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Source regions of granites and their links to tectonic environment: examples from the western United States

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Abstract

This review, in honor of Ilmari Haapala's retirement, reflects on lessons learned from studies of three granitic systems in western North America: (1) Mesoproterozoic samples from west Texas and east New Mexico; (2) Laramide granitic systems associated with porphyry-copper deposits in Arizona; and (3) granites of the Colorado Mineral Belt. The studies elucidate relationships amongst tectonic setting, source material, and magma chemistry.

Mesoproterozoic basement samples are from two different felsic suites with distinct elemental and isotopic compositions. The first suite, the "plutonic province", is dominantly magnesian, calc-alkalic to alkali-calcic, and metaluminous. It has low K_2O/Na_2O and Rb/Sr, and Nd model ages of 1.56 to 1.40 Ga. The second suite, the "Panhandle igneous complex", is magnesian, metaluminous, alkalic, and is part of the Mesoproterozoic belt of magmatism that extends from Finland to southwestern United States. Samples from the Panhandle igneous complex demonstrate three episodes of magmatism: the first pulse was intrusion of quartz monzonite at 1380 to 1370 Ma; the second was comagmatic epizonal granite and rhyolite at 1360 to 1350 Ma. Both of these rock types are high-K to slightly ultra-high-K. The third pulse at 1338 to 1330 Ma was intrusion of ultra-high-K quartz syenite. Nd model ages (1.94 to 1.52 Ga) are distinct from those of the "plutonic province" and systematically older than crystallization ages, implying a substantial crustal input to the magmas.

At the Sierrita porphyry-copper deposit in the Mazatzal Province of southeastern Arizona, trace element, Sr, and Nd isotopic compositions were determined for a suite of andesitic and rhyolitic rocks (67 Ma) intruded by granodiorite and granite. Isotopic composition and chemical evolution are well correlated throughout the suite. Andesite has the least negative initial ε_{Nd} (−4.3) and lowest $^{87}Sr/^{86}Sr_i$ (0.7069). It is also the oldest and chemically most primitive, having low concentrations of Rb, SiO_2, and high concentrations of transition elements. These parameters change through the system to the youngest unit (granite), which has the most negative ε_{Nd} (−8.5), the highest $^{87}Sr/^{86}Sr_i$ (0.7092), and is chemically most evolved. Correlation between chemical and Nd isotopic evolution probably resulted from a continuous process of progressive assimilation, in which mafic magmas invade and incorporate continental crust. Deposits in Arizona with ε_{Nd} values more negative than the −8.5 of Sierrita lie in the older Yavapai province in the northwestern part of the state. The difference in the most negative epsilon Nd implies that Nd isotopic signature is sensitive to the age of the Precambrian domain.

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The granites from the Colorado Mineral Belt were emplaced during the transition from Laramide convergence to mid-Tertiary extension. Three different groups of granites are recognized. The first is Laramide and was formed during assimilation-fractional crystallization involving lower crustal mafic source materials; the second and third groups are mid-Tertiary and represent intracrustal melting of heterogeneous sources. This change in source regions and melt regimes in transition from convergence to extension is fundamental to the Mesozoic and Cenozoic evolution of western North America.

Keywords: Granite; Mesoproterozoic; Laramide; Colorado Mineral Belt; North America

1. Introduction

This article draws on studies of three granite systems of diverse ages in the western United States. These are Mesozoic-aged granites related to porphyry-copper deposits in Arizona (Anthony, 1986; Anthony and Titley, 1988, 1994; Titley and Anthony, 1989), granites of the Colorado Mineral Belt that span the transition from Mesozoic compressional tectonics to mid-Tertiary extension in Colorado (Ouimette, 1993, 1995), and Mesoproterozoic granites of the Southern Granite-Rhyolite Province of Texas and New Mexico (Barnes et al., 1999a, 2002; Amarante et al., 2004). A recurring theme in these studies is the importance of magmatic source materials in controlling fundamental characteristics of granites. This idea is not new; it has been either implicit or explicit in many studies through the decades and was elegantly summarized by Chappell (1979) in the statement "...granites image their sources...". Recently, Frost et al. (2001) advocated a return to a descriptive classification of granitoids in terms of Fe-number, alkali-lime index, and aluminum saturation, and abandonment of the alphabetical typologic nomenclature. One reason the alphabetical nomenclature is so enduring is that it addresses tectonic setting, which is a primary justification for the study of granite petrogenesis. This review presents examples of the first-order correlation between the chemical and isotopic signature of granites and their source regions and argues that the link between granites and tectonics is via the source region. Confusion and obfuscation occur in the alphabetical or any other classification when a direct link is attempted between granite chemistry and tectonics that neglects the important intermediate step of evaluating the role of source materials.

2. The Mesoproterozoic of west Texas and New Mexico

2.1. Observations

This study used core samples from the basement of west Texas and eastern New Mexico (Fig. 1) retrieved from drilling into Precambrian basement during oil exploration. Therefore, the majority consisted of one sample per well resulting in a reconnaissance charac-

