

# Origin of Mesozoic and Tertiary Granite in the Western United States and Implications for Pre-Mesozoic Crustal Structure

## 2. Nd and Sr Isotopic Studies of Unmineralized and Cu- and Mo-Mineralized Granite in the Precambrian Craton

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In the Cordilleran region of the western United States, Mesozoic and Tertiary peraluminous granitic rocks display regional variations in initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ( $\epsilon_{\text{Nd}}$ );  $\epsilon_{\text{Nd}} = -10$  to  $-12$  in southern Arizona,  $-17$  to  $-19$  in the northern Great Basin (NGB), and  $-30$  in the northern Rocky Mountains. Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  values are between 0.710 and 0.721 and show no regional pattern. Metaluminous granitic rocks have a wider range of  $\epsilon_{\text{Nd}}$  values extending from values similar to those of the peraluminous granites to much higher values. The  $^{87}\text{Sr}/^{86}\text{Sr}$  values are mostly fairly low, between 0.705 and 0.710 except in the NGB where values as high as 0.7157 are observed. No systematic differences between the  $\epsilon_{\text{Nd}}$  or  $^{87}\text{Sr}/^{86}\text{Sr}$  values of Cu- or Mo-mineralized and unmineralized granite were discerned, except for Cu-mineralized granite in eastern Nevada and Mo-mineralized granite in Colorado, which have  $\epsilon_{\text{Nd}}$  values higher ( $\sim 0$ ) and lower ( $\sim -10.0$ ), respectively, than unmineralized granite in the same region. Comparison to  $\epsilon_{\text{Nd}}$  values of exposed Precambrian rock suggests that the peraluminous granite, and the Mo granite in Colorado, were derived exclusively from felsic Precambrian basement rocks and that the regional variations in the  $\epsilon_{\text{Nd}}$  values reflect the regional variation in the average crustal age. The Nd data confirm that the Precambrian basement underlying the NGB and eastern California is isotopically distinct from Precambrian crust in the remainder of the western United States. The similarity between the  $\epsilon_{\text{Nd}}$  values of peraluminous granite and Precambrian crust also suggests that the high  $^{147}\text{Sm}/^{144}\text{Nd}$  ( $>0.13$ ) and the low total light rare earth element (LREE) abundances characteristic of peraluminous granite in southern Arizona were imposed during the chemical evolution of the magmas. Metaluminous granite are interpreted to have formed via mixing of mantle-derived magma and large proportions of low  $^{87}\text{Sr}/^{86}\text{Sr}$  (granulite facies) lower crust, except in the eastern NGB where the mantle magmas mixed with a lower crustal source with a significantly higher  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio. REE abundance patterns for metaluminous granite in the NGB are characterized by extreme LREE enrichment, which supports the proposed origin for these rocks by mantle/crust mixing or by remelting of the lower crust alone. No systematic difference exists between the sources of Cu- or Mo-mineralized and unmineralized metaluminous granite, but the data suggest that the Cu sources are in the mantle and the Mo sources are in preexisting crust. Overall, the Nd data indicate that continental interior granite in the western United States was primarily derived from preexisting crust, and although changes in the thermal structure of the continental mantle may have triggered magma formation, the resulting granites do not represent significant juvenile additions to the continental crust.

### INTRODUCTION

The Nd and Sr isotopic compositions of 16 Mesozoic and Tertiary granitic plutons from the Cordilleran region of the western United States (Figure 1) have been determined in order to study the sources of silicic magmas formed within a continental craton. The isotopic data are used to assess the relative importance of mantle and crustal sources in the generation of these granitic rocks and to make inferences regarding the age and structure of the Precambrian crust in the western United States. Sixteen samples of plutons directly associated with major porphyry copper and porphyry molybdenum ore deposits were also analyzed to compare the source regions of unmineralized and Cu- and Mo-mineralized intrusive rocks.

In the first paper in this series (Farmer and DePaolo [1983]; hereafter cited as FD [1983]), Nd and Sr isotopic data were used to show that the source regions of Mesozoic and Tertiary granites varied regularly across the northern Great Basin (NGB) of Nevada and Utah. Granitic rocks that formed nearest the continental margin were primarily derived from the upper mantle, while preexisting continental crust was the

dominant source farther inland. The Nd and Sr isotopic compositions of the crustally derived granites were used to make inferences regarding the age and structure of continental basement beneath the miogeoclinal sedimentary rocks of the eastern Great Basin.

Mesozoic and Tertiary granites are exposed elsewhere in the Cordilleran region of the western United States, from Arizona and New Mexico north to the Canadian border. Most of these granites intrude continental craton (Precambrian basement with a veneer of younger platform sedimentary rocks [King, 1977]) at distances between 500 and 1500 km inland of the present continental margin. By analogy with the granites in the eastern NGB, the Cordilleran granites should have been primarily derived from preexisting crust and so their Nd and Sr isotopic compositions should provide information regarding regional aspects of the age and structure of the Precambrian basement of the western United States. Furthermore, some of the granites are associated with major porphyry copper and molybdenum ore deposits [Hollister, 1978; Titley, 1982]. The results of an isotopic study at the San Manuel porphyry copper deposit in southern Arizona [Farmer and DePaolo, 1982, and manuscript in preparation, 1984] show that Nd is virtually immobile during hydrothermal alteration and ore deposition, which suggests that the initial Nd isotopic composition of Cu-mineralizing granites can be determined even if the rocks are hydrothermally altered. In the present

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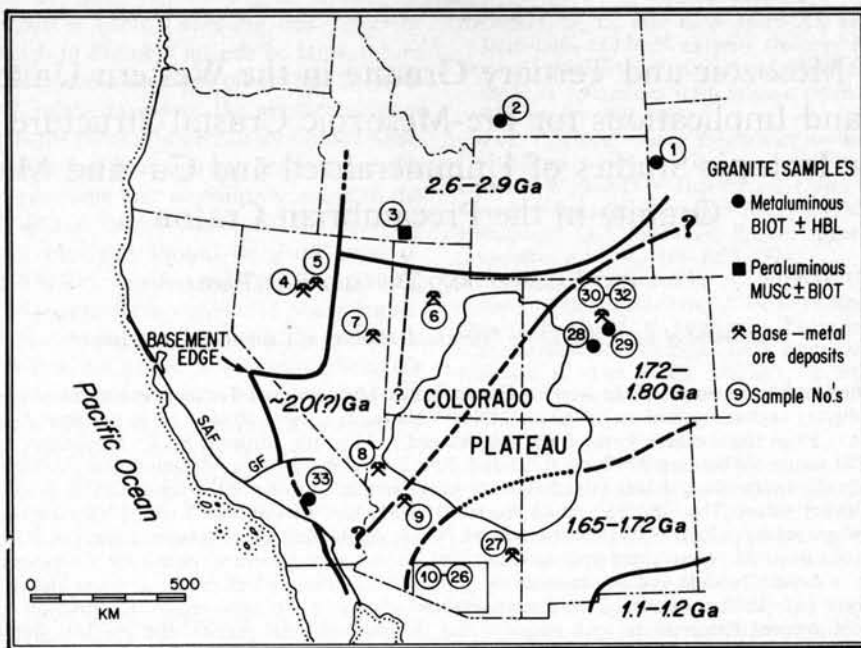


Fig. 1. Sample localities and age provinces in the Precambrian crust of the western United States. Sample numbers for both barren and mineralized granites are those used in Table 2. The 2.0(?) Ga province corresponds to the  $\epsilon_{\text{Nd}}(0) \cong -19$  terrane discussed in the text. Locations for samples 10-26 are in Figure 3. Boundaries between crustal age provinces are from this study and from Van Schmus and Bickford [1981]. SAF, San Andreas fault; GF, Garlock fault.

study the Sr and Nd isotopic compositions of granites directly associated with Cu and Mo mineralization were determined from deposits throughout the Cordillera (Figures 1 and 2) and compared with the isotopic data from unmineralized granites in the same regions to try to correlate granite source regions with the type and degree of base metal mineralization.

#### GEOLOGIC SETTING

For the purposes of this study the most important aspects of Cordilleran geology are the age provinces in the Precambrian basement and the composition, ages, and spatial distribution of Mesozoic and Cenozoic igneous rocks. As described in detail by Van Schmus and Bickford [1981], Condie [1981], and Peterman [1979], the age of the Precambrian basement in

the Cordillera ranges from Archean ( $>2.6$  Ga) in Wyoming and much of Idaho and Montana, to mid-Proterozoic (1.6-1.8 Ga) in Colorado, New Mexico, and Arizona, to late Proterozoic (1.1 Ga) in southernmost New Mexico and west Texas (Figure 1). The basement buried beneath Paleozoic and Mesozoic geoclinal sedimentary rocks in eastern Nevada and western Utah has generally been assumed to be identical in age to mid-Proterozoic crust in Colorado [Condie, 1981]. The Nd data presented in FD [1983], however, show that the basement in Nevada and in portions of Utah and southeast California has an average Nd isotopic composition distinctly different from that of basement in Colorado, which could indicate an early Proterozoic rather than mid-Proterozoic age. The data presented in this study serve to define further the extent of this crustal segment in the western United States.

Post-Precambrian igneous activity commenced in the western United States in the early Mesozoic when the western continental margin shifted from a passive, Atlantic-type margin to a subduction, Andean-type margin [Dickinson, 1981]. Subsequent plutonism can be divided into three main epochs: Jurassic, Cretaceous to early Tertiary, and mid-Tertiary [cf. Armstrong and Suppe, 1973]. The main arc of Jurassic magmatism (about 210-130 Ma ago) extended from the Klamath Mountains and Sierra Nevada south through southeast California, southern Arizona, and into Sonora [Bateman et al., 1963; Burchfiel and Davis, 1981a, b; Shaffiqullah et al., 1980; Damon et al., 1981]. Granitic rocks of this age are primarily metaluminous, calcic to calc-alkaline, and range from tonalite to granite [Bateman et al., 1963; Saleeby, 1981], although alkalic, monzonitic to syenitic intrusions are abundant in the southern portions of the plutonic arc [Miller, 1977; Howard and Shaw, 1982; Sylvester et al., 1978].

The second plutonic epoch (130-50 Ma ago) commenced in the Cretaceous, with the locus of magmatism shifted westward, particularly in the southwest, toward the continental margin [Coney and Reynolds, 1977]. The Peninsular Ranges

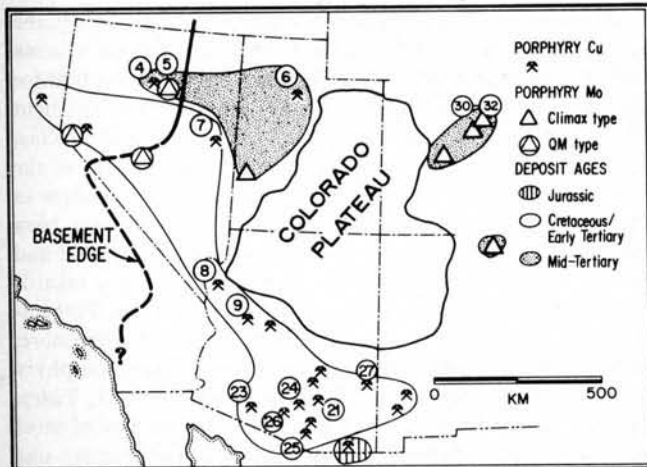


Fig. 2. Distribution of major porphyry Cu and Mo deposits in the western United States. Sampled deposits are numbered; numbers are those used in Table 2. Deposit ages from Titley [1982], Livingston [1973], Westra and Keith [1981], and White et al. [1981]. Basement edge from FD [1983] and from Kistler and Peterman [1973].

Batholith and much of the Sierra Nevada and Idaho batholiths were emplaced at this time [Evernden and Kistler, 1970; Silver *et al.*, 1975]. Cretaceous batholith granites are generally metaluminous and calcic to calc-alkaline [Bateman *et al.*, 1963; Gromet, 1979], except for the Idaho Batholith, which is primarily composed of peraluminous monzogranite [Armstrong *et al.*, 1977].

