of ≤0.2 and represent very homogenous intrusions. In contrast, the Mountain Pass, Eleven Mile Canyon, Eolus, Oak Creek, Priest, northern midcontinent, and miscellaneous central Colorado 1.4 Ga intrusions have REE dispersion values of ≥0.4. Of these, analyses for the central Colorado and northern midcontinent 1.4 Ga intrusions represent data for groups of sparingly sampled intrusions rather than for single intrusions; combination of samples from multiple geographically related but possibly petrogenetically unrelated intrusions likely contributes to the observed REE dispersion. Chondrite-normalized patterns for multiple samples of the 1.4 Ga Priest and Mountain Pass intrusions exhibit somewhat greater REE dispersion. However, overall pattern congruence suggests that somewhat greater REE abundance variations may simply reflect correspondingly less-homogeneous magma reservoirs. In contrast, sets of chondrite-normalized patterns for the 1.4 Ga Eleven Mile Canyon, Oak Creek, and Eolus intrusions each include more than a single population. Each set of patterns includes samples with distinct characteristics, which suggests that each set may represent more than one intrusion, despite each sample set having been identified as representing a particular intrusion. Like average patterns for individual 1.4 Ga granitoids, within-intrusion patterns are generally parallel, which suggest that within each 1.4 Ga intrusion, relative REE fractionation was minor. Consequently, evolution of magma reservoirs represented by each of the 1.4 Ga intrusions involved fractionation processes in which mineral assemblages and their mineral-melt REE distribution coefficients were also relatively invariant.

Chondrite-normalized REE abundances among 1.4 Ga intrusions span nearly an entire order of magnitude. However, aside from total REE content variations and variably developed negative Eu anomalies, average patterns for individual 1.4 Ga intrusions are essentially parallel. The absence of REE fractionation, as would be depicted by relative pattern rotation, suggests that relatively uniform processes contributed to the petrogenesis of most of the 1.4 Ga intrusions. The absence of a relation between total REE content and variable SiO_2 content indicates that absolute REE abundances among the 1.4 Ga intrusions are not principally related to simple differentiation processes involving fractionation or accumulation of their constituent minerals. Instead, the range of REE abundances characteristic of the 1.4 Ga intrusions may reflect dilution processes accompanying variable crustal contaminant assimilation. Importantly, for crustal contaminants to be largely responsible for diluting REE contents among these intrusions, pattern parallelism requires relatively uniform contaminant compositions. Distinct source material REE abundances, as well as variable degrees of partial melting (Hanson, 1980), represent additional factors that may have contributed to the wide array of 1.4 Ga granitoid REE abundances. Both relatively broad REE abundance ranges and chondrite-normalized REE pattern congruence among 1.4 Ga intrusions reflect petrogenetic histories that involved combinations of the enumerated petrologic factors.

Relatively primitive Sr_i values for most of the 1.4 Ga intrusions indicate that significant mantle-derived inputs contributed to the genesis of these magmas. Analogously, Anderson and others (2003) used radiogenic isotope and whole-rock geochemical data to infer a relation between the petrogenesis of ferroan granitoids in Wyoming and tholeiitic mantle-derived magmatism. This interpretation contrasts with inferences derived from Hf isotopic compositions (Goodge and Vervoort, 2006), which suggest that the 1.4 Ga intrusions are not products of fractionation from mafic parental magmas, and experimental data that are consistent with many of them containing substantial crustal contributions. The accumulated observations suggest that derivation of the 1.4 Ga intrusions exclusively by differentiation from tholeiitic basalt magmas or alternatively by partial melting of tonalite to granodiorite in the crust is improbable; more likely, their petrogenesis requires a combination of these processes. Accordingly, Frost and Frost (2011) suggested that ferroan granites in general, and by inference the 1.4 Ga intrusions, represent variable mixing of crust-derived partial melts with differentiates of mantle-derived tholeiitic magma. Primary, mantle-derived mafic magma likely provided the heat required by variable degrees of crustal melting and, importantly, some mantle-derived magma. Elevated, experimentally determined liquidus temperatures (950 °C; Patiño Douce, 1997) for ferroan melts produced by dehydration melting of intermediate-composition calc-alkaline protoliths also require mantle-derived thermal inputs. Given the position of most of the 1.4 Ga intrusions in intracratonic/continental tectonic settings (Bickford and others, 2015), introduction of mantle-derived inputs into the crust requires extensional tectonism that promotes mantle upwelling and resultant crustal underplating by mafic, tholeiitic magma. The observed worldwide spatial and temporal association of felsic ferroan granitoids and relatively mafic igneous rocks (Anderson, 1983) is a predictable consequence of processes accompanying intracratonic extension and crustal underplating by upwelling, mantle-derived tholeiitic magma.