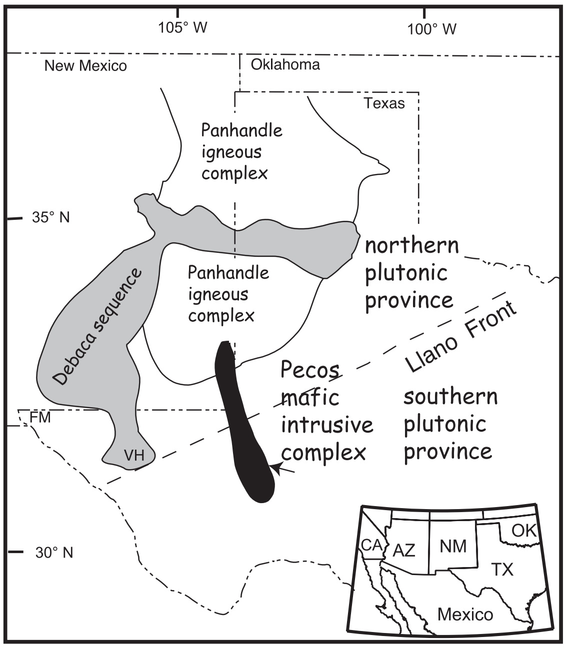

Fig. 1. Location map for Mesoproterozoic geological features of the southern United States; FM—Franklin Mountains, VH—Van Horn Mountains. Other features as described in text. Inset shows location relative to the United States and Mexico; CA—California, AZ—Arizona, NM—New Mexico, TX—Texas, OK—Oklahoma. Modified from Amarante et al. (2004).

terization of the distribution of igneous rock types in the area (Barnes et al., 1999a). Petrography of the samples was originally described by Flawn (1956), Muehlberger et al. (1967), and Thomas et al. (1984) and was used to draft the Decade of North American Geology (DNAG) basement map for the area. A second set of cuttings came from 41 closely spaced wells that penetrated the Southern Granite-Rhyolite Province in the Panhandle area of west Texas (Barnes et al., 2002). Approximately half of the wells penetrate the basement at least 90 m, another quarter as much as 190 m, and some more than 210 m. Detailed logs of all wells are in Barnes (2001), and a summary figure of stratigraphic columns and interpretative cross-sections are in Barnes et al. (2002). Finally, samples were studied from a well, the Mescalero #1, that penetrated approximately 2652 m of basement in eastern New Mexico. The well includes from top to bottom Mesoproterozoic Debaca sequence (a cover sequence of metasedimentary and metavolcanic rocks intruded by gabbros), which is in depositional contact with underlying rocks from the Southern Granite-Rhyolite Province. The latter are analogous in age and lithology to samples from the Panhandle area. Geophysical logs for the well correlate to lithology and seismic reflection profiles, yielding a three-dimensional interpretation of this basement area (Amarante et al., 2004).

Petrography, whole-rock chemistry, mineral chemistry, and Nd isotopes were used to characterize the samples. Whole-rock chemistry was used to classify the samples according to the scheme of Frost et al. (2001) and to explore the influence of source material on melt composition (e.g., Patiño Douce, 1996, 1999). Mineral chemistry was used primarily to estimate the oxidation state of the magma. A traditional method for determining oxidation state is to determine the composition of iron-oxide minerals. The studies included here used, however, the composition of biotite in equilibrium with quartz, K-feldspar, and magnetite (Wones and Eugster, 1965; Wones, 1972). For this assemblage, high Mg numbers correlate with high oxidation states, because Fe^{3+} partitions into magnetite. Nd isotopic signature was used to discriminate between crustal provinces of different ages and to evaluate mixing of reservoirs during magma genesis.

Two felsic suites were recognized on the basis of the criteria described above (Table 1; Barnes et al., 1999a, 2002). The first suite, referred to as the “plutonic province” (cf., Fig. 1), is dominantly magnesian, metaluminous, calc-alkalic to alkalic-calcic, with a few ferroan, metaluminous, and alkalic samples. Biotite chemistry indicates that the magnesian samples are moderately to highly oxidized, and the ferroan samples are strongly reduced. Nd model ages (calculated according to Nelson and DePaolo, 1985) are 1.35 to 1.34 Ga for the ferroan samples and 1.56 to 1.40 Ga for the magnesian samples. No crystallization ages exist for the plutonic province. The second suite is from the Panhandle area of the Southern Granite-Rhyolite Province and is referred to as the “Panhandle igneous complex”. It consists of undeformed epizonal granites and ignimbritic rhyolites intruded by two generations of mafic sills and dikes. It is distinct from the plutonic province in that it is magnesian, metaluminous, but alkalic rather than calc-alkalic or alkali-calcic, and is characterized by $K_2O/Na_2O>1$ and $Rb/Sr>1$. Biotite chemistry indicates that all samples are highly oxidized, and Nd model ages, which range from 1.94 to 1.52 Ga, are older than in the plutonic province. U–Pb dates on zircon yield crystallization ages of 1.38 to 1.34 Ga for the Panhandle igneous complex (Barnes et al., 2002, and references therein).

The samples from the 41 closely spaced wells yield a detailed picture of the Panhandle igneous complex that clarifies its characteristics and serves as an important contribution to understanding Mesoproterozoic magmatism in southern Laurentia. Petrography, geochemistry, and geochronology define three pulses of magmatism. The first pulse, intrusion of quartz monzonite, occurred at 1380 to 1370 Ma; the second pulse was contemporaneous emplacement of comagmatic, high-K epizonal granite and rhyolite at 1360 to 1350 Ma. The third pulse of magmatism, at 1338 to 1330 Ma, was intrusion of ultra-high-K quartz syenite. Biotite chemistry implies that all samples are highly oxidized. In fact, these samples are among the highest Mg numbers for biotite from ~1.4 Ga magmatism in western North America (Barnes et al., 2002, Fig. 13). F/Cl ratios in the biotites are uniform and low for the granites and rhyolite, and higher and more variable for the monzonite and syenite.