Approximately 80 Ma ago the zone of magmatism became greatly enlarged and extended far inland, particularly in Sonora [Silver *et al.*, 1975; Damon *et al.*, 1981], and in the SW United States [Coney and Reynolds, 1977]. The inland migration in magmatism apparently culminated 60–70 Ma ago with calc-alkaline magmatism in Colorado and W Texas [Lipman, 1981; Simmons and Hedge, 1978]. In southern Arizona, granites of this age formed during the Laramide orogeny [Damon *et al.*, 1964], and some are associated with major Cu deposits [Titely, 1982]. Two sets of compositionally and temporally distinct granites have been recognized in this region [Keith and Reynolds, 1981]. The first set, 80–60 m.y. in age, consists primarily of metaluminous calc-alkaline granitic rocks of intermediate to silicic composition and include the intrusions associated with the porphyry copper deposits [Titely, 1982]. The second set, 50–60 Ma in age, consists of peraluminous leucocratic granite [Keith *et al.*, 1980; Haxel *et al.*, 1980a; Reynolds *et al.*, 1982]. These peraluminous granites compose the southern half of a north-south trending belt that formed during the Late Cretaceous and early Tertiary throughout the eastern part of the Cordillera [Miller and Bradfish, 1980].

Following a hiatus in igneous activity during Eocene time [Snyder *et al.*, 1976; Cross and Pilger, 1978; Damon *et al.*, 1981], a third period of magmatism affected much of the western United States during the mid-Tertiary. The mid-Tertiary magmatism in Nevada migrated southwestward with time [Stewart *et al.*, 1977] and can be characterized as primarily calc-alkaline and intermediate to silicic. Mid-Tertiary igneous activity also took place in Colorado, first producing calc-

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Major copper and molybdenum deposits in the western United States (Figure 2) are characterized by vein, veinlet, and disseminated Cu-sulfide mineralization, with ore deposition occurring during hydrothermal circulation induced by the emplacement of a granitic magma at shallow levels in the crust [Lowell and Guilbert, 1970; Titely, 1982; Hollister, 1978]. Most Cu-porphyry systems in the western United States also contain by-product Mo [Westra and Keith, 1981; Kesler, 1973]. In the southwest United States the porphyry copper deposits are associated with granitic magmas produced during each of the three magmatic epochs (Figure 2). The majority of the deposits formed in southern Arizona during the emplacement of the Late Cretaceous calc-alkaline monzogranites [Titely, 1982; Titely and Beane, 1981].

Porphyry Mo deposits are also distributed throughout much of the western United States (Figure 2) and can be divided into two classes on the basis of the bulk compositions of the granitic rocks associated with mineralization [White *et al.*, 1981] (see also Westra and Keith [1981]). The "Climax"-type deposits consist of disseminated and stockwork molybdenite mineralization associated with alkalic syenogranite porphyries. Such deposits formed primarily during the Mid-Tertiary magmatic event, both in the Rocky Mountains region and in the eastern Great Basin [Bookstrom, 1981]. "Quartz-monzonite"-type Mo deposits are associated with monzogranite porphyries and are characterized by high Cu:Mo ratios relative to the Climax-type deposits. Deposits of this type are exposed primarily in the Great Basin and are associated with monzogranites emplaced during both Cretaceous and mid-Tertiary magmatism.

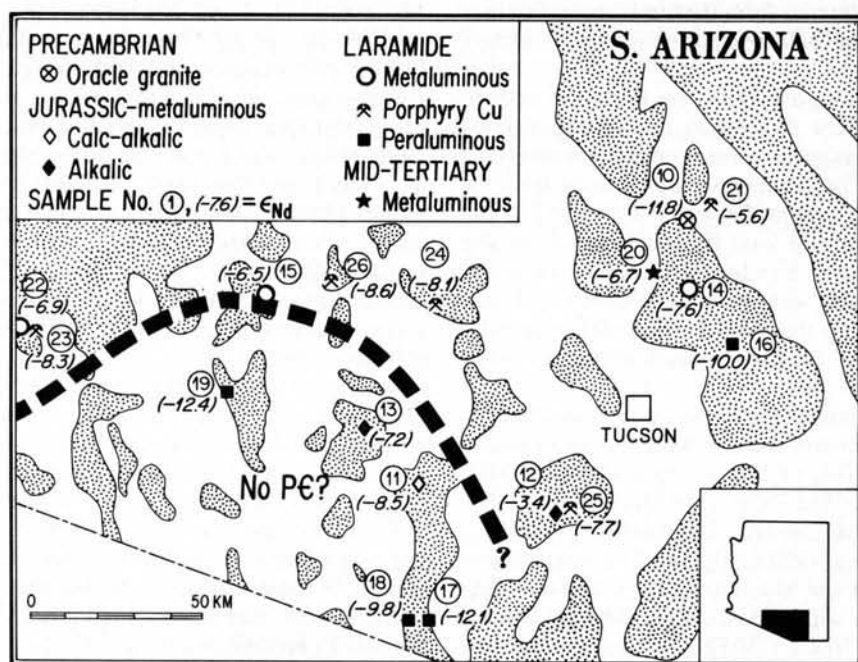


Fig. 3. Sample localities and granite  $\epsilon_{Nd}$  values (in parentheses) in southern Arizona. Autochthonous Precambrian basement rocks are not exposed south of the dashed line [Haxel *et al.*, 1980a]. Note the lack of any systematic spatial variations in  $\epsilon_{Nd}$  values.

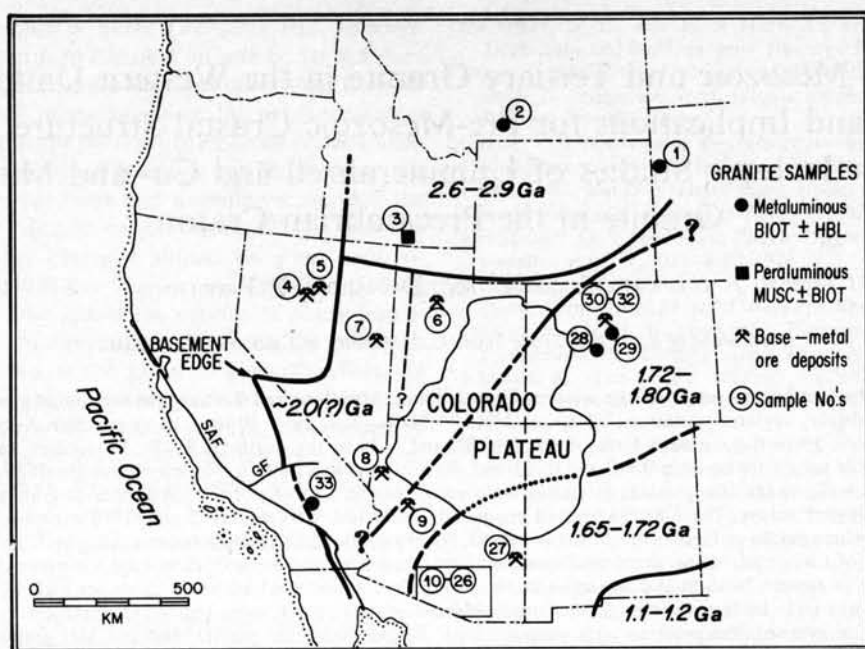


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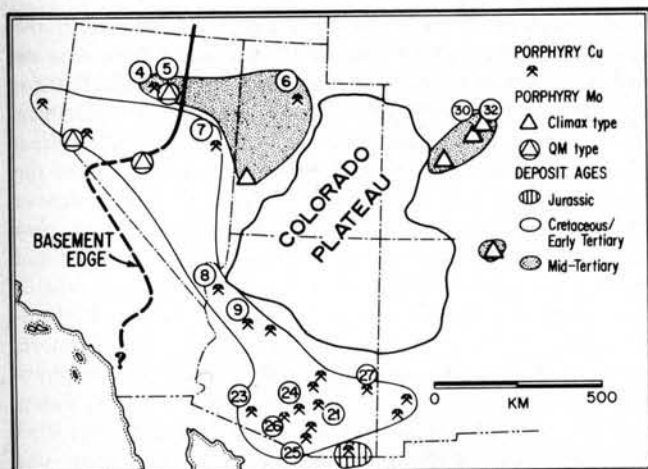


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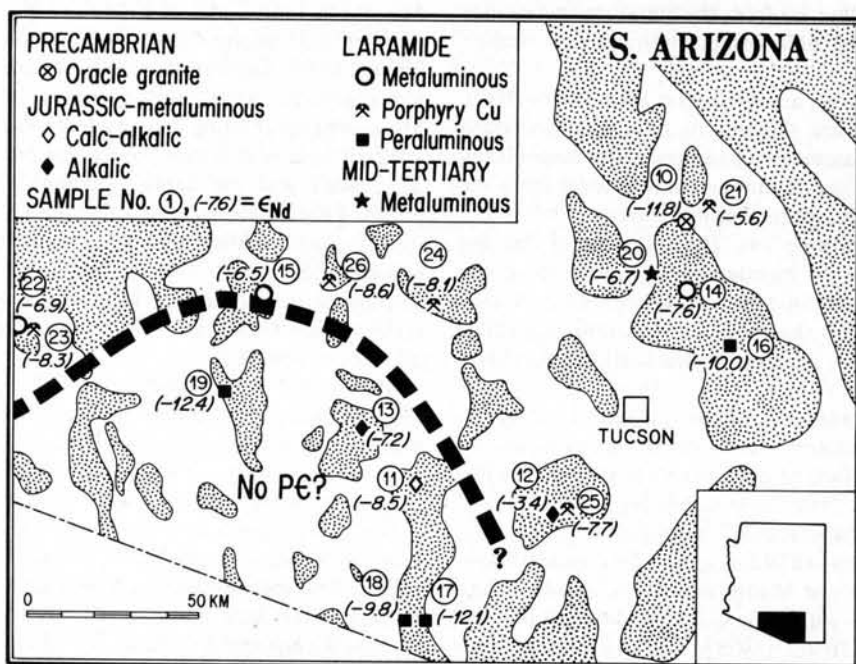


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TABLE 1. Bulk Chemical Analysis for Selected Cordilleran Granites

	Northern Rocky Mountains			Southern Arizona												Colorado	
				Metaluminous						Peraluminous							
	1 <sup>a</sup>	2 <sup>a</sup>	3 <sup>a</sup>	11 <sup>b</sup>	12 <sup>c</sup>	13 <sup>b</sup>	14 <sup>d</sup>	15 <sup>d</sup>	22 <sup>e</sup>	20 <sup>f</sup>	26 <sup>g</sup>	16 <sup>h</sup>	17 <sup>b</sup>	19 <sup>b</sup>	28 <sup>a</sup>	29 <sup>i</sup>	
SiO <sub>2</sub>	64.5	54.8	71.2	65.7	68.1	66.7	62.7	59.0	65.3	68.5	65.5	76.4	72.8	74.6	69.8	67.5	
Al <sub>2</sub> O <sub>3</sub>	15.2	15.4	14.8	16.2	14.4	15.0	16.1	16.2	15.7	14.4	15.2	14.6	14.7	14.8	15.1	15.5	
Fe <sub>2</sub> O <sub>3</sub>	...	...	...	...	...	...	2.1	2.8	2.1	2.1	...	0.4	...	...	...	2.2	
Fe <sub>2</sub> O <sub>3</sub> *	7.2	14.1	3.0	3.5	3.4	3.3	...	...	...	...	4.6	...	1.3	0.4	3.0	...	
FeO	...	...	...	...	...	...	2.7	3.9	2.0	1.9	...	0.3	...	...	...	1.6	
MgO	1.0	2.3	0.7	1.2	1.0	1.5	2.9	3.3	1.8	1.4	3.0	0.1	0.3	0.1	0.6	0.7	
CaO	3.3	5.7	2.9	3.0	1.5	1.2	4.7	5.2	3.7	2.6	3.9	1.2	1.3	0.9	3.2	3.3	
Na <sub>2</sub> O	5.1	3.8	3.8	3.2	2.9	3.9	3.7	3.6	3.8	3.7	3.4	3.7	4.1	3.8	4.7	3.6	
K <sub>2</sub> O	3.1	2.3	3.0	5.1	7.1	6.1	2.8	2.6	4.1	4.3	3.3	3.6	4.1	4.2	3.1	4.1	
H <sub>2</sub> O <sup>-</sup>	...	...	...	0.17	...	0.24	0.26	0.12	0.14	...	...	...	0.12	...	...	0.26	
H <sub>2</sub> O <sup>+</sup>	...	...	...	0.49	...	0.77	0.94	1.1	0.62	...	...	...	0.27	...	...	0.08	
LOI	1.1	0.7	0.5	0.5	...	1.0	...	...	...	...	...	...	...	...	0.7	...	
Molecular Al <sub>2</sub> O <sub>3</sub> (K <sub>2</sub> O + CaO + Na <sub>2</sub> O)	0.86	0.81	1.00	1.00	0.95	1.00	0.91	0.89	0.91	0.92	0.94	1.20	1.09	1.19	0.90	0.95	

<sup>a</sup>Analysis by L. Knauer, University of California, Los Angeles; data from powders used for isotopic analyses.