Metallogeny

Globally, many ferroan, slightly peraluminous, highly evolved A-type granitoids poor in P but strongly enriched in F, Li (lithium), Rb, Cs, Sn, Zr, Y, and HREEs are associated with rare-metal, high-field-strength, or REE mineral deposits (Dall'Agnol and others, 2012). However, the geochemistry of the ferroan 1.4 Ga intrusions of the conterminous United States is generally distinct relative to globally distributed A-type/ferroan granitoids with associated mineral deposits. Correspondingly, most of the 1.4 Ga intrusions lack associated mineral deposits of any type.

Very few samples of the 1.4 Ga intrusions contain anomalously elevated ore metal concentrations. In particular, abundances of Co, Cr, Cu, Mo (molybdenum), Ni, Sc, Sn, Ta, V, W (tungsten), and Zn in most samples of these intrusions are similar to that of average granites (Turekian and Wedepohl, 1961). Although abundances of Pb, Th, and U are characteristically elevated in the 1.4 Ga intrusions relative to average granite abundances, these concentrations are not economically significant. Notably, total REE contents of many samples of the 1.4 Ga intrusions are elevated relative to those of average granites. Almost half of the samples of the 1.4 Ga intrusions for which REE data are available contain more than 240 ppm total REEs, whereas average granites contain 200–240 ppm total REEs. Although most of the 1.4 Ga granitoid samples contain less than 600 ppm total REEs, a handful contain even greater REE abundances, ranging to as much as 2,500 ppm. However, despite locally elevated REE contents, none of these geochemical anomalies constitute REE ore.

Spatial and temporal relations suggest that mineral deposits, in two specific instances, may be genetically related to 1.4 Ga granitoid magmatism in the conterminous United States. Kisvarsanyi (1972) hypothesized that iron oxide-copper-gold (IOCG) and iron oxide-apatite (IOA) deposits are directly related to the 1.4 Ga intrusions in the St. Francois Mountains of southeastern Missouri, and Castor (2008) proposed a relation between the Mountain Pass LREE deposit and potassic 1.4 Ga igneous rocks in southeastern California. Relations between igneous rocks and IOCG and IOA deposits have been investigated globally, but genetic links remain uncertain (Barton, 2014; Nold and others, 2014). Relations between ore and particular igneous intrusions are not easily demonstrated, and igneous rocks coeval and cospatial with IOCG systems have highly variable compositions (Barton, 2014). Consequently, no individual igneous rock composition is known to be more prospective than others relative to potential for associated deposits. IOCG and IOA deposit formation likely requires a magmatic heat source, but magmatic sources for ore components included in these deposits have not been identified (Barton, 2014). Consequently, although mineral deposits in the St. Francois Mountains and at Mountain Pass may be genetically related to magmatism, they are unusual relative to other similar-age 1.4 Ga intrusions in the conterminous United States, which do not seem to have fostered the physiochemical environment conducive to deposit formation.

Southeast Missouri

REE-enriched IOA and IOCG deposits in southeast Missouri are temporally and spatially associated with approximately 1.4 Ga intrusive and extrusive rocks (Kisvarsanyi, 1972; Panno and Hood, 1983; Nold and others, 2014), but establishing definitive genetic relations between these igneous rocks and the deposits they host has proven difficult. Although geochronologic data indicate that the 1.4 Ga igneous rocks and IOA/IOCG deposits they contain are broadly coeval (Aleinikoff and others, 2016; Neymark and others, 2016), no additional observations support a genetic role for these igneous rocks. Gleason and others (2000) concluded that REE mineral deposit formation in southeast Missouri is independent of igneous rock composition and that the role of magmatism in deposit formation cannot be substantiated. Specifically, Nd isotopic data do not indicate uniquely whether fluids responsible for mineralization were derived from magmas represented by the 1.4 Ga igneous rocks in this area or from some other deep source. The isotopic data do indicate that these fluids, if not derived from these magmas, did equilibrate with the solidified igneous rocks that host deposits (Gleason and others, 2000). Similarly, in documenting the diversity of igneous rock compositions associated with IOA/IOCG deposits, felsic intrusions associated with deposits in southeast Missouri in particular, Barton (2014) concluded that basinal brines, not magmatic fluids, were critical to the formation of these deposits.

The absence of relations between IOA and IOCG mineral deposits and other 1.4 Ga intrusions in the conterminous United States suggests that the spatial and temporal associations between these types of deposits and 1.4 Ga intrusions in southeast Missouri are unusual. The inability to establish robust genetic relations between these deposits and coeval/cospatial igneous rocks suggests that these intrusions serve merely as passive ore hosts, though the magmas they represent may have supplied the heat required for mineralizing processes. Consequently, undiscovered deposit potential associated with other 1.4 Ga intrusions in the conterminous