Table 1
Characteristics of Mesoproterozoic granites from western Texas and eastern New Mexico

Lithology	Classification	Chemistry	Oxidation state	Nd isotopes	Comments
Panhandle igneous complex					
• Quartz monzonite (1380 to 1370 Ma) granite/rhyolite (1360 to 1350 Ma)	Magnesian-metaluminous to peraluminous-alkalic	High-K to borderline ultra-high-K $K_2O/Na_2O>1$ Rb/Sr>1	Oxidized, amongst most oxidized of ~1.4 Ga granitoids of North America	t_{DM}=1.94 to 1.52 Ga	t_{DM} greater than crystallization age
• Quartz syenite (1338 to 1330 Ma)		Ultra-high-K	High F/Cl relative to granite/rhyolite		
Plutonic province					
• Crosbyton gravity and magnetic high	Ferroan-metaluminous-alkalic		Reducing	t_{DM}=1.35 to 1.34 Ga	
• Deformed granitoids	Magnesian-metaluminous-calc-alkalic to alkali-calcic	$K_2O/Na_2O<1$ Rb/Sr<1	Intermediate to high	t_{DM}=1.56 to 1.40 Ga	
Mafic rocks					
• Alkaline	Low Mg number	No Nb anomaly in majority of samples	Not applicable	PMIC: t_{DM}=1.53 Ga panhandle: t_{DM}=1.56 to 1.44 Ga Debaca sequence: t_{DM}=1.26 Ga	Detrital zircon from base of Debaca sequence: 1690 and 1320 Ma populations
• subalkaline	High Mg number				

t_{DM} is depleted mantle model age calculated according to DePaolo (1988).

Mafic rocks are ubiquitous (Table 1) and include samples from the Debaca sequence and Pecos mafic intrusive complex, a voluminous layered mafic intrusion (Kargi and Barnes, 1995; Barnes et al., 1999b) with a clear gravity and seismic reflection signature (Adams and Miller, 1995). Mafic rocks also are found as sills and dikes in the 41 wells of the Panhandle igneous complex. They constitute a substantial portion (~20% to 30%) of the cuttings, creating a bimodal character to the rock types. In the Mescalero #1 well, mafic rocks are found as diorite associated with the Mesoproterozoic quartz syenite and as gabbro intruding the overlying Debaca sequence. The mafic rocks are in part alkaline, in part subalkaline, and the majority lacks a negative Nb anomaly. The subalkaline rocks tend to have lower Fe numbers, whereas the alkaline rocks have high Fe numbers and are more evolved. The oldest Nd model ages are from the Panhandle igneous complex (1.56 to 1.44 Ga) and the Pecos mafic intrusive complex (1.53 Ga). A model age for one sample from the Debaca sequence is distinctly younger at 1.26 Ga. SHRIMP analysis of detrital zircon from an arkose at the base of Debaca sequence in the Mescalero #1 well yields populations at 1708 and 1308 Ma (Barnes, 2001; Amarante et al., 2004). The immediately underlying quartz syenite is 1332 Ma. $^{40}Ar/^{39}Ar$ spectra for hornblende and biotite from the gabbros that intrude the upper portion of the Debaca sequence in this well yield apparent ages of ~1090 Ma.

2.2. Interpretation

2.2.1. Ages of mafic magmatism

The Nd model ages for mafic samples indicate that the rocks are Mesoproterozoic; because, these are only model ages, no more detailed interpretation is warranted. This point is made clear in the Franklin Mountains of west Texas, where mafic dikes and sills with Nd model ages of 1.47 to 1.31 Ga (Patchett and Ruiz, 1989; Barnes et al., 1999b) crosscut the Red Bluff granitic suite, which has a U–Pb zircon age of 1.12 Ga (Shannon et al., 1997). A second example is the Pecos mafic intrusive complex with its Nd model age of 1.53 Ga compared to U–Pb crystallization ages of 1163 to 1072 Ma (Keller et al., 1989). Crystallization ages, on the other hand, do support at least two cycles of mafic magmatism. The first one is associated with the Debaca sequence and is bimodal. Ages for this magmatism are from zircons in a felsic tuff in the Casner Marble of the Franklin Mountains (Pittenger et al., 1994) and a series of zircon ages for the Allamore and Tumbledown formations in the Van Horn Mountains (Bickford et al., 2000). The second cycle of mafic magmatism is Grenvillian in age (~1.1 Ga) and is represented by the gabbros crosscutting the Debaca sequence in the Mescalero #1 well and the Pecos mafic intrusive complex. The Grenville was a time of pervasive mafic magmatism in this southern part of Laurentia. Examples include diabase sills in the Apache Group of Arizona (Wrucke, 1989) and the Cardenas basalt in the Unkar Group (Larson et al., 1994; Timmons et al., 2001).

2.2.2. Petrogenesis of the basement rocks and tectonic implications

Source indicators summarized in Table 1 argue strongly that the majority of the felsic rocks are crustal melts. These indicators include the oxidized nature of the magmas as deduced from biotite chemistry, with the argument being that mantle derived magmas are generally reduced, and the observation that Nd model ages are older than crystallization ages for the Panhandle igneous complex. The Nd model ages are similar to the ages of the Paleoproterozoic crust from this portion of Laurentia, while the crystallization ages of the Panhandle igneous complex are Mesoproterozoic. Given this geologic context for the Nd model ages, it is most reasonable to hypothesize that Paleoproterozoic crust was involved in magma genesis. The possible exceptions to this conclusion are the ferroan samples from the plutonic province. Insufficient detail exists for the ferroan samples to discuss their petrogenesis other than to observe that their ferroan chemistry and reduced oxidation state make them candidates to be either (1) melts of mafic crustal underplate, as has been interpreted for the 1.43 Ga Sherman batholith of southeast Wyoming (Frost et al., 1999) or (2) end stage crystallization of a mafic magmatic system, as is the case for the 1.12 Ga Red Bluff granitic suite of the Franklin Mountains (Shannon et al., 1997). The samples come from the basement in the vicinity of the "Crosbyton high" of west Texas, an ovoid gravity and magnetic high, which would be consistent with involvement of mafic rocks in their genesis.