<sup>b</sup>G. Haxel (personal communication, 1982).

<sup>c</sup>J. Kurtz (personal communication, 1982).

<sup>d</sup>Banks [1980, Table 2, sample 11].

<sup>e</sup>Gilluly [1946, Table 4, sample 3].

<sup>f</sup>Coney and Reynolds [1980, Table E-2, sample 15580].

<sup>g</sup>Bolin [1976, Table 9, average of samples 1-4].

<sup>h</sup>Coney and Reynolds [1980, Table E-2, sample 155848].

<sup>i</sup>Young [1972], as reported by Simmons and Hedge [1978, Table 1, sample 3].

## SAMPLES

Unmineralized granitic rocks from the eastern Cordillera were collected from as broad an area as possible (Figures 1 and 3) and from intrusions emplaced during each of the three magmatic epochs. Sample locations and modes are given in the appendix. Available XRF bulk compositional data are given in Table 1. Some of the bulk chemical analyses were determined from the same powders used for the isotopic analyses (courtesy of L. Knauer). However, most of the major element compositional data are from the literature and so may not exactly represent the bulk compositions of the samples used in this study.

The mid-Tertiary plutons analyzed were from the northern Rocky Mountains and are thought to have intruded crust underlain by Archean basement. The samples represent (1) the Almo pluton, a weakly peraluminous monzogranite from the core of the Albion Mountains metamorphic terrane in S Idaho [Armstrong, 1968; Armstrong and Hills, 1967], (2) the Big Timber pluton, a strongly metaluminous diorite from the southern Crazy Mountains in Montana [Wolff, 1938; Tappe and Larsen, 1967], and (3) the Vanocker laccolith, a metaluminous quartz latite from the eastern Black Hills [Matthews, 1981; Lisenbee, 1981].

Samples of barren granitic rocks that intrude the Proterozoic (1.6-1.8 b.y. old) craton were collected from Colorado and southern Arizona. Two plutons from the Colorado Mineral Belt were analyzed: The Twin Lakes granodiorite [Wilshire, 1969] and the Montezuma monzogranite [Lovering, 1935]. Rare earth element (REE), Rb, and Sr concentrations and Sr isotopic data for the Montezuma stock and for many other Tertiary intrusives within the Colorado Mineral Belt are given by Simmons and Hedge [1978]. The two plutons analyzed in this study are not associated with any economic ore deposits, but both have minor base metal mineralization [Lovering, 1935; Bookstrom, 1981].

An extensive suite of samples collected from southern Ari-

zona (Figure 3) included granites from all three plutonic epochs and with a wide range of bulk compositions (Table 2 and the appendix). Alkaline Jurassic plutons were sampled in the northern Comobabi Mountains (the quartz syenite phase of the Ko Vaya intrusive complex [Haxel et al., 1978]) and at Sierrita (the Harris Ranch monzogranite [West and Aiken, 1982]). The calc-alkalic, Jurassic granodiorite at Kitt Peak in the Quinlan Mountains [Haxel et al., 1980b] was also analyzed. Samples of unmineralized Late Cretaceous calc-alkalic intrusions were obtained from a quartz diorite in the Cimarron Mountains (unit Tkgd of Briskey et al. [1978]) and from the Leatherwood quartz diorite in the Santa Catalina Mountains [Banks, 1980; Keith et al., 1980]. Early Tertiary peraluminous monzogranites were sampled in the southern Baboquivari Mountains (granite of Presumido Peak: [Haxel et al., 1980a, 1982; Wright and Haxel, 1982], the Sierra Blanca [Haxel et al., 1980a], and the Santa Catalina Mountains (Wilderness granite [Banks, 1980]). The sole mid-Tertiary pluton sampled was the calc-alkalic Catalina monzogranite from the Santa Catalina Mountains [Banks, 1980]. In addition, a Jurassic calc-alkalic monzogranite from the western Mojave Desert region of southern California was analyzed (sample 33, Figure 1 [Knauer, 1983]).

Most samples were single, hand-sized portions of the freshest rock obtainable from each pluton. The one exception is the sample from the Jurassic Harris Ranch monzogranite at Sierrita, which was hydrothermally altered during Late Cretaceous intrusive activity [West and Aiken, 1982].

Samples of intrusive rocks directly related to porphyry Cu deposits were obtained from Arizona and the Great Basin (Figure 2). Fresh samples were obtained from a deep drill core in the mid-Tertiary granodiorite porphyry at Copper Canyon, Nevada [Theodore and Blake, 1975] and from deep segments of mineralizing granodiorite or monzogranite exposed through normal faulting at Ajo [Gilluly, 1946] and Lakeshore, Arizona [Huyck, 1982]. A powdered sample of an unmineralized Late Cretaceous monzonite from Silverbell [Rich-

TABLE 2a. Trace Element Concentrations and Ratios for Unmineralized Granites

Sample	Location From Figures 1-3	Type	Rb	Sr	Sm	Nd	$\frac{87\text{Rb}}{86\text{Sr}}$	$\frac{147\text{Sm}}{144\text{Nd}}$	Sr/Nd
<i>Northern Rocky Mountains</i>									
81 SD VLQM-1	1, Black Hills	qtz latite	83.1	119	8.25	46.1	2.02	0.1082	2.6
81 MT CMGD-1	2, Crazy Mountains	diorite	55.5	978	6.26	36.7	0.164	0.1033	26.6
81 ID APGD-1	3, Albion Mountains	monzogranite	64.7	396	4.81	35.0	0.472	0.0832	11.3
<i>Southern Arizona: Precambrian</i>									
81 AZ OG-10	10, Santa Catalina Mountain	Monzogranite	220.5	160	11.58	56.5	3.983	0.1239	2.8
<i>Southern Arizona: Jurassic</i>									
80 AZ PUP-11	11, Baboquivari Mountains	granodiorite	219.5	381	9.55	52.2	1.665	0.1107	7.3
82 AZ ST-4	12, Sierrita Mountains	monzogranite	305.9	134	6.40	32.6	6.597	0.1186	4.1
81 AZ PR-363	13, Comobabi Mountains	qtz syenite	199.4	218	6.96	40.3	2.646	0.1047	5.4
<i>Southern Arizona: Late Cretaceous</i>									
81 AZ LW-1	14, Santa Catalina Mountain	qtz diorite	349.9	615	4.38	23.9	1.644	0.1109	25.7
80 AZ PUP-9	15, Cimarron Mountains	qtz diorite	119.6	628	5.98	32.4	0.550	0.1117	19.4
81 AZ WG-1	16, Santa Catalina Mountain	peraluminous granite	112.1	313	2.39	11.4	1.035	0.1271	27.5
80 AZ PUP-32	17, Baboquivari Mountains	peraluminous granite	274.6	163	2.35	9.2	4.869	0.1540	17.7
81 AZ PUP-22	18, Baboquivari Mountains	peraluminous granite	345	197	2.79	15.0	5.06	0.1123	13.1
81 AZ PR-364	19, Sierra Blanca	peraluminous granite	197	66	6.94	25.7	8.66	0.1636	2.57
<i>Southern Arizona: Mid-Tertiary</i>									
81 AZ CG-1	20, Santa Catalina Mountain	monzogranite	185.8	388	6.29	37.6	1.384	0.1013	10.3
<i>California</i>									
A 80-8	33, Emerson Lake	monzogranite	123.6	341	5.41	30.3	1.048	0.1080	11.3
<i>Colorado</i>									
81 CO TLGD-1	28, Sawatch Range	granodiorite	72.8	1087	4.00	23.7	0.194	0.1020	45.9
81 CO MDG-1	29, Front Range	monzogranite	162.7	419	6.14	37.7	1.123	0.0984	11.1

Concentrations in ppm.

ard and Courtright, 1966] studied by J. Kurtz was also analyzed. Hydrothermally altered samples of granodiorite to monzogranite included (1) potassically altered (alteration nomenclature from Meyer and Hemley [1967]) rock at Bingham, Utah [Lanier et al., 1978], and Bagdad [Anderson et al., 1955], (2) potassic-phyllic altered rock from Mineral Park [Wilkinson et al., 1982] and Morenci [Moolick and Durek, 1966], previously analyzed petrographically and chemically by Laine [1974], (3) phyllic-altered monzogranite from the Tripp pit at Ely, Nevada [James, 1976], (4) potassic-phyllic altered rock

from Sierrita [West and Aiken, 1982] analyzed for major element chemistry by J. Kurtz (personal communication, 1982).

Weakly altered samples of intrusive rock at the Henderson Climax-type porphyry Mo deposit in Colorado [Wallace et al., 1978; White et al., 1981] and the Buckingham "quartz-monzonite"-type deposit in Nevada [Blake et al., 1979] were analyzed. Samples of the Urad, Dailey, and Seriate porphyritic syenogranite stocks were obtained from Henderson. These stocks are associated with very different amounts of Mo mineralization (Seriate highest, Urad lowest (R. Carten, personal

TABLE 2b. Trace Element Concentrations and Ratios for Mineralized Granites

Sample	Location From Figures 1-3	Alteration	Rb	Sr	Sm	Nd	$\frac{87\text{Rb}}{86\text{Sr}}$	$\frac{147\text{Sm}}{144\text{Nd}}$	Sr/Nd
<i>Porphyry Molybdenum: Henderson Mine-Colorado (Climax-type)</i>									
UGP-1	30, Urad Stock	fresh syenogranite	549.5	12.0	3.62	24.7	132.3	0.0887	0.49
DG-1	31, Dailey Stock	fresh syenogranite	501	5.1	1.58	10.4	283.9	0.0920	0.49
SG-1	32, Seriate Stock	fresh syenogranite	563.8	—	2.53	12.2	—	0.1258	—
<i>Porphyry Molybdenum: Buckingham-Nevada ("Quartz-Monzonite" Type)</i>									
79 NV BMMO-1	5, Battle Mountain	fresh monzogranite	302.7	313	4.67	26.5	2.795	0.1064	11.8
<i>Porphyry Copper: Arizona</i>									
80 AZ MP-10	8, Mineral Park	potassic/phyllic	231.8	120	5.51	33.4	5.583	0.0999	3.59
81 AZ B-1	9, Bagdad	potassic	249.6	365	0.88	5.5	1.976	0.0962	66.4
81 AZ PUP-62	22, Ajo	propylitic	122.8	535	5.34	36.3	0.663	0.0890	14.7
81 AZ PR-350	23, Ajo	fresh monzogranite	54.6	593	4.09	23.5	0.266	0.1055	25.2
82 AZ SB-2A	24, Silverbell	potassic/phyllic	148.0	403	3.65	22.3	1.061	0.0990	18.1
82 AZ ST-2	25, Sierrita	potassic/phyllic	177.2	360	2.95	18.7	1.423	0.0954	19.3
81 AZ PR-328	26, Lakeshore	fresh/granodiorite	128.3	644	3.70	20.0	0.576	0.1121	32.2
80 AZ M-10	27, Morenci	potassic/phyllic	176.5	540	1.53	8.16	0.945	0.1138	66.2
80 AZ QDP-1	21, San Manuel	potassic/phyllic	59.1	278	3.28	19.0	0.614	0.1044	14.6
<i>Porphyry Copper: Great Basin</i>									
79 NV CUC-1	4, Copper Canyon	fresh monzogranite	180.8	388	1.36	6.44	1.347	0.1280	60.2
79 UT BM-5b	5, Bingham	potassic	246.8	365	3.80	29.4	1.954	0.0782	12.4
79 NV TPE-1	7, Ely	phyllic	253.5	263	3.56	19.8	2.786	0.1087	13.3