United States is limited because the temporal and spatial association between 1.4 Ga igneous rocks and IOA and IOCG deposits in southeast Missouri appears to be fortuitous. Furthermore, shallow crustal levels indicated by coeval volcanic rocks overlying the 1.4 Ga intrusions in southeast Missouri differ from the geologic framework characteristic of the other 1.4 Ga intrusions, where coeval volcanic rocks are largely absent. This lack of overlying coeval volcanic rocks suggests that erosion has exposed relatively deeper crustal levels, below those at which genetically related IOA and IOCG deposits might be preserved. Mineral deposit formation requires optimizing ore metal availability (source), fluid characteristics (transport medium), structural setting (conduits), and host rock reactivity/receptivity (sink). In southeast Missouri at 1.4 Ga, the geologic conditions required for deposit formation fostered development of IOA and IOCG deposits. Although the early phase of voluminous 1.4 Ga magmatism in southeast Missouri may have supplied the heat required by coeval (Aleinikoff and others, 2016; Neymark and others, 2016) mineralizing processes, these ferroan magmas and their solidified equivalents did not otherwise contribute demonstrably to mineralizing processes but did serve as suitable ore deposit hosts. Perhaps other 1.4 Ga intrusions also hosted genetically related IOA and IOCG deposits but uplift and erosion resulted in deposit removal.

Mountain Pass

The geochemical characteristics of 1.4 Ga silicate igneous rocks (largely shonkinite and syenite, but including some granite) that host LREE-rich carbonatite rocks at the Mountain Pass deposit in southeast California are unique among 1.4 Ga intrusions. The ultrapotassic syenites (Castor, 2008) at Mountain Pass are restricted to a small geographic province that contains several other geochemically distinct, small-volume intrusions, including those at Barrel Spring (Gleason and others, 1994). As previously noted, the distinctly LILE-enriched syenites at Mountain Pass are the sole example of peralkaline rocks among the 1.4 Ga intrusions in the conterminous United States.

Radiogenic isotope characteristics of the Barrel Spring intrusions, also relevant to the Mountain Pass syenites because of the geologic and petrologic similarities between these rocks, indicate that these rocks could not have been derived by partial melting of enclosing Mojave crustal province basement, but they could reflect more isotopically primitive source materials of the mafic lower crust or lithospheric mantle (Gleason and others, 1994). The source for the Barrel Spring and Mountain Pass syenites contained 5 to 10 times the REE endowment characteristic of typical crust or mantle materials, and the petrogenesis of magmas represented by these intrusions is not easily related to that of the 1.4 Ga intrusions that have more conventional compositions (Gleason and others, 1994). Accordingly, Gleason and others (1994, p. 194) concluded that syenites at Barrel Spring and Mountain Pass "…occur only in a restricted area of the eastern Mojave Desert and northwestern Arizona that spans the boundary between the Mojave province and the Arizona province" and that "Melting in a distinctive, ancient lithospheric zone (crust or mantle) peculiar to this region during the mid-Proterozoic thermal event may have produced these magmas."

U-Pb zircon geochronology results suggest that Mountain Pass LREE-enriched carbonatite ore, which formed 1,375±5 million years ago (Ma), is significantly younger than the host syenites (DeWitt and others, 1987). Although Poletti and others (2016) suggested that a small volume of the igneous rock present at Mountain Pass may be coeval with the carbonatite ore, no plausible thermal scenario is consistent with crystallization of most of the igneous rocks at Mountain Pass, which have a weighted mean age of 1,417.3±4.6 Ma (Premo and others, 2013), having provided the thermal energy and geochemical components required by the much younger LREE mineralization. Thus, the apparent age difference between the Mountain Pass syenites and the younger LREE deposits largely precludes a direct relation between syenitic magmatism and LREE mineralization at Mountain Pass. Peculiarities of the crust-mantle section and thermal and geochemical regimes prevailing at 1.4 Ga beneath Mountain Pass are likely directly responsible for Mountain Pass LREE-deposit genesis. Further, Poletti and others (2016) used geochemical data to demonstrate that the carbonatite and ultrapotassic rocks were not comagmatic but were likely derived from the same source. Accordingly, potential for similar carbonatite-related LREE mineralization, beyond the particular crust-mantle regime above which Mountain Pass and Barrel Spring intrusions reside, is limited. Consequently, the potential for additional LREE deposits akin to those at Mountain Pass, but associated with other 1.4 Ga intrusions in the conterminous United States, is similarly restricted; the effective permissive setting for these deposits appears to be limited to the distinctive tectonic block sandwiched between the Mojave and the Arizona provinces.