The chemistry of the Panhandle igneous complex is consistent with their source being intermediate composition meta-igneous rock (Patiño Douce, 1996, 1999). This type of source material has been suggested for rapakivi granites of similar age in Finland (Rämö and Haapala, 1995) and is in contradistinction to the ferroan, alkali-calcic, metaluminous Sherman batholith, whose source is considered to be mafic (Frost et al., 1999). An active controversy exists concerning the tectonic setting for the 1.4 Ga magmatic event and what, if any, Phanerozoic analog is applicable. Several petrogenetic studies (e.g., Rämö and Haapala, 1995; Anderson and Cullers, 1999; Frost et al., 1999; Haapala and Rämö, 1999; Barnes et al., 2002) have presented evidence for a dominantly crustal origin of the magmas, probably triggered by heat from contemporaneous mafic magmatism. In the Phanerozoic, such bimodal magmatism is most often associated with hot spots or extension. An important observation for the theme of this paper is that the tectonic setting can generate magmas with contrasting characteristics, examples being the Panhandle igneous complex and the Sherman batholith, with the contrast being a function of the source material. Finally, with respect to tectonic evolution in the Mesoproterozoic, a number of studies indicate that there were three cycles of magmatism at ~1.4, 1.2, and 1.1 Ga (e.g., Rämö et al., 2003; Amarante et al., 2004). These suites tend to be magnesian or ferroan and calc-alkalic to alkalic, and are distinct from the magnesian, calcic to calc-alkalic suites. The latter suites are common in, for example, the Mesozoic Cordilleran batholiths of western North America and thus are typical of the plutonic portions of continental magmatic arcs. It is significant for the interpretation of the tectonic setting of Mesoproterozoic magmatism in southern Laurentia that the three cycles of magmatism are not characterized by Cordilleran-style igneous activity. Furthermore, the southwestern United States has no record of Cordilleran-style magmatism during intervals between these cycles, as has been suggested for Sweden by Åhäll et al. (2000).

3. Porphyry-copper mineralized granites of Arizona

3.1. Observations

The western United States is composed of an amalgamation of Archean and Proterozoic provinces (Karlstrom and CD-ROM Group, 2002), with, for example, the Archean Wyoming Province, as well as the Paleoproterozoic Yavapai and Mazatzal provinces. In Arizona, the Yavapai province occupies the northwestern part of the state and is 1.80 to 1.75 Ga in age. The Mazatzal Province in the southeastern part of the state is 1.70 to 1.68 Ga in age (Fig. 2). Superposed on this Proterozoic grain is Laramide-aged granitic magmatism associated with porphyry-copper deposits. A number of studies have been conducted to explore petrogenesis of the igneous rocks associated with porphyry-copper deposits. Among the first that included Nd isotopic data was a reconnaissance study by Farmer and DePaolo (1984), followed by a more detailed study of petrologic evolution for a single porphyry-copper deposit, the Sierrita deposit south of Tucson, Arizona (Anthony and Titley, 1988, 1994). This research was continued by the University of Arizona research group with additional chemical and Nd, Sr isotopic studies (Asmerom et al., 1991; Lang and Titley, 1998), and Pb isotopic studies of igneous rocks and ore minerals (Bouse et al., 1999). All these demonstrated the fundamental importance of the Proterozoic domains or provinces on the nature of magmatism and metallogeny (Titley, 2001). The theme of close linkages between characteristics of granites and type of mineralization was pioneered for tin-mineralized rapakivi granites by Ilmari Haapala (e.g., Haapala, 1977a,b, 1995, 1997).

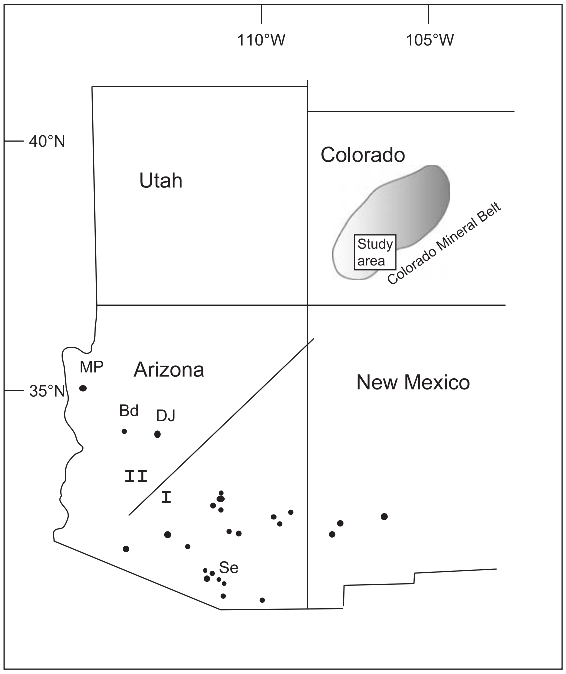

Fig. 2. Map of Proterozoic terranes of Arizona and the Colorado Mineral Belt. Terrane I, Mazatzal (1.70 to 1.68 Ga); Terrane II, Yavapai (1.80 to 1.75 Ga). Dots indicate locations of porphyry-copper deposits in Arizona and New Mexico with deposits referred to in text indicated; Se—Sierrita, MP—Mineral Park, Bd—Bagdad, and DJ—Diamond Joe. Location of the Laramide and mid-Tertiary samples discussed in the text is indicated by the rectangle in the southwestern section of the Colorado Mineral Belt. Modified from Titley and Anthony (1989) and Titley (2001).