TABLE 3a. Isotopic Data From Unmineralized Granites

Sample	Age, Ma	$f_{\text{Sm}/\text{Nd}}$	$f_{\text{Rb}/\text{Sr}}$	$\left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}}\right)_{\text{meas}}$	$\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right)_{\text{meas}}$	$\epsilon_{\text{Nd}}$	$\epsilon_{\text{Sr}}$	$T_{\text{DM}}^{\text{Nd}}, \text{Ga}$	$T_{\text{DM}}^{\text{Sr}}, \text{Ga}$
<i>Northern Rocky Mountains</i>									
81 SD VLQM-1	50	-0.450	23.0	$0.511495 \pm 13$	$0.70657 \pm 3$	-6.1	+30	1.0	0.1
81 MT CMGD-1	50	-0.475	0.95	$0.511077 \pm 10$	$0.70784 \pm 6$	-14.2	+47	1.6	3.0
81 ID APGD-1	30	-0.577	4.62	$0.510284 \pm 12$	$0.71044 \pm 3$	-29.9	+82	2.3	1.2
<i>Southern Arizona: Precambrian</i>									
81 AZ OG-10	1,440	-0.370	46.4	$0.511197 \pm 19$	$0.78546 \pm 4$	-11.8 <sup>a</sup>	+1094 <sup>a</sup>	1.8	1.4
<i>Southern Arizona: Jurassic</i>									
80 AZ PUP-11	165	-0.437	18.8	$0.511307 \pm 15$	$0.71104 \pm 5$	-8.5	+40	1.3	0.4
82 AZ ST-4	200	-0.397	77.5	$0.511558 \pm 12$	$0.71974 \pm 3$	-3.4	-46	1.0	0.2
81 AZ PR-363	150	-0.468	30.5	$0.511397 \pm 12$	$0.71278 \pm 3$	-7.2	+40	1.2	0.2
<i>Southern Arizona: Late Cretaceous</i>									
81 AZ LW-1	70	-0.436	18.6	$0.511409 \pm 16$	$0.70987 \pm 3$	-7.6	+54	1.2	0.3
80 AZ PUP-9	68	-0.432	5.6	$0.511466 \pm 18$	$0.71019 \pm 3$	-6.5	+74	1.1	1.0
81 AZ WG-1	47	-0.354	11.3	$0.511303 \pm 25$	$0.71295 \pm 5$	-10.0	+111	1.9	0.8
80 AZ PUP-32	58	-0.217	57.0	$0.511200 \pm 18$	$0.72481 \pm 8$	-12.1	+232	2.7	0.3
80 AZ PUP-22	58	-0.429	59.3	$0.511301 \pm 16$	$0.71620 \pm 5$	-9.8	+108	1.4	0.2
81 AZ PR-364	58	-0.168	102.1	$0.511188 \pm 14$	$0.72298 \pm 5$	-12.4	+162	3.1	0.2
<i>Southern Arizona: Mid-Tertiary</i>									
81 AZ CG-1	26	-0.485	15.5	$0.511479 \pm 24$	$0.7091 \pm 2$	-6.7	+59	1.0	0.3
<i>California</i>									
A80-8	153	-0.451	11.5	$0.511261 \pm 12$	$0.71140 \pm 3$	-9.5			
<i>Colorado</i>									
81 COTLDG-1	50	-0.481	1.3	$0.511528 \pm 18$	$0.70630 \pm 5$	-5.4	+24	1.0	1.1
81 COMGD-1	39	-0.500	12.4	$0.511381 \pm 14$	$0.70929 \pm 3$	-8.4	+10	1.1	0.4

<sup>a</sup>Calculated for  $T = 70$  Ma.

communication, 1982)) and were analyzed to try to correlate their Sr and Nd isotopic compositions with the degree of Mo mineralization. A drill core sample of the mineralizing monzogranite at Buckingham was analyzed. Further descriptions of all the Cu- and Mo-mineralizing granites are given in the appendix.

Except for the powdered samples obtained from Silverbell and Sierrita, all altered rock used for the isotopic analyses were derived from 2–3 g portions of pervasively altered, vein-free material, chiseled out of 5–6 cm thick rock slabs. These slabs were cut from hand-samples on a water-cooled diamond

saw. Veins were avoided to minimize the possibility of introducing country rock derived material into the powders used for the isotopic analyses. Only the Ely sample contained significant vein material. Both mineralized and unmineralized samples underwent successive HF and HClO<sub>4</sub> dissolutions in open beakers. Residues were dissolved in Teflon bombs.

## RESULTS

Isotopic and selected trace element data from both the mineralized and unmineralized granites are summarized in Tables 2 and 3. The analytical techniques and data representation

TABLE 3b. Isotopic Data From Mineralized Granites

Sample	Age, Ma	$f_{\text{Sm}/\text{Nd}}$	$f_{\text{Rb}/\text{Sr}}$	$\left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}}\right)_{\text{meas}}$	$\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right)_{\text{meas}}$	$\epsilon_{\text{Nd}}$	$\epsilon_{\text{Sr}}$	$T_{\text{DM}}^{\text{Nd}}, \text{Ga}$	$T_{\text{DM}}^{\text{Sr}}, \text{Ga}$
<i>Porphyry Mo: Henderson Mine-Colorado</i>									
UGP-1	24	-0.549	+1574	$0.511312 \pm 14$	$0.7741 \pm 2$	-9.9	+348	1.1	~0
DG-1	24	-0.532	+3379	$0.511331 \pm 18$	$0.84157 \pm 6$	-9.6	+572	1.1	~0
SG-1	24	-0.361	...	$0.511338 \pm 18$	...	-9.5	...	1.5	...
<i>Porphyry Mo: Buckingham-Nevada</i>									
79 NV BMMO-1	90	-0.459	32.2	$0.511479 \pm 16$	$0.71218 \pm 4$	-6.3	+60	1.0	0.2
<i>Porphyry Cu: Arizona</i>									
80 AZ MP-10	72	-0.492	65.5	$0.511165 \pm 22$	$0.71806 \pm 7$	-12.2	+113	1.4	0.2
81 AZ B-1	71	-0.511	22.5	$0.511227 \pm 14$	$0.71418 \pm 3$	-11.0	+110	1.3	0.4
81 AZ PUP-62	63	-0.548	6.9	$0.511437 \pm 18$	$0.70854 \pm 3$	-6.9	+50	0.9	0.7
81 AZ PR-350	63	-0.464	2.2	$0.511373 \pm 14$	$0.70782 \pm 2$	-8.3	+45	1.2	1.5
82 AZ SB-2A	67	-0.497	11.6	$0.511379 \pm 20$	$0.71109 \pm 3$	-8.1	+80	1.1	0.5
82 AZ ST-2	61	-0.515	15.9	$0.511404 \pm 10$	$0.70970 \pm 2$	-7.7	+57	1.0	0.3
81 AZ PR-328	67	-0.430	5.9	$0.511361 \pm 18$	$0.70953 \pm 6$	-8.6	+65	1.3	0.8
80 AZ M-10	55	-0.422	10.3	$0.511498 \pm 14$	$0.70805 \pm 4$	-6.0	+41	1.4	0.4
80 AZ QDP-1	70	-0.469	6.3	$0.511506 \pm 22$	$0.71496 \pm 4$	-5.6	+141	1.0	1.5
<i>Porphyry Cu: Great Basin</i>									
79 NV CUC-1	38	-0.349	15.0	$0.511490 \pm 14$	$0.70978 \pm 3$	-6.4	+65	1.3	0.3
79 UT BM-5b	38	-0.603	22.3	$0.510868 \pm 18$	$0.71014 \pm 2$	-18.4	+66	1.5	0.3
79 NV TPE-1	109	-0.447	32.1	$0.511811 \pm 18$	$0.7088 \pm 2$	+0.7	-3	0.6	0.1

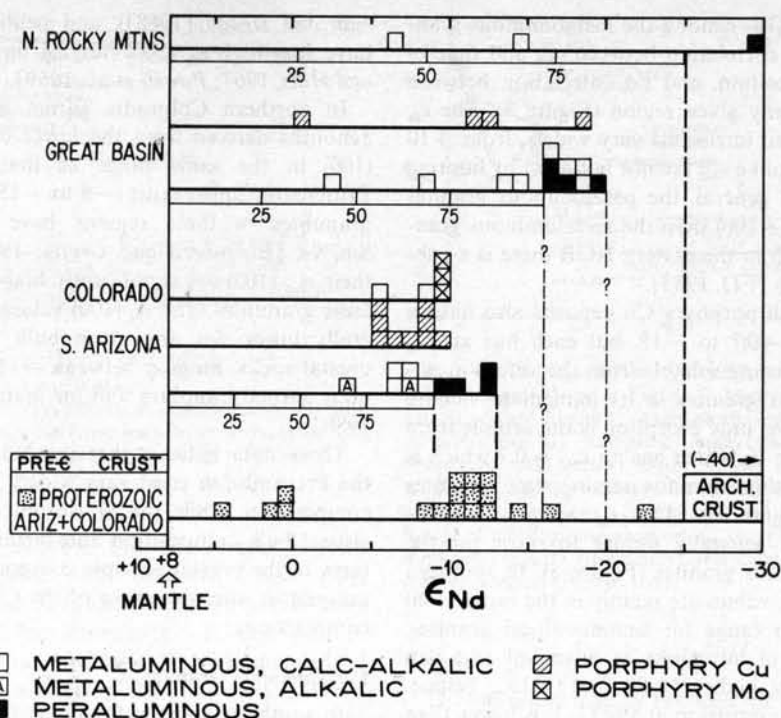


Fig. 4. Histograms of initial  $\epsilon_{Nd}$  values for Cordilleran granites. Data from this study and FD [1983]. Great Basin data are from granites exposed east of Roberts Mountains Thrust and include data from mineralized intrusions at Bagdad and Mineral Park in northern Arizona. The  $\epsilon_{Nd}$  values for Precambrian basement are  $\epsilon_{Nd}$  (100 m.y.) values and are from Wooden *et al.* [1982], DePaolo [1981b], and from this study (Oracle granite, Table 3). Dashed vertical lines define the  $\epsilon_{Nd}$  range for the peraluminous granites in each geographic region, except in the northern Rocky Mountains, where the dashed line is the upper  $\epsilon_{Nd}$  (100 m.y.) limit for Archean crust. Bar scales beneath each set of histograms show the approximate percentages of crustal Nd in the metaluminous granites in each region (calculated assuming that granites formed via mixing of mantle magma ( $\epsilon_{Nd} = +8$ ) and a crustal end-member with  $\epsilon_{Nd} = -10$  in southern Arizona and Colorado,  $-18$  in the NGB, and  $-25$  in the northern Rocky Mountains).

follow that of FD (1983). The  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  refer to initial isotopic compositions, normalized to a model chondritic reservoir (CHUR) for Nd, and to a model whole earth reservoir (UR) for Sr. The  $\epsilon_{Nd}$  (0) and  $\epsilon_{Sr}$  (0) refer to present-day values. The  $f_{Sm/Nd}$  and  $f_{Rb/Sr}$  values (Table 3) are model enrichment factors relative to CHUR and UR, respectively.  $T_{DM}^{Nd}$  and  $T_{DM}^{Sr}$  are Nd and Sr model ages relative to a "depleting" mantle [DePaolo, 1981b]. The  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  values are presented as histograms in Figures 4 and 5, respectively. In these diagrams, granites from the Cordillera have been divided into three geographic groups: the three plutons from the northern Rocky Mountains region, the granites from the eastern NGB, and the granites from Colorado and Arizona.

As illustrated in Figure 4,  $\epsilon_{Nd}$  values of unmineralized granites in the Cordillera vary widely from  $-3.4$  to  $-29.9$ . In each

geographic region, however, there appears to be a characteristic lower limit of  $\epsilon_{Nd}$ , which is  $-12$  in Colorado and Arizona,  $-30$  in the northern Rocky Mountains, and about  $-19$  in the eastern NGB. The  $\epsilon_{Nd}$  values for the peraluminous granites define the lower  $\epsilon_{Nd}$  limit for granites in each region and are very consistent in regions where multiple samples have been analyzed ( $-10$  to  $-12$  in southern Arizona, and  $-17$  to  $-19$  in the NGB). Metaluminous granites have a much wider range of  $\epsilon_{Nd}$ , but the  $\epsilon_{Nd}$  values overlap those of the peraluminous granites. The  $\epsilon_{Nd}$  values are as high as  $-6$  in the northern Rocky Mountains,  $-5$  in Colorado,  $-3.5$  in southern Ari-

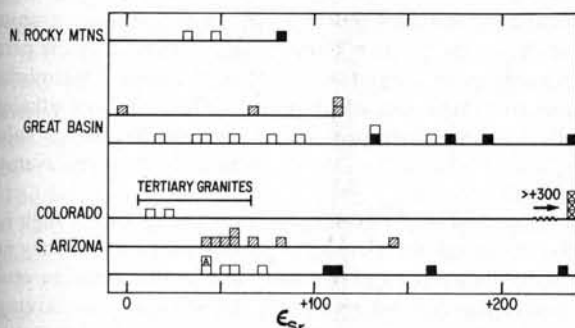


Fig. 5. Histograms of initial  $\epsilon_{Sr}$  for Cordilleran granites. Symbols as in Figure 4. Range of values for Tertiary granites in Colorado from Simmons and Hedge [1978].