Discussion

The geographically dispersed group of approximately 1.4 Ga intrusions constitutes a volumetrically significant component of the geologic framework of the conterminous United States. The 1.4 Ga intrusions exposed in the northern and southern midcontinent regions, across the Southwest, throughout the central Rocky Mountains, beneath the Great Plains, and sparingly in the northern Rockies (Idaho) are grossly similar to the set of A-type granitoids exposed around the globe. However, most of the 1.4 Ga intrusions in the conterminous United States are better referred to as ferroan granites and include some that are weakly magnesian. Approximately 1.4 Ga magmatism in the conterminous

United States is characterized by two temporal peaks, one between 1.455 and 1.405 Ga and a second between 1.405 and 1.320 Ga. Intrusions in each subregion have distinct age distributions. In some subregions, igneous activity is essentially continuous through the full duration of broadly 1.4 Ga magmatism; intrusion ages are bimodally distributed in others, and 1.4 Ga intrusions in the remaining subregions define single magmatic pulses, some as short as 5 m.y. Ages of broadly 1.4 Ga intrusions in the United States do not vary systematically across their geographic extent, nor do they exhibit magmatic synchronicity among regions.

Our geochemical data are in accord with interpretations (Dall'Agnol and others, 2012) that the petrogenesis of ferroan granitoids involves (1) incompletely mixed mantle- and crust-derived magmas and (2) an extensional tectonic setting. The tectonic setting and character of the juvenile continental crust domains that host ferroan granitoid intrusions may also be critical to their petrogenesis. Condie (1982) suggested that the addition of hundreds of kilometers of Paleoproterozoic juvenile sialic crust southward from the Laurentian core was a consequence of a long-lived outboard (southward)-migrating arc system, coupled with formation and closure of successive back-arc basins. Continental growth of this sort is driven by a subduction regime that alternates between compression and extension (slab retreat) accompanied by the addition of basaltic magma into the crust during lithospheric stretching and related decompression melting, processes akin to extensional accretionary orogeny (Collins, 2002). Crustal growth achieved in this fashion contrasts with accretionary models because the resulting continental augmentation is accompanied by complex extensional tectonics and reflects back-arc processes that thin the continental-transitional continental crust sufficiently to provide the thermal energy required for melting and bimodal intracratonic magmatism at some distance inboard from continental margins (Karlstrom and others, 2001). The Paleoproterozoic (1.9–1.6 Ga) host domains formed during fragmentation of the supercontinent Columbia and accompanying superplume magmatism, whereas 1.4 Ga granitoid magmatism reflects extension-driven continental augmentation and cratonization following supercontinent fragmentation.

Ferroan 1.4 Ga granitoid magmatism in the United States may also reflect the generation of radiogenic heat in fertile, juvenile Paleoproterozoic crust as well as conductive heat derived from mantle upwelling (Dewane and Van Schmus, 2007) during the final stages of supercontinent breakup. The widespread distribution of the 1.4 Ga intrusions in the conterminous United States and their compositional diversity are likely consequences of the compositional diversity and broad extent of the Paleoproterozoic juvenile crustal domains that host the ferroan granitoids south and west of the Laurentian core. The correlation between broad Paleoproterozoic juvenile crustal domains and significant Mesoproterozoic ferroan magmatism hosted therein suggests processes that, although not unique to the Precambrian, were critical to widespread 1.4 Ga magmatism in the conterminous United States. Voluminous 1.4 Ga magmatism probably reflects the changing array of processes that governed the Earth's evolution and to which particular host domains were required precursors (Dall'Agnol and others, 2012).

Diverse compositional characteristics of the 1.4 Ga intrusions are key to understanding the petrogenesis of the magmas they represent. Classification of ferroan granites (Frost and Frost, 2011) into eight subtypes, and their weakly magnesian variants, constrains the petrogenesis of these intrusions because each compositional subtype can be correlated with particular magmatic processes. In particular, numerous ferroan, peraluminous 1.4 Ga intrusions in the conterminous United States likely represent low degrees of partial melting of preexisting, intermediate-composition granitoid rock at relatively elevated crustal pressures; different pressures, related to melting at diverse crustal depths, controls whether the resulting magmas are calc-alkalic or alkali-calcic. The moderately numerous, weakly magnesian and peraluminous 1.4 Ga intrusions reflect more advanced partial melting of crust-derived intermediate-composition granitoid rocks at lower pressure. In contrast, the ferroan but metaluminous granitoids represent extensive differentiation of tholeiitic basalt (Frost and Frost, 2011). Accordingly, the large group of ferroan but metaluminous 1.4 Ga intrusions probably represent differentiates of mantle-derived tholeiitic magma; their wide-ranging alkalinity reflects the balance between clinopyroxene versus plagioclase fractionation. The more alkalic granitoids represent greater clinopyroxene fractionation, at higher pressure, whereas those that are more calcic reflect greater plagioclase fractionation, consistent with lower pressure conditions. Peralkaline 1.4 Ga intrusions, restricted to those at Mountain Pass, have compositions consistent with derivation by differentiation of alkali basalt (Frost and Frost, 2011). The diversity of compositions and isotopic characteristics among the 1.4 Ga intrusions are indicative of both mantle-derived mafic inputs and more evolved contributions generated by partial melting of crustal protoliths; the petrogenesis of these intrusions requires contributions from multiple distinct sources. We suggest that the 1.4 Ga intrusions in the conterminous United States depict crustal melting events in an extensional, intracratonic setting that accompanied mantle upwelling and emplacement of tholeiitic basaltic magma at or near the base of the crust. Subsequently, primary mafic mantle-derived magmas assimilated crust-derived partial melts, and the variably mingled and mixed silicate liquids formed variably homogenized storage reservoirs; continued polybaric magma evolution ensued within reservoirs lodged at various heights in the crust.