At the Sierrita porphyry-copper deposit in the Mazatzal Province of southeastern Arizona, elemental and Sr and Nd isotopic data for whole-rock samples, biotite compositions, and trace-element analyses of mineral separates were determined for a suite of magnesian, calc-alkalic, metaluminous rocks. The suite consists of 67-Ma volcanic rocks (andesite, rhyolite) intruded by granodiorite and granite. Isotopic composition and chemical evolution are well correlated throughout the suite. The andesite has the least negative initial ε_{Nd} (−4.3) and lowest $^{87}Sr/^{86}Sr_i$ (0.7069). The andesite is also the oldest and chemically most primitive rock type, having low concentrations of Rb, SiO_2, and high concentrations of the transition elements. These parameters change through the system to the youngest unit (granite), which has the most negative ε_{Nd} (−8.5), highest $^{87}Sr/^{86}Sr_i$ (0.7092), and is chemically the most evolved. The only deposits with ε_{Nd} values more negative than the −8.5 of Sierrita are Mineral Park (−11), Bagdad (−11), and Diamond Joe (−14). These deposits lie in the older Yavapai province in the northwestern part of the state.

Magmas associated with porphyry-copper deposits tend to be quite oxidized, resulting in the biotite coexisting with magnetite, potassium feldspar, and quartz being phlogopitic (Anthony and Titley, 1988, and references therein). A rigorous calculation of oxidation state from this equilibrium assemblage requires knowledge of the Fe^{2+}/Fe^{3+} ratio for the biotites, which was determined for the Sierrita samples from a combination of Mössbauer spectroscopy and wet chemical methods. Values of log fO_2 from Wones (1972) for Sierrita samples for all intrusive phases (the diorite, granodiorite, and granite) varied from approximately −15 at 700 °C to −17 at 600 °C. These values are approximately at the NNO buffer at the higher temperatures and approach the hematite–magnetite buffer at lower temperatures. The values of oxygen fugacity agree with estimates made from the magnitude of the positive Eu anomaly for feldspar separates from the granodiorite. Finally, whole-rock REE patterns suggest early crystallization of amphibole, which is corroborated by petrography.

3.2. Interpretation

The correlation between chemical and Nd isotopic evolution is interpreted to have resulted from a continuous process of progressive assimilation in which mafic magmas invade and incorporate continental crust. Inverse modeling, using geophysical matrix inversion code and combined assimilation-fractional crystallization (AFC) equations, yields a number of insights. Isotopic and elemental data fit best a value of *r* (the rate of assimilation relative to crystallization) between 0.2 and 0.7 (Anthony and Titley, 1988). The goodness of fit of the model in matrix inversion is measured by the diagonal of the model resolution matrix, with a value of unity corresponding to small standard deviations. The values of the diagonal for *r* values between 0.7 and 0.2 were usually greater than 0.69 and as high as 0.98 (Anthony and Titley, 1988). Second, the inverse modeling converged best at isotopic values for the assimilant very similar to the observed values for the granite. This strengthened the hypothesis, based on the observation of consistent differences in most negative ε_{Nd} in Yavapai versus Mazatzal, that the granites were in isotopic equilibrium with the crustal reservoir. Finally, the solution for *f*, the fraction of melt remaining during AFC, is sensitive to whether the initial isotopic values, i.e., the input parameters, for the mantle reservoir were values appropriate to depleted mantle or to enriched, lithospheric mantle. For depleted mantle isotopic values, the first magmatism (the andesite) represented an *f* of 0.8, and the final granites a value of 0.2. When chondritic values were used to represent a lithospheric signature, the values of *f* were 0.8 and 0.5 for the andesite and the granite, respectively.

Using the ε_{Nd} value of −8.5 of the granites and the age of the Paleoproterozoic crust in southeastern Arizona (1.7 Ga), one can calculate that the crustal source materials had a $^{147}Sm/^{144}Nd$ of approximately 0.135. Similar calculations for the Sr data yield a $^{87}Rb/^{86}Sr$ of 0.30. These ratios are quite different from those of felsic (upper crustal) rocks and are consistent with assimilation of intermediate to mafic, mid- to lower crustal rocks. This interpretation agrees with data from Esperança et al. (1988), who report lower crustal xenoliths of amphibolite in latites from central Arizona with Nd model ages of 2.3 to 1.5 Ga, ε_{Nd} of −9, and $^{87}Sr/^{86}Sr_i$ of 0.7081. Corroborative evidence for an amphibolite source is found in the petrography, chemistry, and oxidation state of the Sierrita rock suite. Early crystallization of amphibole requires water contents of 3% to 4% in the magma, which suggests a crustal source that has not yet undergone dehydration. Mueller (1971) argues that this same magmatic water content would be an effective buffer and oxidant, thus explaining the high oxidation states of the Sierrita magmas.

A final implication of the Sierrita study is that the Nd isotopic signature is sensitive to the age of the Precambrian domain. The incremental change in ε_{Nd} is approximately one epsilon unit per 100 my, and thus the more negative epsilon values for deposits from the Yavapai domain can be attributed to the greater age of that crustal province rather than to a source with a different long-term Sm/Nd ratio. The importance of the contrasting Precambrian domains has been reinforced in subsequent investigations. These include Pb isotopic studies of igneous rocks and ore minerals (Bouse et al., 1999), Ag/Au ratios (Titley, 2001), and most recently Os isotopes (Barra et al., 2002) for Arizona. Recent studies in the Death Valley region of California (Rämö et al., 2002) also document that the isotopic signature of Mesozoic Cordilleran plutons reflects diverse Precambrian lithospheric terranes. The study also finds isotopic evidence for mixing between mantle-derived magmas and Precambrian crust in the magma genesis process.