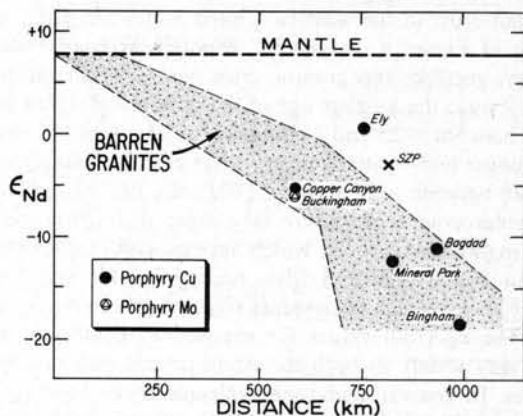


Fig. 6. The  $\epsilon_{Nd}$  versus distance for mineralized granites in the Great Basin and northern Arizona. Distance scale is line A-A' from Figure 1 of FD [1983]. Shaded field is the range of  $\epsilon_{Nd}$  values for barren NGB granites.

zona, and  $-2.5$  in the NGB. Among the metaluminous granites, there is no apparent correlation between  $\epsilon_{Nd}$  and time of intrusion, or bulk composition, and no correlation between  $\epsilon_{Nd}$  and position within any given region (Figure 3). The  $\epsilon_{Sr}$  values of the unmineralized intrusions vary widely, from  $+10$  to  $+240$  (Figure 5), but unlike  $\epsilon_{Nd}$  are not bounded by limiting values in each region. In general, the peraluminous granites have higher  $\epsilon_{Sr}$  values ( $> +100$ ) than the metaluminous granites ( $\epsilon_{Sr} < +100$ ), although in the eastern NGB there is a substantial amount of overlap [FD, 1983].

Granites associated with porphyry Cu deposits also have a wide range of  $\epsilon_{Nd}$  from  $+0.7$  to  $-18$ , but each has an  $\epsilon_{Nd}$  value that is virtually indistinguishable from the values in unmineralized metaluminous granites in its immediate vicinity (Table 4 and Figure 4). The only exception is the sample from Ely (79NV TPE-1; Figure 2), which has an  $\epsilon_{Nd} = 0.7$  which is substantially higher than the values for unmineralized granites in eastern Nevada (Figure 6). The  $\epsilon_{Sr}$  values for Cu-mineralizing granites are generally similar to those for the unmineralized metaluminous granites (Figure 5). In southern Arizona and the NGB,  $\epsilon_{Sr}$  values are mainly in the range  $+40$  to  $+70$ , identical to the range for unmineralized granites. However, the  $\epsilon_{Sr}$  values of intrusions at Silverbell and San Manuel are considerably higher ( $+80$  and  $+132$ , respectively), while the  $\epsilon_{Sr}$  of the intrusion at Ely ( $-3$ ) is lower than any other granite yet analyzed in eastern Nevada, correlating with the high  $\epsilon_{Nd}$  of this sample.

The syenogranite porphyries associated with the Henderson Mo deposit all have lower  $\epsilon_{Nd}$  ( $-9.6$  to  $-9.9$ ) than the two unmineralized, metaluminous granites analyzed from Colorado ( $\epsilon_{Nd} = -5.4$  to  $-8$ , Table 3 and Figure 4). The  $\epsilon_{Sr}$  values for these stocks are widely variable ( $+300$  to  $+600$ ) and much higher than any of the barren granites in the Colorado Mineral belt (Figure 5) [Simmons and Hedge, 1978]. In contrast, the Buckingham porphyry Mo at Battle Mountain has relatively high  $\epsilon_{Nd}$  ( $-6.3$ ) and low  $\epsilon_{Sr}$  ( $+60$ ), and both values are identical to those of the barren intrusions in central Nevada and to those of the neighboring Cu-mineralizing intrusion at Copper Canyon.

#### MAGMA SOURCES

As described by FD (1983), the  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  of young granites can be used to infer their source regions if the isotopic compositions of potential mantle and crustal sources are known. In the Cordillera, Precambrian continental crust is one likely source of the young granites. The  $\epsilon_{Nd}$  data from exposed Precambrian crust in the western United States are given at the bottom of Figure 4. In general, exposed Archean metasedimentary, gneissic, and granitic crust has  $\epsilon_{Nd}$  (100) values ( $\epsilon_{Nd}$  100 m.y. ago; the average age of the granites analyzed in this study) between  $-25$  and  $-40$  [Wooden *et al.*, 1982], whereas the younger mid-Proterozoic crust has correspondingly higher  $\epsilon_{Nd}$  (100) between  $-22$  and  $+4$  [DePaolo, 1981b]. Among the mid-Proterozoic rocks, there is a clear distinction between mafic, metavolcanic rocks, which have  $\epsilon_{Nd}$  (100) values ranging between  $0$  and  $+5$ , and felsic rocks (e.g.,  $1.7$  and  $1.4$  b.y. granitic rocks) which have values mostly  $\epsilon_{Nd}$  between  $-10$  and  $-12$ . The  $\epsilon_{Sr}$  (100) values for exposed Precambrian crustal rocks vary widely in both the Archean and mid-Proterozoic terranes. In general, mafic metavolcanic rocks have  $\epsilon_{Sr}$  (100) less than  $+50$  [cf. Hedge *et al.*, 1967], whereas granite, orthogneiss, and felsic metavolcanic rocks have  $\epsilon_{Sr}$  (100) values roughly between  $+100$  and  $+4000$  (references cited by Peterman [1979], Lanphere [1968], Livingston [1969], and Peter-

man and Hedge [1968]), and pelitic metasedimentary rocks have very high  $\epsilon_{Sr}$  (100) ranging up to  $+8000$  [cf. Armstrong and Hills, 1967; Powell *et al.*, 1969].

In northern Colorado, garnet granulite and charnockite xenoliths derived from the lower continental crust have  $\epsilon_{Nd}$  (100) in the same range as that of exposed felsic mid-Proterozoic upper crust ( $-8$  to  $-15$  [DePaolo, 1981b]). Mafic granulites in these regions have high, nearly chondritic, Sm/Nd [Ehrenberg and Griffin, 1979], which suggests that their  $\epsilon_{Nd}$  (100) are significantly higher than the values for the felsic granulites. The  $\epsilon_{Sr}$  (100) values of the granulites are generally lower, for any given bulk composition, than upper crustal rocks, ranging between  $-15$  and  $+70$  for less aluminous garnet granulites and for mafic granulites [James *et al.*, 1980].

These data indicate that the Nd isotopic compositions of the Precambrian crust vary widely with crustal age and bulk composition, while the Sr isotopic composition depends on crustal bulk composition and metamorphic grade. These features of the crustal isotopic compositions must be taken into account in interpretations of the Cordilleran granite isotopic compositions.

#### Peraluminous Granites

In southern Arizona the range of  $\epsilon_{Nd}$  for the peraluminous granites ( $-10$  to  $-12$ ) corresponds to the most commonly observed values for felsic, mid-Proterozoic crust (Figure 4). This observation strongly suggests that the peraluminous granites were derived primarily from such crust. Similarly, in the northern Rocky Mountains the extremely negative  $\epsilon_{Nd}$  of the peraluminous Almo pluton ( $-29.9$ ) is approximately the same as the average  $\epsilon_{Nd}$  value expected for Archean crust. These data as well as the data on the peraluminous granites in the NGB [FD, 1983] indicate that peraluminous granites throughout the western United States were derived by melting of typical felsic Precambrian basement rocks and that the regional variations in granite  $\epsilon_{Nd}$  result from regional variations in the average crustal  $\epsilon_{Nd}$ .

The  $\epsilon_{Sr}$  values of the peraluminous granites do not exhibit consistent regional variations (Figure 5) but do provide information about the crustal magma sources. The  $\epsilon_{Sr}$  values require source Rb/Sr ratios between  $0.05$  and  $0.3$ , which are generally lower than those of the immediate wall rocks for the intrusions [cf. Armstrong and Hills, 1967]. This suggests that the crustal source was at a substantially greater depth than the current level of exposure. Wright and Haxel [1982] reached a similar conclusion for granites in southern Arizona on the basis of field relationships.

#### Metaluminous Granites

In southern Arizona and Colorado, metaluminous granites have consistently higher  $\epsilon_{Nd}$  and lower  $\epsilon_{Sr}$  than either the peraluminous granites (Figures 4 and 5) or the felsic Precambrian basement in these regions (Figure 7). Only the calc-alkaline Kitt Peak granodiorite in southern Arizona has an  $\epsilon_{Nd}$  value low enough ( $-8.5$ ) to be derived exclusively from the average local crust.

The two most likely explanations for the relatively high  $\epsilon_{Nd}$  and low  $\epsilon_{Sr}$  of the metaluminous granites are (1) that they are formed by anatexis of deep-seated, mafic Precambrian crust that had higher Sm/Nd and lower Rb/Sr ratios than average felsic rocks of the crust and (2) that they formed by interaction of mantle-derived melts with large proportions of felsic lower crust. To account for the low  $\epsilon_{Sr}$  values of the metaluminous

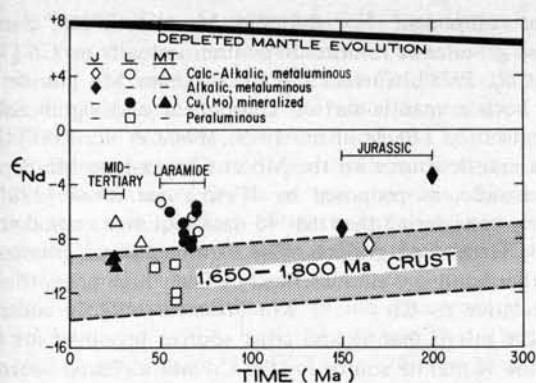


Fig. 7. Granite  $\epsilon_{\text{Nd}}$  versus crystallization age in Colorado and southern Arizona. Range of  $\epsilon_{\text{Nd}}$  for felsic mid-Proterozoic crust and the depleted mantle evolution curve are from DePaolo [1981b].

granites, the latter model requires that the mixing process involved a crustal end-member with low Rb/Sr (Figure 8), a characteristic which could be due to Rb depletion in the lower crust during granulite grade metamorphism  $\sim 1.7$  b.y. ago.

These two possibilities cannot be fully discriminated on the basis of the available data. Models of the composition of the crust in the southwestern United States, based on crustal xenolith populations in kimberlites on the Colorado Plateau, suggest a relatively mafic lower crust [McGetchin and Silver, 1972]. On the other hand, the wide range of correlated  $\epsilon_{\text{Nd}}$  and  $\epsilon_{\text{Sr}}$  for metaluminous granites in the eastern NGB [FD, 1983] strongly suggests that those granites formed by mixing of mantle-derived magmas and a felsic lower crust. We prefer a mantle magma/crust mixing model for the Cordilleran metaluminous granites, since this model is consistent with the sources inferred for metaluminous continental-interior granites in the NGB. Given this model, and assuming that the mantle magmas were derived from a LREE-depleted reservoir [cf. DePaolo, 1981b] and mixed with a felsic crust of mid-Proterozoic age (the  $\epsilon_{\text{Nd}}$  evolution of both reservoirs shown in Figure 7), the calculated percentages of mantle-derived Nd in the Arizona and Colorado granites are low and vary over a restricted range (Figure 4) from about zero (Kitt Peak; sample 80 AZ PUP-11) to a maximum of about 30% (Harris Ranch, 82 AZ ST-4).

A more modern sample of what we infer for the evolution of the metaluminous granites is described by Musselwhite *et al.* [1983]. In a 12 m.y. volcanic complex in the eastern Mojave desert region, quartz latite pumice has  $\epsilon_{\text{Nd}} \cong -7$ , whereas the local basement country rocks have  $\epsilon_{\text{Nd}}$  values of  $-9$  to  $-18$ . In this case the quartz latite is clearly associated with alkalic basalt, which has  $\epsilon_{\text{Nd}}$  values as high as  $+2.4$ . This magmatic system was undoubtedly driven by heat carried into the crust by mantle-derived basalt, and the latite, though largely derived from the crust, retains a component of mantle-derived material. The latite is inferred to be representative of a pluton emplaced into the middle to upper crust beneath the volcanic field.

Too few data from the metaluminous granites in the northern Rocky Mountains are available to make any conclusions regarding their source regions. However, if their wide range of  $\epsilon_{\text{Nd}}$  (Table 3) is indicative of mixing between mantle and an Archean crust source, then the Vanocker laccolith in the Black Hills ( $\epsilon_{\text{Nd}} = -6$ ) must have a substantial mantle component (Figure 4), despite having been emplaced far into the continent interior (Figure 1).