Conclusions

Our investigation of 1.4 Ga magmatism in the conterminous United States has resulted in numerous conclusions concerning their petrogenesis and metallogeny.

1. The 1.4 Ga intrusions represent voluminous magmatism across broad swaths of the conterminous United States.
2. The majority of these intrusions are composed of relatively evolved ferroan granite.
3. The 1.4 Ga intrusions include two distinct age populations that are not uniformly distributed in space and time.
4. Broadly 1.4 Ga intrusions in each subregion form distinct age populations relative to those in other subregions.
5. In the conterminous United States, significant mineral deposits are associated with ferroan intrusions only at Mountain Pass and in the St. Francois Mountains because of unusual local circumstances, but the remaining 1.4 Ga intrusions have neither associated mineral deposits nor significant potential for undiscovered deposits.
6. Approximately 1.4 Ga magmatism in the conterminous United States is a manifestation of extensional tectonism associated with periodic but aborted continental fragmentation and intracratonic mantle upwelling.
7. The distribution of voluminous 1.4 Ga intrusions in the conterminous United States is correlated with juvenile Paleoproterozoic crustal domains, which suggests that these host domains were a required precursor.
8. The petrogenesis of 1.4 Ga intrusions in the conterminous United States reflects mantle-derived thermal and mass input, crustal partial melting, and variable mixing and homogenization of these two components.
9. Compositional variation among many 1.4 Ga intrusions in the conterminous United States reflects low-degree partial melting of preexisting, intermediate-composition igneous sources.
10. Compositional variation among 1.4 Ga intrusions in the conterminous United States reflects variable petrogenetic conditions, including crustal source lithologic diversity and variable depth (pressure) and extent of partial melting.

Acknowledgments

Investigations undertaken as part of this study were conducted as part of the Basement Tectonic Framework and Petrogenesis and REE metallogenesis of 1.4 Ga magmatism in the conterminous United States Projects funded by the U.S. Geological Survey Mineral Resources Program. Constructive reviews by P.L. Verplanck and J.N. Aleinikoff are much appreciated and helped clarify data presentation and interpretation.

References Cited

Aleinikoff, J.N., Selby, D., Slack, J.F., Day, W.C., Pillers, R.M., Cosca, M.A., Seeger, C.M., Fanning, C.M., and Samson, I.M., 2016, U-Pb, Re-Os, and Ar/Ar geochronology of rare earth element (REE)-rich breccia pipes and associated host rocks from the Mesoproterozoic Pea Ridge Fe-REE-Au deposit, St. Francois Mountains, Missouri: Economic Geology, v. 111, p. 1883–1914.

Anders, Edward, and Ebihara, Mitsuru, 1982, Solar-system abundances of the elements: Geochimica et Cosmochimica Acta, v. 46, 2362–2380.

Anderson, I.C., Frost, C.D., and Frost, B.R., 2003, Petrogenesis of the Red Mountain pluton, Laramie anorthosite complex, Wyoming—Implications for the origin of A-type granite: Precambrian Research, v. 124, p. 243–267.

Anderson, J.L., 1983, Proterozoic anorogenic granite plutonism of North America, *in* Medaris, L.G., Jr., Byers, C.W., Mickelson, D.M., and Shanks, W.C., eds., Proterozoic geology—Selected papers from an International Proterozoic Symposium: Geological Society of America Memoir 161, p. 133–154.

Anderson, J.L., and Bender, E.E., 1989, Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America: Lithos, v. 23, p. 19–52.

Anderson, J.L., and Cullers, R.L., 1978, Geochemistry and evolution of the Wolf River batholith, a late Precambrian rapakivi massif in north Wisconsin, U.S.A.: Precambrian Research, v. 7, p. 287–324.

Bankey, Viki; Cuevas, Alejandro; Daniels, David; Finn, C.A.; Hernandez, Israel; Hill, Patricia; Kucks, Robert; Miles, Warner; Pilkington, Mark; Roberts, Carter; Roest, Walter; Rystrom, Victoria; Shearer, Sarah; Snyder, Stephen; Sweeney, Ronald; and Velez, Julio, 2002, Magnetic anomaly map of North America: U.S. Geological Survey Special Map, 1 sheet, scale 1:10,000,000, 31-p. pamphlet. [Prepared by the North American Magnetic Anomaly Group, with members from the Geological Survey of Canada, the U.S. Geological Survey, and the Consejo de Recursos Minerales de México.]