4. Laramide to Tertiary magmatism in the Colorado Mineral Belt

4.1. Observations

In western North America, the transition from Mesozoic to Cenozoic is represented by two periods of magmatism: the first, associated with Laramide tectonism, is from 75 to 45 Ma, and the second is mid-Tertiary, from 45 to 29 Ma (Christiansen and Yeats, 1992). These time intervals reflect a change in tectonic regime from subduction to extension, as the North American plate overrode the Farallon plate (Severinghaus and Atwater, 1990). Our study of this transition (Ouimette, 1993, 1995) focused on the southern portion of the Colorado Mineral Belt, a northeast-striking Mesoproterozoic (~1.4 Ga) shear zone (Tweto and Sims, 1963), which was reactivated in the Mesozoic and Cenozoic by plutonism and related ore deposits (Stein and Crock, 1990; Cunningham et al., 1994). The Colorado Mineral Belt is associated with a major gravity low (Isaacson and Smithson, 1976). The study characterized two stocks from the Laramide and nine from the mid-Tertiary. The study area (Fig. 2) lies within the transition from the central Colorado Mineral Belt to the southern Colorado Mineral Belt of Stein and Crock (1990).

Table 2 and Figs. 3 and 4 summarize the characteristics of the samples studied. They are divided into three groups, Laramide (Group I) and two from the Mid-Tertiary, based on major and trace element composition. The Laramide suite is magnesian, calc-alkalic, and metaluminous, which is a signature shared by the majority of Cordilleran granitoids (Frost et al., 2001). It is characterized by moderate REE slopes (Fig. 3) and negative Nb, P, and Ti anomalies (Fig. 4). A notable feature on the multielement diagram is that Ta is decoupled from Nb, resulting in a Nb/Ta ratio of 5. These rocks correspond to the Laramide suite of Stein and Crock (1990), for which ε_{Nd} values of -1 to -9 have been reported. The range in ε_{Nd} suggests that mixing of source reservoirs may have been significant. The mid-Tertiary rocks are divided into two groups on the basis of major and trace element chemistry. The first (Group II) is magnesian, alkali-calcic, and peraluminous. It is characterized by a steep REE slope and a multielement diagram with patterns similar to the Laramide suite, but with deeper anomalies at the same SiO_2 content. The steep REE patterns suggest residual garnet in the source, and the peraluminous nature of the rocks implies metasedimentary source material. These Group II samples are chemically equivalent to the mid-Tertiary granite suite of the southern Colorado Mineral Belt (Stein and Crock, 1990) that has ε_{Nd} values of -7 to -9. Stein and Crock argue that the limited range in isotopic values implies a homogeneous source. The third group is magnesian, alkali-calcic, and borderline metaluminous/peraluminous. It has a third, distinctive REE pattern with an inflection at Eu. The multielement pattern is also distinctive, with negative anomalies at Sr, P, and Ti. For this suite, Nb is coupled with Ta, resulting in a Nb/Ta ratio of 14 to 16, within the range reported as typical for crustal rocks (Barth et al.,

Table 2
Characteristics of granites associated with the Colorado Mineral Belt

	Age	Classification	Trace element chemistry	Comments
Laramide (Group I)	72–71 Ma	Magnesian Calc-alkalic Metaluminous	Moderate REE slope $(La/Yb)_n$=11–12 Nb decoupled from Ta	Source material lower crustal and mafic
Mid-Tertiary (Group II)	41–40 Ma	Magnesian Alkali-calcic Peraluminous	Steep linear REE slope $(La/Yb)_n$=13–45 Nb decoupled from Ta	Steep REE and peraluminosity imply metasedimentary source
Mid-Tertiary (Group III)	37–29 Ma	Magnesian Alkali-calcic Metaluminous/ peraluminous	Break in REE slope at Eu $(La/Yb)_n$=5–16 Nb coupled to Ta	Correlates with Stein and Crock (1990) granodiorite/quartz monzonite suite