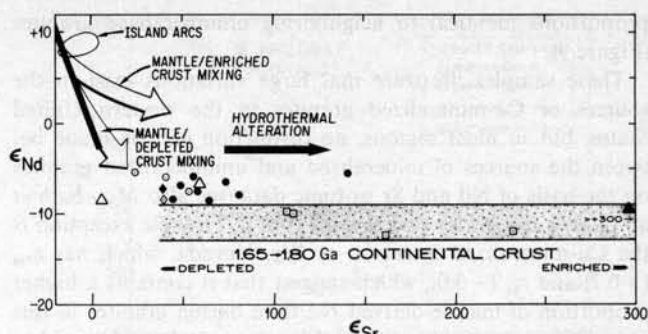


Fig. 8. The  $\epsilon_{\text{Nd}}$  versus  $\epsilon_{\text{Sr}}$  for Colorado and southern Arizona granites. Symbols as in Figure 7. Mineralized granites (solid circles) extend toward higher  $\epsilon_{\text{Sr}}$  than barren metaluminous granites due to contamination by radiogenic upper crustal Sr during hydrothermal alteration (solid arrow). Open arrows depict generalized trends in granite  $\epsilon_{\text{Nd}}$  and  $\epsilon_{\text{Sr}}$  expected for mixing of a depleted mantle magma with a depleted lower crustal source and an enriched upper crust. Range of mid-Proterozoic crust  $\epsilon_{\text{Nd}}$  from Figure 4;  $\epsilon_{\text{Sr}}$  range estimated from granite data (this study) and from  $\epsilon_{\text{Sr}}$  values for Precambrian crust (references given in text).

#### Porphyry Cu/Mo

The overall similarity between the Sr and Nd isotopic compositions of metaluminous Cu-mineralized and unmineralized granites in the western United States suggests that both have similar source regions. For example, in southern Arizona the low  $\epsilon_{\text{Nd}}$  values suggest that all metaluminous were mostly derived from Precambrian basement but contain minor components of mantle-derived material. The generally low  $\epsilon_{\text{Sr}}$  values ( $< +60$ ) indicate that the crustal component had low  $\epsilon_{\text{Sr}}$  and therefore was probably deep in the crust. The higher  $\epsilon_{\text{Sr}}$  ( $+80$  and  $+141$ , respectively) of the Silverbell and San Manuel samples (and also the high  $\epsilon_{\text{Sr}}$  of the unmineralized Harris Ranch pluton at Sierrita) are interpreted to be the result of contamination by radiogenic upper crustal Sr during hydrothermal alteration associated with mineralization [Farmer and DePaolo, 1982] and do not reflect a high  $\epsilon_{\text{Sr}}$  crustal magma source. In the Great Basin the Bingham stock was apparently derived primarily from Rb-depleted, felsic basement similar to the sources of nearby unmineralized granites [FD, 1983], whereas the intrusion at Copper Canyon is interpreted to have formed by mixing between mantle-derived magma and deep-seated eugeoclinal sedimentary rocks, in

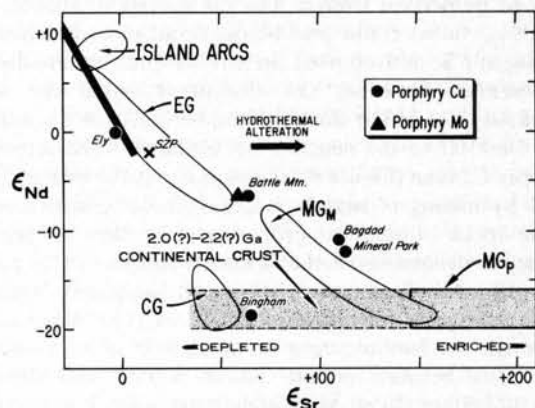


Fig. 9. The  $\epsilon_{\text{Nd}}$  versus  $\epsilon_{\text{Sr}}$  for mineralized and barren NGB granites. Fields for peraluminous ( $\text{MG}_p$ ) and metaluminous (EG,  $\text{MG}_m$ ) granites in Nevada, and metaluminous granites in central Utah (CG) from FD [1983]. Mineralized granites generally plot near the fields defined by the barren granites in their respective regions.

proportions identical to neighboring unmineralized granites (Figure 9).

These samples illustrate that large variations exist in the sources of Cu-mineralized granites in the western United States, but in most regions, no distinction can be made between the sources of mineralized and unmineralized granites on the basis of Nd and Sr isotopic data (see also *Moorbath et al.* [1967] and *Titley and Beane* [1981]). The sole exception is the Cu-mineralized intrusion at Ely, Nevada, which has  $\epsilon_{Nd}$  (+0.7) and  $\epsilon_{Sr}$  (-3.0), which suggest that it contains a higher proportion of mantle-derived Nd than barren granites in this area (75% versus about 0%; Figures 4 and 9). Other hydrothermally altered granites in eastern Nevada and western Utah (the Silver Zone Pass pluton and the Jurassic pluton at Gold Hill) are also characterized by relatively high  $\epsilon_{Nd}$  [FD, 1983]. These observations suggest that unlike elsewhere in the western United States, mineralized granites in the miogeocline of the NGB are distinguishable from unmineralized granites on the basis of  $\epsilon_{Nd}$ . The Nd isotopic data may, therefore, be useful as a prospecting tool in this region.

The sources of Cu-mineralized granites at Mineral Park and Bagdad in northern Arizona (Figure 2) remain ambiguous since neither the Nd isotopic compositions of unmineralized granites or Precambrian basement in this area are well known. The  $\epsilon_{Nd}$  (-11 to -12) and  $\epsilon_{Sr}$  (+110 to +113) are similar both to peraluminous granites derived from  $\epsilon_{Nd}$  (0)  $\cong$  -10 Precambrian crust in southern Arizona and to unmineralized metaluminous granites in the NGB, which are interpreted to be mixtures between mantle magmas and  $\epsilon_{Nd}$  (0)  $\cong$  -19 crust (Figure 9).

The granite porphyries at the Henderson Climax-type Mo deposit all have  $\epsilon_{Nd}$  between -9.5 and -9.9, independent of the amount of associated Mo mineralization. These  $\epsilon_{Nd}$  values are indistinguishable from the  $\epsilon_{Nd}$  of felsic crust in Colorado (Figure 7), which suggests that the granite magmas were derived exclusively from mid-Proterozoic crust, in contrast to unmineralized metaluminous granites in Colorado which have higher  $\epsilon_{Nd}$  (-5.4 to -8.4; Figures 4 and 8), indicating that they may contain a component of mantle-derived Nd. The  $\epsilon_{Sr}$  values of the Henderson granites (> +300) are low relative to their immediate wall rocks (the Silver Plume granite with  $\epsilon_{Sr}$  (0) greater than +1000 [Peterman and Hedge, 1968]) but are substantially higher than the unmineralized metaluminous granites in Colorado ( $\epsilon_{Sr}$  from +10 to +60 (Table 3) [Simmons and Hedge, 1978]). Therefore the Henderson granites appear to be derived from a Rb-rich midcrustal source, but the high  $\epsilon_{Sr}$  values could also be the result of contamination by radiogenic Sr derived from the Silver Plume granite during hydrothermal alteration. On the other hand, the Mo-mineralized intrusion at Buckingham, Nevada, has  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  values identical to the neighboring Cu-mineralized intrusion at Copper Canyon (Figure 9), suggesting that the two granites formed by mixing of mantle magmas and eugeoclinal sedimentary rocks in identical proportions. Further studies are necessary to determine whether a mantle component, as determined by Nd isotopes, always discriminates "quartz-monzonite"-type Mo deposits from "Climax-type" deposits.

Although the isotopic data reveal that little or no correlation exists between granite source regions and the occurrence of either Cu or Mo ore deposits, a weak correlation does exist between granite sources and the type of base metal mineralization. In general, the Cu-mineralized granites all contain a mantle component (with the notable exception of Bingham), and the Mo-mineralized granites contain a felsic (?)

crustal component. For example, Mo-mineralized, crustally derived granites at Henderson contain virtually no Cu [Wallace et al., 1978], whereas the Buckingham Mo granite contains both a mantle-derived component and significant Cu mineralization [Blake et al., 1979; White et al., 1981]. Note that a mantle source for the Mo at Climax-type Mo deposits in Colorado, as proposed by Westra and Keith [1981], is unlikely considering that the Nd data require a crustal source for the Henderson granites. The Cu-mineralized granites, on the other hand, are characterized by fairly high proportions of Mo relative to Cu (~5% Mo [Gilmour, 1982]), consistent with the mixed mantle and crust sources proposed for these granites. A mantle source for the Cu and a crustal source for the Mo is therefore reasonably consistent with the available data and with models for the sources of these metals based on studies of Mo and Cu deposits worldwide [Hollister, 1978; White et al., 1981]. It should be emphasized, however, that the proportions of mantle- and crust-derived material (as defined by Nd isotopes) do not control whether a deposit will form or the Cu/Mo ratio of a deposit that does form. The latter case is well illustrated by the Copper Canyon and Buckingham granites which have identical sources but are associated with much different proportions of Cu and Mo mineralization. Therefore some other parameter(s), such as differences in the depths of exposure at different deposits (assuming a vertical zonation in the metal mineralization [Lowell and Guilbert, 1970]), must account for the type of mineralization observed. The magma source may only control the types of base metal metallization which could potentially be associated with a given granite.

#### PRECAMBRIAN BASEMENT AGE AND COMPOSITION

The isotopic data presented here serve to define further the boundaries of Nd isotopic provinces in the Precambrian crust of the western United States. The  $\epsilon_{Nd}$  of the Almo pluton in southern Idaho (-29.9) indicates that the Archean basement in this region has a significantly different Nd isotopic composition from the basement inferred to underlie the NGB, which has an  $\epsilon_{Nd}$  (0) of about -19. The boundary between these two crustal terranes must be located between Gold Hill, Utah (cf. sample 79UTGH-1 [FD, 1983]), and the Raft River Range in northern Utah, where the southernmost Archean basement in this region is exposed [Compton et al., 1977]. The southernmost extent of the  $\epsilon_{Nd}$  (0) = -19 basement is not well constrained by the available data but may reach into northern Arizona, as evidenced by the relatively low  $\epsilon_{Nd}$  of Cu-mineralized granites in this region.

In southeast California, basement with average  $\epsilon_{Nd}$  (0) of -19 is inferred to underlie the Old Woman Mountains [FD, 1983], but granite analyzed from near Emerson Lake (A80-8; sample 33, Figure 1) has an  $\epsilon_{Nd}$  value of -12 (Table 3). However, the latter granite, because it is part of the Jurassic batholith belt, may contain a mantle component and so its  $\epsilon_{Nd}$  value may not be the same as that of the average Precambrian crust [see FD, 1983]. Further Nd isotopic data from exposed Precambrian rocks in the Mojave Desert are required to establish the isotopic structure of the crust in southeastern California.

The  $\epsilon_{Nd}$  values of the peraluminous granites in Arizona (-10 to -12) are different from those determined on similar rocks in eastern Nevada, north-central Utah, and eastern California, as described above. These data, along with the data on the 1.4-b.y. Oracle granite (80 AZ OG-10) indicate that felsic Precambrian basement in southern Arizona is isotopically distinct from basement rocks in the Great Basin and eastern Mojave but similar isotopically to the basement in Colorado

[DePaolo, 1980]. Silver [1968] infers an age difference of about 100 m.y. between crust in southern Arizona (1.68–1.72 Ma old), and north-central Arizona and Colorado (1.72–1.80 Ma old), but this age difference is too short to produce a very large difference in Nd isotopic composition.

Our interpretations of isotope provinces in the basement of the southwestern United States are summarized in Figure 20. Although the exact locations of the boundaries are not well constrained, the existence of three, rather than two [Condie, 1981], major crustal provinces in this area seems now well established on the basis of these data and data reported elsewhere [Bennett *et al.*, 1984; B. K. Nelson and D. J. Depaolo, manuscript in preparation, 1984]. The  $\epsilon_{Nd}(0) = -30$  and  $\epsilon_{Nd}(0) = -19$  provinces correspond to the 2.6- and 1.8-Ga crustal terranes. The  $\epsilon_{Nd}(0) = -19$  province either represents crust formed during a third, previously unrecognized crust formation event at about 2.2 Ga or, more likely, a crustal segment composed of admixed 2.6- and 1.8-Ga crust equivalent to the 1.8 Ga old Penokean terrane in Wisconsin [Nelson *et al.*, 1983].