Barton, M.D., 2014, Iron oxide(–Cu–Au–REE–P–Ag–U–Co) systems, section 20 *of* Scott, S.D., ed., Geochemistry of mineral deposits, v. 13 *of* Holland, Heinrich, and Turekian, Karl, eds., Treatise on geochemistry (second edition): Elsevier, p. 515–541.

Bauer, P.W., and Pollock, T.R., 1993, Compilation of Precambrian isotopic ages in New Mexico: New Mexico Bureau of Mines and Mineral Resources Open-File Report 389, 128 p.

Bickford, M.E., Cullers, R.L., Shuster, R.D., Premo, W.R., and Van Schmus, W.R., 1989, U-Pb zircon geochronology of Proterozoic and Cambrian plutons in the Wet Mountains and southern Front Range, Colorado, *in* Grambling, J.A., and Tewksbury, B.J., eds., Proterozoic geology of the southern Rocky Mountains: Geological Society of America Special Paper 235, p. 49–64.

Bickford, M.E., Harrower, K.L., Hoppe, W.J., Nelson, B.K., Nusbaum, R.L., and Thomas, J.J., 1981, Rb-Sr and U-Pb geochronology and distribution of rock types in the Precambrian basement of Missouri and Kansas: Geological Society of America Bulletin, Part I, v. 92, p. 323–341.

Bickford, M.E., and Mose, D.G., 1975, Geochronology of Precambrian rocks in the St. Francois Mountains, southeast Missouri: Geological Society of America Special Paper 165, 48 p.

Bickford, M.E., Van Schmus, W.R., Karlstrom, K.E., Mueller, P.A., and Kamenov, G.D., 2015, Mesoproterozoic-trans-Laurentian magmatism—A synthesis of continent-wide age distributions, new SIMS U-Pb ages, zircon saturation temperatures, and Hf and Nd isotopic compositions: Precambrian Research, v. 265, p. 286–312.

Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: Canadian Mineralogist, v. 46, p. 779–806.

Collins, W.J., 2002, Nature of extensional accretionary orogens: Tectonics, v. 21, p. 6-1–6-12.

Condie, K.C., 1982, Plate tectonics model for Proterozoic continental accretion in the southwestern United States: Geology, v. 10, p. 37–42.

Condie, K.C., and Budding, A.J., 1979, Geology and geochemistry of Precambrian rocks, central and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 35, 59 p.

Cousens, B.L., Prytulak, Julie, Henry, C.D., Alcazar, Al, and Brownrigg, Tim, 2008, Geology, geochronology, and geochemistry of the Miocene-Pliocene ancestral Cascades arc, northern Sierra Nevada, California and Nevada—The roles of the upper mantle, subducting slab, and the Sierra Nevada lithosphere: Geosphere, v. 4, p. 814–828.

Dall'Agnol, Roberto, Frost, C.D., and Ramo, O.T., 2012, IGCP Project 510 "A-type granites and related rocks through time"—Project vita, results, and contribution to granite research, *in* Dall'Agnol, Roberto, Frost, C.D., and Ramo, O.T., eds., A-type granites and related rocks through time: Lithos, v. 151, p. 1–16.

Day, W.C., Slack, J.F., Ayuso, R.A., and Seeger, C.M., 2016, Regional geologic and petrologic framework for iron oxide ± apatite ± rare earth element and iron oxide copper-gold deposits of the Mesoproterozoic St. Francois Mountains terrane, southeast Missouri, USA: Economic Geology, v. 111, p. 1825–1858.

Dewane, T.J., and Van Schmus, W.R., 2007, U-Pb geochronology of the Wolf River batholith, north-central Wisconsin—Evidence for successive magmatism between 1484 Ma and 1468 Ma: Precambrian Research, v. 157, p. 215–234.

DeWitt, Ed, Kwak, L.M., and Zartman, R.E., 1987, U-Th-Pb and $^{40}Ar/^{39}Ar$ dating of the Mountain Pass carbonatite and alkalic igneous rocks, S.E. Cal: Geological Society of America Abstracts with Programs, v. 19, no. 1, p. 642.

du Bray, E.A., Holm-Denoma, C.S., San Juan, C.A., Lund, Karen, Premo, W.R., and DeWitt, Ed, 2015, Geochemical, modal, and geochronologic data for 1.4 Ga A-type granitoid intrusions of the conterminous United States: U.S. Geological Survey Data Series 942, 19 p., accessed January 16, 2016, at https://doi.org/10.3133/ds942.

Ewart, A., 1982, The mineralogy and petrology of Tertiary–Recent orogenic volcanic rocks with special reference to the andesitic-basaltic compositional range, *in* Thorpe, R.S., ed., Andesites—Orogenic andesites and related rocks: New York, John Wiley and Sons, p. 25–87.

Farmer, G.L., Glazner, A.F., and Manley, C.R., 2002, Did lithospheric delamination trigger late Cenozoic potassic volcanism in the southern Sierra Nevada, California?: Geological Society of America Bulletin, v. 114, p. 754–768.