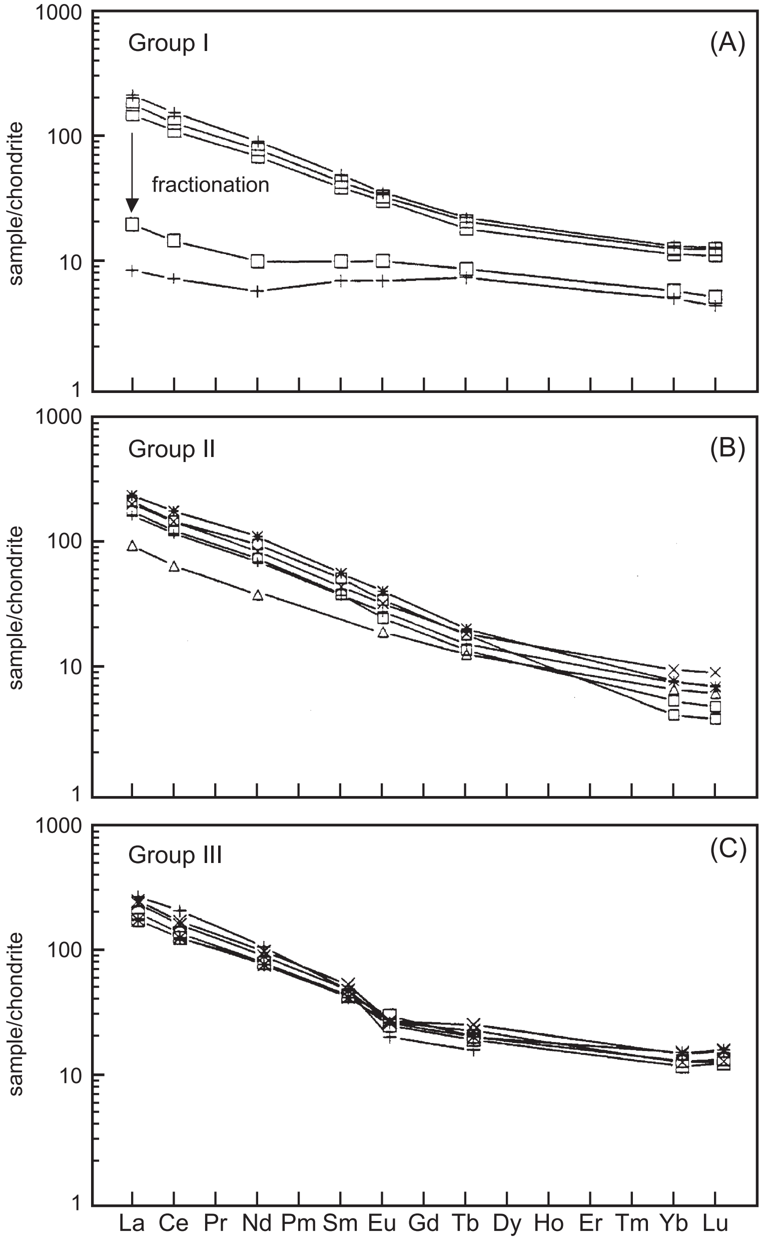

Fig. 3. Chondrite-normalized rare-earth element compositions for Laramide and mid-Tertiary granites of the Colorado Mineral Belt (modified from Ouimette, 1995). (A) Group I, Laramide-aged plutons: the arrow shows the change in REE pattern that accompanies increase in SiO_2; (B) Group II, mid-Tertiary granites (41–40 Ma) with steep REE patterns; (C) Group III, mid-Tertiary granites (37–29 Ma) with inflection of REE pattern at Eu. Other characteristics of the groups are summarized in Table 2 and Fig. 4. Normalizing values from Anders and Ebihara (1982).

2000). These samples are chemically equivalent to the mid-Tertiary granodiorites and quartz monzonites of the central Colorado Mineral Belt of Stein and Crock, and have ε_{Nd} values of -8 to -11.

4.2. Interpretation

The most significant observation from this study of the Colorado Mineral Belt is that changes in the

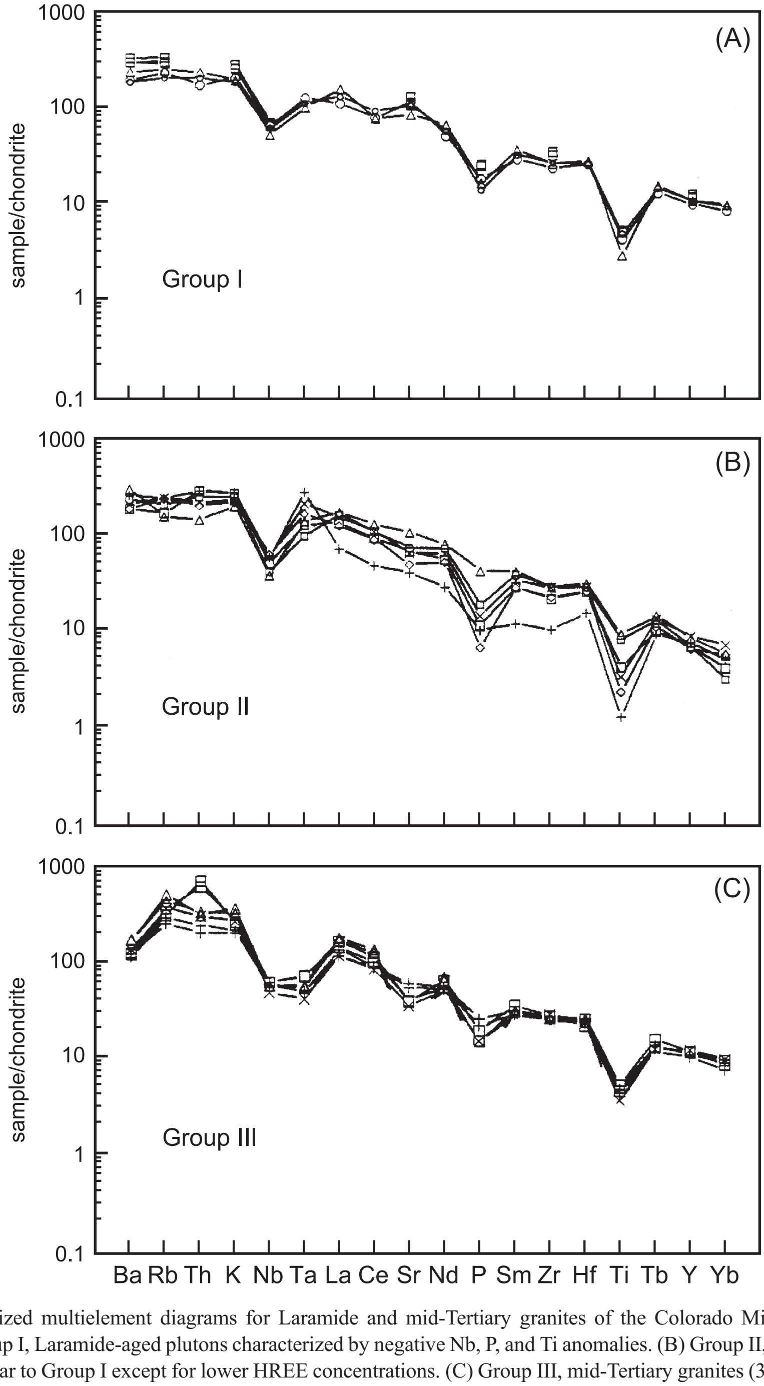

Fig. 4. Chondrite-normalized multielement diagrams for Laramide and mid-Tertiary granites of the Colorado Mineral Belt (modified from Ouimette, 1995). (A) Group I, Laramide-aged plutons characterized by negative Nb, P, and Ti anomalies. (B) Group II, mid-Tertiary granites (41–40 Ma) with patterns similar to Group I except for lower HREE concentrations. (C) Group III, mid-Tertiary granites (37–29 Ma) with coupling of Nb and Ta. Other characteristics of the groups are summarized in Table 2 and Fig. 3. Chondrite normalizing values from Anders and Ebihara (1982).