The Nd data from the early Tertiary peraluminous granites in southern Arizona also indicate that the absence of exposed autochthonous Precambrian rocks from a large portion of south-central Arizona (the region south of the dashed line in Figure 3) does not mean that Precambrian basement does not underlie this area [cf. Haxel *et al.*, 1980a]. The peraluminous granites in this region (Figure 3), such as those at Sierra Blanca (81 AZ PR-364) and Presumido Peak (80 AZ PUP-32,22), have isotopic characteristics that require their derivation from 1.7 Ga continental crust. We conclude that Precambrian basement is almost certainly present in this part of south-central Arizona.

The Sr isotopic compositions of the Cordilleran granites provide evidence regarding the isotopic composition of the deep crust in the western United States. Metaluminous granites in the eastern NGB have consistently different  $\epsilon_{Sr}$  values than those in southern Arizona and Colorado (Figure 5). When compared as a function of the estimated proportion of crustally derived Nd that they contain (Figure 10), the NGB granites, consistently, have higher  $\epsilon_{Sr}$ . These data confirm the existence of regional variations in the Rb-Sr isotopic characteristics of the lower continental crust at the time of Cretaceous and Tertiary plutonism [FD, 1983]. The craton regions (Colorado, Arizona, and central Utah) had low  $\epsilon_{Sr}$ , Rb-

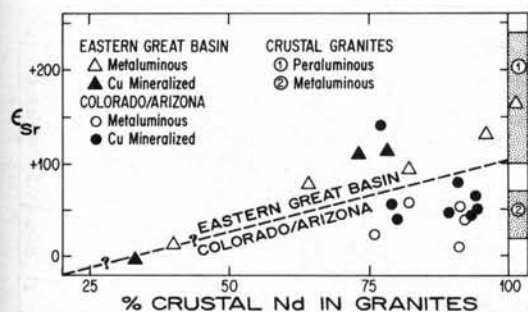


Fig. 10. The  $\epsilon_{Sr}$  versus percent crustal Nd for the Cordilleran granites. Percentages calculated assuming mixing of mantle magma with  $\epsilon_{Nd} = +8$  and crust with  $\epsilon_{Nd} = -18$  (for NGB granites) and  $-10$  (in Colorado and southern Arizona). Shaded regions at right margin of diagram show range of  $\epsilon_{Sr}$  for crustally derived granites in the Cordillera (region 1 are peraluminous granites; region 2 are metaluminous). Dashed line separates metaluminous granites in eastern Great Basin from those in southern Arizona and Colorado. Note that  $\epsilon_{Sr}$  of mineralized granites (solid circles) may be high due to contamination by upper crustal Sr.

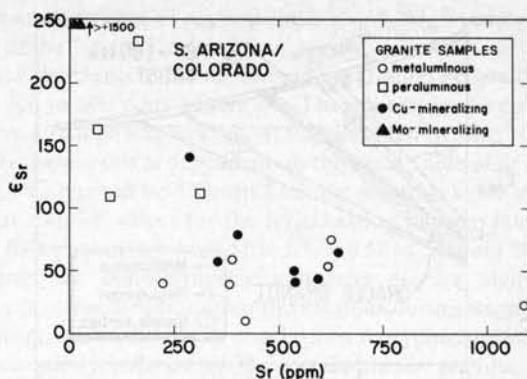


Fig. 11. The  $\epsilon_{Sr}$  versus Sr concentrations for granites in southern Arizona and Colorado.

depleted (or mafic?) lower crust. In the miogeocline (eastern Nevada) the lower crust had a markedly higher  $\epsilon_{Sr}$ , reflecting a crust more Rb-rich in comparison to Sr. The high  $\epsilon_{Sr}$  of peraluminous granites relative to metaluminous granites in southern Arizona (Figures 5 and 10) implies that the former were derived from a moderately high-Rb/Sr and high- $\epsilon_{Sr}$  "mid-crustal" source. These data suggest that a vertical zonation in  $\epsilon_{Sr}$  may be common in the cratonal basement of the western United States.

#### PETROGENETIC MODELING

##### Peraluminous Granites

All peraluminous granites in the Cordillera are interpreted to have been derived from Precambrian crystalline basement. In terms of the magma evolution model of FD [1983], stage 1 evolution was in moderate Rb/Sr, felsic continental crust. The observed range of  $\epsilon_{Sr}$  implies either that the crustal sources were isotopically inhomogeneous or that a period of stage 2 evolution (assimilation) took place at shallower levels in the crust.

The highly silicic and peraluminous character of these granites is probably traceable to stage 1 processes. Experimental data indicate that high  $\text{SiO}_2$  magmas can be produced directly from the crust under water-saturated, amphibolite grade, PT conditions [Wyllie, 1977]. Moderate PT conditions are consistent with the inference that the peraluminous granites were derived from a midcrustal, and not lower crustal, source. The bulk composition of the source, prior to partial melting, is not known but apparently was not strongly peraluminous, since, as described above, pelitic metasedimentary rocks in the western United States, regardless of metamorphic grade, have  $\epsilon_{Sr}$  values that are much higher than those of the peraluminous granites. However, it may not be possible to produce peraluminous parental melts via anatexis unless the source is at least mildly peraluminous (e.g., weakly weathered granitic material [Clemens and Wall, 1981]). An alternative possibility is that the peraluminous granites could be the result of crystal fractionation of hornblende or epidote from a metaluminous or transitional parental melt [Cawthorn and Brown, 1976; Zen, 1980]. However, no hornblende-bearing or metaluminous granites related to the peraluminous granites have been identified in the field in south-central Arizona [Haxel *et al.*, 1980a].

The trace element compositions of the peraluminous melts are characterized by variable, but generally high, Sm/Nd ratios and low Sr contents (Figure 11) relative to the metaluminous granites. The relatively high Sm/Nd ratios of samples from the Sierra Blanca and Baboquivari Mountains (samples

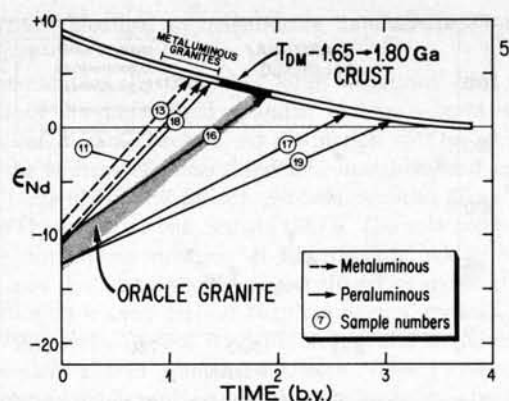


Fig. 12. The Nd evolution curves and model ages for selected southern Arizona granites. Range of  $T_{DM}$  model ages for mid-Proterozoic crust from DePaolo [1981b]. Evolution curves are solid for the peraluminous granites and dashed for metaluminous. Sample numbers (Table 2) are shown on each curve. Stippled field shows the isotopic evolution of the Oracle granite. Range of model ages for metaluminous granites in southern Arizona labeled on the depleted mantle evolution curve.

81 AZ PR-364 and 80 AZ PUP-32) are thought to be the result of substantial Sm-Nd fractionation from their crustal sources, since these granites have  $T_{DM}^{Nd}$  model ages much older ( $>2.0$  Ga) than the age of the crust from which they were derived (Figure 12). Assuming a source  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of about 0.133 in the source (calculated using  $\epsilon_{Nd}(0) = -11$  and a crust formation age  $T_{CF}$  of 1.8 Ga),  $\alpha_{Sm/Nd}$  values ( $\text{Sm}/\text{Nd}_{\text{rock}}/\text{Sm}/\text{Nd}_{\text{source}}$  [FD, 1983]) for these two samples are about 1.2. The indicated LREE depletions during magma evolution are probably due to stage 3 crystal fractionation of a LREE-enriched phase such as allanite or monazite [Miller and Mittlefehldt, 1982; Mittlefehldt and Miller, 1983]. The generally low-LREE concentrations in the peraluminous granites (Table 2) can also be accounted for in this manner.

The low Sr concentrations (Figure 11) of the peraluminous granites could be a reflection of a low Sr abundance in their crustal source, residual plagioclase in the source, or fractionation of plagioclase during stage 3 magma evolution. The well-developed Eu anomaly in the one peraluminous granite for which full REE abundance data are available (81 AZ PUP-32; Figure 18) argues in favor of one of the latter explanations.

#### Metaluminous Granites

The preferred interpretation of the isotopic data from the metaluminous granites in the Northern Rocky Mountains, Colorado, and Arizona suggests that all these granites underwent stage 1 evolution in the upper mantle, followed by extensive stage 2 evolution in low  $\epsilon_{Sr}$  lower continental crust. The one exception is the Kitt Peak pluton, which may have been derived from magma generated in the lower crust alone. In this model the evolution of the major element chemistry of these granites can be only loosely constrained but must depend in a complex fashion on the PT,  $\text{H}_2\text{O}$ , and extent of partial melting in either the upper mantle or lower crust [cf. Burnham, 1979], the mixing mechanisms during stage 2 evolution, and the degree and nature of stage 3 magma differentiation. It can be concluded, however, that since the isotopic compositions of all metaluminous granites in southern Arizona are similar (Figure 7), the chemical distinction between the alkalic and calc-alkalic granites did not arise by differences in their stage 2 evolution, for example, by differences in the amount of crust assimilated by mantle magmas. Instead, ini-

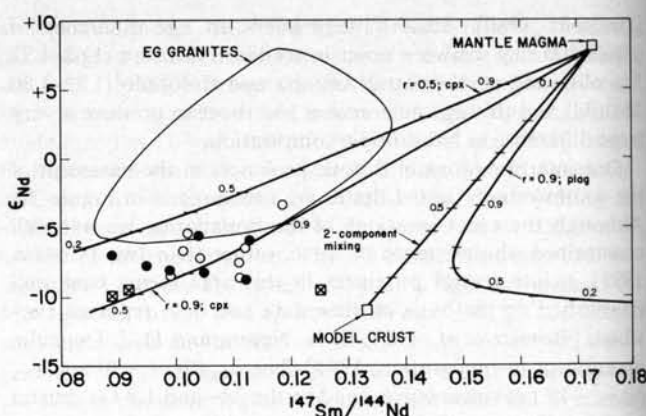


Fig. 13. The  $\epsilon_{Nd}$  versus  $^{147}\text{Sm}/^{144}\text{Nd}$  for southern Arizona and Colorado metaluminous granites and various curves modeling mixing between a mantle magma ( $\text{Nd} = 19$  ppm,  $\text{Sm} = 5$  ppm; generated as by FD [1983] (Figure 12)) and mid-Proterozoic continental crust. The  $^{147}\text{Sm}/^{144}\text{Nd}$  of crust (0.133) calculated assuming  $\epsilon_{Nd}(0) = -11$  and a crust formation age of 1.8 b.y. Mixing was modeled either as two-component mixing or as assimilation/fractional crystallization (AFC) using  $D_{\text{Sm}}$  and  $D_{\text{Nd}}$  for fractionating phases (cpx, plg) from Hanson [1980]. EG field from FD [1983].

tial differences in the compositions of the parental magmas, which were retained during the subsequent evolution of the magmas, or differences in stage 3 evolution, must be responsible for the contrasting bulk compositions of the granite suites.

The metaluminous granites are characterized by  $^{147}\text{Sm}/^{144}\text{Nd}$  values which vary within a fairly narrow range between 0.09 and 0.12 (Figure 13). For granites in southern Arizona and Colorado these values are generally lower than values calculated for the crust (about 0.13; see caption for Figure 13). These low Sm/Nd ratios, combined with  $\epsilon_{Nd}(0)$  values elevated relative to the mid-Proterozoic crust, result in young  $T_{DM}$  model ages for these granites (0.7–1.0 b.y., Figure 12). If it is assumed that the metaluminous granites formed by mixing of mantle magmas with the lower crust, then the low  $^{147}\text{Sm}/^{144}\text{Nd}$  and high  $\epsilon_{Nd}$  values can be modeled using the assimilation/fractional crystallization (AFC) model [DePaolo, 1981c] if the  $r$  values, the ratio of the mass rate of assimilation to the mass rate of crystal fractionation, are high (0.5–0.9), and the fractionating phase(s) are depleted in LREE (e.g., clinopyroxene; see Figure 13 caption for details of calculations). Since

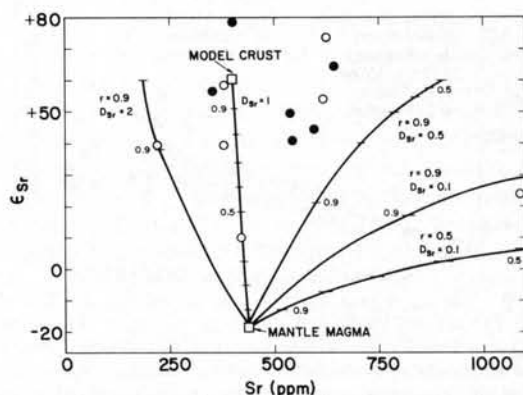


Fig. 14. The  $\epsilon_{Sr}$  versus Sr concentration for metaluminous granites in Colorado and southern Arizona and various model mixing curves. Mantle magma generated as by FD [1983] (see figure 11). Model crust has a low  $\epsilon_{Sr}$  (+60) and a Sr content equal to that estimated for average lower crust (400 ppm [Taylor and McLennan, 1981]).