Frost, B.R., and Frost, C.D., 2008, A geochemical classification of feldspathic igneous rocks: Journal of Petrology, v. 49, p. 1955–1969.

Frost, C.D., Bell, J.M., Frost, B.R., and Chamberlain, K.R., 2001, Crustal growth by magmatic underplating—Isotopic evidence from the northern Sherman batholith: Geology, v. 29, p. 515–518.

Frost, C.D., and Frost, B.R., 2011, On ferroran (A-type) granitoids—Their compositional variability and modes of origin: Journal of Petrology, v. 52, p. 39–53.

Frost, C.D., Frost, B.R., Bell, J.M., and Chamberlain, K.R., 2002, The relationship between A-type granites and residual magmas from anorthosite—Evidence from the northern Sherman batholith, Laramie Mountains, Wyoming, USA: Precambrian Research, v. 119, p. 45–71.

Gill, J.B., 1981, Orogenic andesites and plate tectonics: New York, Springer-Verlag, 390 p.

Gleason, J.D., Marikos, M.A., Barton, M.D., and Johnson, D.A., 2000, Neodymium isotopic study of rare earth element sources and mobility in hydrothermal Fe oxide (Fe-P-REE) systems: Geochimica et Cosmochimica Acta, v. 64, p. 1059–1068.

Gleason, J.D., Miller, C.F., Wooden, J.L., and Bennett, V.C., 1994, Petrogenesis of the highly potassic 1.42 Ga Barrel Spring pluton, southeastern California, with implications for mid-Proterozoic magma genesis in the southwestern USA: Contributions to Mineralogy and Petrology, v. 118, p. 182–197.

Goodge, J.W., and Vervoort, J.D., 2006, Origin of Mesoproterozoic granites in Laurentia—Hf isotope evidence: Earth and Planetary Science Letter, v. 243, p. 711–731.

Green, T.H., 1982, Anatexis of mafic crust and high pressure crystallization of andesite, *in* Thorpe, R.S., ed., Andesites—Orogenic andesites and related rocks: New York, John Wiley and Sons, p. 465–487.

Hanson, G.N., 1980, Rare earth elements in petrogenetic studies of igneous systems: Annual Review of Earth and Planetary Sciences, v. 8, p. 371–406.

Hildreth, Wes, and Moorbath, Stephen, 1988, Crustal contributions to arc magmatism in the Andes of central Chile: Contributions to Mineralogy and Petrology, v. 98, p. 455–489.

Hoppe, W.J., Montgomery, C.W., and Van Schmus, W.R., 1983, Age and significance of Precambrian basement samples from northern Illinois and adjacent states: Journal of Geophysical Research—Solid Earth, v. 88, p. 7276–7286.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548.

Karlstrom, K.E., Ahall, K.-I., Harlan, S.S., Williams, M.L., McLelland, James, and Geissman, J.W., 2001, Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia: Precambrian Research, v. 111, p. 5–30.

Kisvarsanyi, E.B., 1972, Petrochemistry of a Precambrian igneous province, St. Francois Mountains, Missouri: Missouri Geological Survey and Water Resources Report of Investigations 51, 96 p.

Le Maitre, R.W., 1989, A classification of igneous rocks and glossary of terms: Oxford, United Kingdom, Blackwell Scientific, 193 p.

Loewy, S.L., Connelly, J.N., Dalziel, I.W.D., and Gower, C.F., 2003, Eastern Laurentia in Rodinia—Constraints from whole-rock Pb and U/Pb geochronology: Tectonophysics, v. 375, p. 169–197.

Loiselle, M.C., and Wones, D.R., 1979, Characteristics and origin of anorogenic granites: Geological Society of America Abstracts with Programs, v. 11, no. 7, p. 468.

Lund, Karen, Box, S.E., Holm-Denoma, C.S., San Juan, C.A., Blakely, R.J., Saltus, R.W., Anderson, E.D., and DeWitt, E.H., 2015, Basement domain map of the conterminous United States and Alaska: U.S. Geological Survey Data Series 898, 41 p., accessed January 24, 2016, at https://doi.org/10.3133/ds898.

Macdonald, Ray, Smith, R.L., and Thomas, J.E., 1992, Chemistry of the subalkalic silicic obsidians: U.S. Geological Survey Professional Paper 1523, 214 p.

Miyashiro, Akiho, 1974, Volcanic rock series in island arcs and active continental margins: American Journal of Science, v. 274, p. 321–355.

Neymark, L.A., Holm-Denoma, C.S., Pietruszka, A.J., Aleinikoff, J.N., Fanning, C.M., Pillers, R.M., and Moscati, R.J., 2016, High spatial resolution U-Pb geochronology and Pb isotope geochemistry of magnetite-apatite ore from the Pea Ridge iron oxide-apatite deposit, St. Francois Mountains, southeast Missouri, USA: Economic Geology, v. 111, p. 1915–1933.