chemical signature of the granites correlate to the transition in tectonic style from Laramide convergence to mid-Tertiary extension. Based on the combination of elemental and isotopic data, Stein and Crock (1990) proposed a model of assimilation and fractional crystallization involving mantle and mafic, amphibolitic to granulitic lower crust to generate the Laramide granitoids. This combination of source and process is very similar to the porphyry-copper-related granitoids described in the previous section. Both Group II and Group III samples, because of their negative ε_{Nd} values, are interpreted to originate from crustal sources with little or no mantle chemical input. Group II mid-Tertiary granites, with their REE patterns, suggesting garnet in the source and their peraluminosity, were probably derived from metasedimentary sources. Group III mid-Tertiary samples are isotopically and chemically distinct from the Group II samples, requiring that heterogeneous crustal sources were tapped during the mid-Tertiary time interval (Ouimette, 1995).

This shift in source regions as a function of the changing tectonic style has recently been documented for New Mexico by McMillan et al. (2000). They found that at ~36 Ma, volcanism changed abruptly from an arc-like, convergent signature to a bimodal suite. The mafic rocks in this latter suite have elemental and isotopic characteristics that imply they are partial melts of lithosphere with small amount of contamination of lower crustal material. The coeval rhyolitic magmas on the other hand reflect the involvement of upper-crustal components. Barton (1996), in his overview of Mesozoic and Cenozoic magmatism in southwestern North America, reached a similar conclusion. He found that there are two distinctive types of igneous suites: the first consists of calc-alkalic to alkalic rocks formed during periods of convergence and compression. These suites vary from early intermediate and mafic rocks to late felsic rocks over intervals lasting 20 to 50 Ma. The second suite is formed during periods of quiescence or extensional tectonics and is characterized by contemporaneous igneous rocks having widely different compositions.

5. Discussion and conclusions

The three studies described here provide examples of the importance of source materials in determining the chemical and petrological characteristics of granites. The role of source was seen in the differences between the plutonic province and the Panhandle igneous complex in the Mesoproterozoic basement, in the fundamentally different isotopic and metallogenic character of Laramide granites from the Yavapai and Mazatzal provinces in Arizona, and in the changes in elemental character for Laramide versus mid-Tertiary granites in the Colorado Mineral Belt.

The three characteristics most useful are oxidation state, as revealed in these studies through mafic mineral chemistry, isotopic signature, and elemental chemistry. Many previous studies have discussed one or more of these indicators. The following examples are not meant to be an exhaustive review, but rather to highlight some of the pioneering studies. These include, for the oxidation state of the magma, a study by Mueller (1971), which demonstrated the importance of iron content and water fugacity in buffering magmatic oxidation states. Mueller argued that, given the difficulty of changing either parameter during the main stage of differentiation, these variables are inherited from the source. Oxidation state can move away from established buffers during late-stage processes as documented by Czamanske and Wones (1973) and Pichavant et al. (1996). These studies provide examples where magmatic processes do modify the initial oxidation state. They perhaps best illustrate how unusual modification is for the main stage of magmatism and, therefore, that the majority of magmas are buffered by their sources. This point has also been argued by Carmichael (1991) and Blevin and Chappell (1992). A pioneering study on the inheritance of radiogenic and stable isotopic signatures in granites was by McCulloch and Chappell (1982), in which they showed consistent difference in Nd, Sr, and O isotopic values for I- and S-type granites. Numerous others that use isotopic signatures to image source region of magmas followed their study. Important contributions pertinent to Mesozoic and Cenozoic granites of the western United States include Farmer and DePaolo (1983, 1984), Anthony and Titley (1988), Barton (1996), and Lang and Titley (1998). Finally, inherited elemental composition was the original motivation for the Australian typological classification and nomenclature of granites. This is implicit in the original use of “infra” and “supra” for “I” and “S”. A follow-on study by Burnham (1992) showed the consistent variations in normative mineralogy for the different granite types of Australia. Elemental inheritance has been brought to a very sophisticated state by Patino Douce and others (e.g., Patiño Douce, 1999), who have provided, through experimental studies, a rigorous evaluation of the chemical composition of magmas as a function of source lithology and chemistry.

The studies reviewed here also demonstrate a strong correlation between the source regions tapped during magma genesis and tectonic setting. For the Laramide of both Arizona and Colorado, AFC processes involving mantle-derived magmas and mafic lower crust characterize convergent tectonic settings. For nonconvergent settings in both the Mesoproterozoic and the mid-Tertiary, the style of magmatism shifted to intracrustal melting of heterogeneous sources. Implicit in this conclusion is that fundamentally different melt regimes may exist for convergent vs. nonconvergent tectonism. The observations presented in this paper leave a twofold challenge for future avenues of study. The first is to continue to refine chemical and petrological characteristics, source materials, and tectonic setting of magmatic suites. The second is to conduct studies that document melt regimes to elucidate the reasons for different melt regimes in individual tectonic settings. A recent example of such a study is from the Mesozoic of New Zealand (Klepeis et al., 2003). A principal justification for continued study is that unraveling the answers to these questions will enhance the role that granites play in interpreting past tectonic environments.

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