Nold, J.L., Dudley, M.A., and Davidson, Paul, 2014, The southeast Missouri (USA) Proterozoic iron metallogenic province—Types of deposits and genetic relationships to magnetite-apatite and iron oxide-copper-gold deposits: Ore Geology Reviews, v. 57, p. 154–171.

Panno, S.V., and Hood, W.C., 1983, Volcanic stratigraphy of the Pilot Knob iron deposits, Iron County, Missouri: Economic Geology, v. 78, p. 972–982.

Patiño Douce, A.E., 1997, Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids: Geology, v. 25, p. 743–746.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 956–983.

Peterman, Z.E., and Hedge, C.E., 1968, Chronology of Precambrian events in the Front Range, Colorado: Canadian Journal of Earth Sciences, v. 5, p. 749–756.

Poletti, J.E., Cottle, J.M., Hagen-Peter, G.A., and Lackey, Jade Star, 2016, Petrochronological constraints on the origin of Mountain Pass ultrapotassic and carbonatite intrusive suite, California: Journal of Petrology, v. 57, p. 1555–1598.

Premo, W.R., DeWitt, E.H., Moscati, R.J., Cosca, M.A., Stoesser, Douglas, and Premo, V.L., 2013, Ages and Pb-Sr-Nd isotopes of silicate rocks at Mountain Pass, southern California: Geological Society of America Abstracts with Programs, v. 45, no. 7, p. 113.

Rogers, J.J.W., and Santosh, M., 2002, Configuration of Columbia, a Mesoproterozoic supercontinent: Gondwana Research, v. 5, p. 5–22.

Rutherford, M.J., and Hill, P.M., 1993, Magma ascent rates from amphibole breakdown—An experimental study applied to the 1980–1986 Mount St. Helens eruption: Journal of Geophysical Research, v. 98, p. 19667–19685.

Shand, S.J., 1951, Eruptive rocks: New York, John Wiley, 488 p.

Skjerlie, K.P., and Johnston, A.D., 1993, Fluid-absent melting behavior of an F-rich tonalitic gneiss at mid-crustal pressures—Implications for the generation of anorogenic granites: Journal of Petrology, v. 34, p. 785–815.

Streckeisen, Albert, 1976, To each plutonic rock its proper name: Earth-Science Reviews, v. 12, p. 1–33.

Sun, S.-S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts—Implications for mantle composition and processes, *in* Saunders, A.D., and Norry, M.J., eds., Magmatism in the ocean basins: Geological Society of London Special Publication 42, p. 313–345.

Thomas, W.A., Tucker, R.D., Astini, R.A., and Denison, R.E., 2012, Ages of pre-rift basement and synrift rocks along the conjugate rift and transform margins of the Argentine Precordillera and Laurentia: Geosphere, v. 8, p. 1366–1383.

Tohver, E., Bettencourt, J.S., Tosdal, R., Mezger, K., Leite, W.B., and Payolla, B.L., 2004, Terrane transfer during the Grenville orogeny—Tracing the Amazonian ancestry of southern Appalachian basement through Pb and Nd isotopes: Earth and Planetary Science Letters, v. 228, p. 161–176.

Turekian, K.K., and Wedepohl, K.H., 1961, Distribution of the elements in some major units of the Earth's crust: Geological Society of America Bulletin, v. 72, p. 175–192.

Van Schmus, W.R., and Bickford, M.E., 1981, Proterozoic chronology and evolution of the Midcontinent region, North America, *in* Kroner, A., ed., Precambrian plate tectonics: Elsevier Scientific Publishing, Developments in Precambrian Geology, v. 4, p. 261–296.

Van Schmus, W.R., Medaris, L.G., Jr., and Banks, P.O., 1975, Geology and age of the Wolf River batholith, Wisconsin: Geological Society of America Bulletin, v. 86, p. 907–914.

Watson, E.B., 1979, Zircon saturation in felsic liquids—Experimental results and applications to trace element geochemistry: Contributions to Mineralogy and Petrology, v. 70, p. 407–419.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, p. 220–259.

Wood, D.A., Joron, J.-L., and Treuil, Michel, 1979, A re-appraisal of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings: Earth and Planetary Science Letters, v. 45, p. 326–336.

Publishing support provided by the Science Publishing Network,
Denver Publishing Service Center

For more information concerning the research in this report, contact the
Center Director, USGS Geology, Geophysics, and Geochemistry Science Center

Box 25046, Mail Stop 973
Denver, CO 80225
(303) 236-1800

Or visit Geology, Geophysics, and Geochemistry Science Center website at
https://minerals.cr.usgs.gov/

This publication is available online at
https://doi.org/sir20175111

USGS

du Bray and others—**Review of the Geochemistry and Metallogeny of 1.4 Ga Granitoid Intrusions of the Conterminous United States**—SIR 2017–5111

ISSN 2328-0328 (online)
https://doi.org/sir20175111