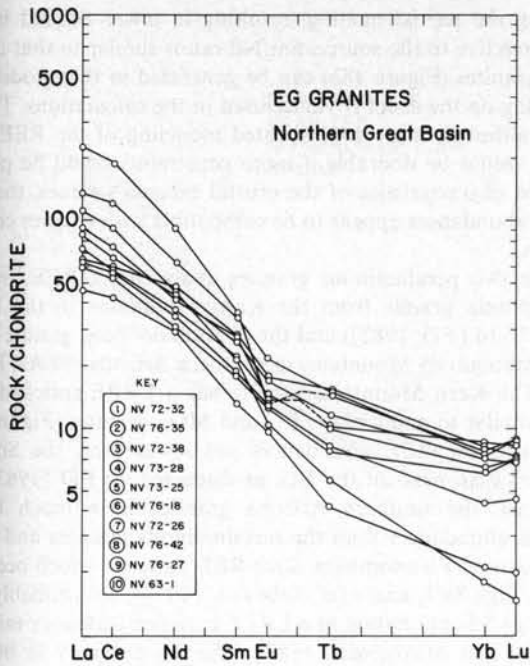


Fig. 15. Chondrite-normalized REE patterns for EG granites. Samples are numbered sequentially according to decreasing La concentrations (left margin). Data from L. Haskin (personal communication, 1981).

the low  $\epsilon_{Nd}$  values require  $M_a/M_m^0$  values (the ratio of the mass of "assimilated" crust to the original mass of mantle magma [FD, 1983]) ranging between about 1.0 and 2.0, the conclusion is that the magmas reached the upper crust only after very extensive interaction with the lower crust. The uniformly high  $M_a/M_m^0$  values contrast with granites in the eastern NGB which have  $M_a/M_m^0$  values as low as about 0.3 [FD, 1983]. Differences in the crustal structure of the craton versus the miogeoclinal, such as a greater crustal thickness in the former at the time of granite formation, could account for

the restricted range of  $\epsilon_{Nd}$  and the high  $M_a/M_m^0$  observed for most of the "craton" granites.

The Sr contents of the metaluminous granites generally vary from 300 to 600 ppm (Figure 14). These moderate Sr contents also require high  $r$  values (about 0.9) and high  $M_a/M_m^0$  (about 1.0). However, this is dependent on the exact value of  $\epsilon_{Sr}$  of the crust, which could be different from the assumed value of +60 (Figure 14).  $D^{Sr}$  values for the fractionating phase(s) may also have to be relatively high ( $1 > D^{Sr} > 0.5$ ) to account for the moderate Sr concentrations and may require significant plagioclase fractionation from the magmas during stage 2 or 3 evolution. All of the above conclusions regarding the isotopic and chemical evolution of the metaluminous granites apply also to the mineralized granites in southern Arizona and Nevada.

#### REE ABUNDANCES IN CORDILLERAN GRANITES

REE abundances from many of the NGB granites [FD, 1983] and several southern Arizona granites considered in this paper, were determined by L. Haskin (personal communication, 1981). These data can be used to test the inferences drawn from the Sm, Nd, Rb, and Sr concentrations and the isotopic data regarding the magmatic sources and evolution of these rocks.

The REE abundances of all the metaluminous granites are similar, and all are characterized by strongly fractionated REE patterns and LREE (La, Ce, Sm) enrichments. All metaluminous granites in Nevada and western Utah (EG and MG<sub>m</sub> granites [FD, 1983]) have virtually identical patterns (Figures 15 and 16), with linear to concave-up patterns in the middle (Sm, Eu, Tb) and heavy (Yb, Lu) REE. LREE abundances are high (Ce = 50–200 × chondrite values), whereas HREE abundances are low, between 2 and 10 × chondritic. A few of the granites (particularly among the MG<sub>m</sub> granites) have weakly developed Eu anomalies. Metaluminous granites in central Utah (CG granites [FD, 1983]) have slightly steeper LREE patterns and greater LREE enrichments (Ce = 150–300 × chondrite; Figure 17). MREE and HREE are also more

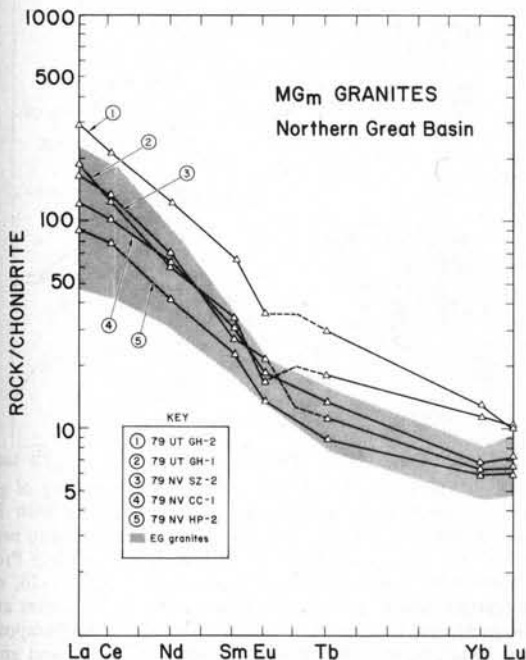


Fig. 16. Chondrite-normalized REE patterns for MG<sub>m</sub> granites. Field for EG granites from Figure 15 (excluding samples 3 and 10).

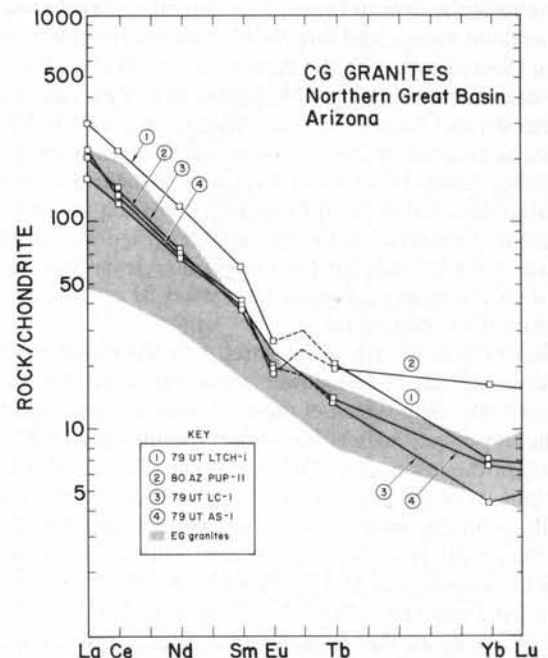


Fig. 17. Chondrite-normalized REE patterns for CG granites and the Kitt Peak pluton in southern Arizona (80 AZ PUP-11).

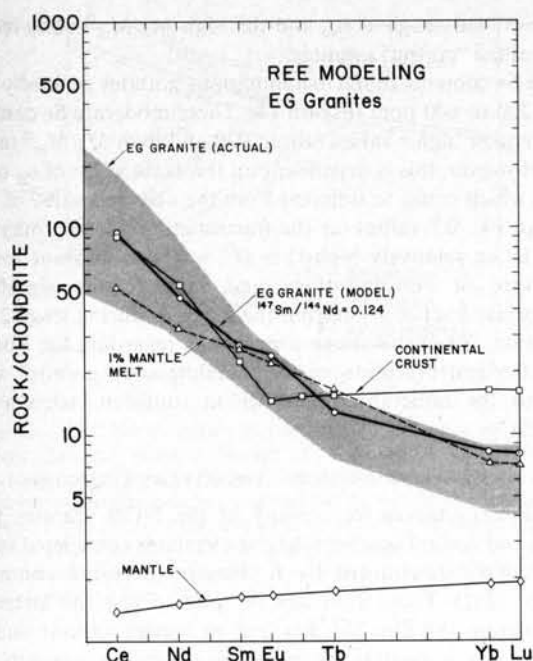


Fig. 18a. Modeling of EG REE patterns using AFC calculations. Depleted mantle has  $1.5\text{--}2.0 \times$  chondrite REE abundances and a Sm/Nd from DePaolo and Johnson [1979]. One percent melt produced by model melting of mantle composed of 55% ol, 25% opx, 15% cpx, and 5% gar, using  $D$  values for REE from Hanson [1980]. Model continental crust is PAAS sedimentary composite from Nance and Taylor [1976]. Model EG granite produced via mixing of the 1% mantle melt with the model crust, assuming that  $r = 0.5$  and  $F = 0.7$ .

strongly fractionated than in the EG and  $MG_m$ , resulting in a crossover, between Tb and Yb, in the REE patterns of the CG and EG granites.

Most of the EG granites for which REE data are available are from western Nevada and are interpreted to have formed via mixing between mantle melts and eugeoclinal sedimentary rocks. In an assimilation/fractional crystallization (AFC) model [DePaolo, 1981c],  $r$  values of about 0.5 and  $F$  values (the ratio of the final to the original magma mass) of about 0.7 best account for  $\epsilon_{Nd}$  and Sm/Nd of these granites [FD, 1983]. Using these constraints, the concentrations of the other REE were calculated, using the AFC model, with a parental mantle magma derived from 1% partial melting of a LREE-depleted mantle source and a crustal contaminant with average shale REE abundances [Nance and Taylor, 1976]. The REE pattern and abundances that result from this calculation are very similar to those observed in the EG granites (Figure 18a). Therefore the full REE data for the EG granites are at least consistent with the model proposed for the origin of these granites based on the isotopic data.

The CG granites are all interpreted to have been produced by partial melting of felsic lower continental crust; the metaluminous bulk composition of these granites is interpreted to be a function of partial melting under granulite-grade PT conditions in the lower crust [Wyllie, 1977]. The extreme LREE enrichments in the granites can be reproduced from a garnet-bearing granulite lower crust, as shown in Figure 18b. In this calculation the granulite crust is arbitrarily assumed to have the REE abundances of average shale. A 20% partial melt of this crust (residuum = 70% cpx, 23% gar, and 7% plag) results in a magma that is enriched in LREE and depleted in HREE relative to the source, very similar to the average REE abundances of the CG granites. Sm and Nd are fractionated

during the partial melting, resulting in lower Sm/Nd in the melt relative to the source. Sm/Nd ratios similar to that of the CG granites (Figure 18b) can be generated in this model, depending on the exact  $D$  values used in the calculations. Therefore, although more sophisticated modeling of the REE patterns would be desirable if more constraints could be placed on the characteristics of the crustal magma sources, the CG REE abundances appear to be compatible with a lower crustal origin.

The two peraluminous granites analyzed for REE are the Tungstona granite from the Kern Mountains in the NGB (NV 77-10 [FD, 1983]) and the Presumido Peak granite from the Baboquivieri Mountains in southern Arizona (80 AZ PUP-32). The Kern Mountains sample has a LREE-enriched pattern similar to many of the EG and  $MG_m$  granites (Figure 19), although the REE abundances are lower (and the Sm/Nd higher) than most of the EG, as discussed by FD [1983]. In contrast, the southern Arizona granites have much lower LREE abundances than the metaluminous granites and have pronounced Eu anomalies. Such REE patterns, which occur in many high  $SiO_2$  rocks [cf. Jahn et al., 1979], are probably due to stage 3 fractionation of a LREE-enriched accessory mineral [Miller and Mittlefehldt, 1982]. The Eu anomaly in 80 AZ PUP-32 suggests that plagioclase was also fractionating at this time. Therefore the REE data support the conclusion that the peraluminous granites in southern Arizona have low total REE and high Sm/Nd resulting from stage 3 crystal fractionation.

#### PARENTAL MAGMA GENERATION

The inferred source regions and evolutionary histories of granites in the Cordillera can be used to constrain tectonic

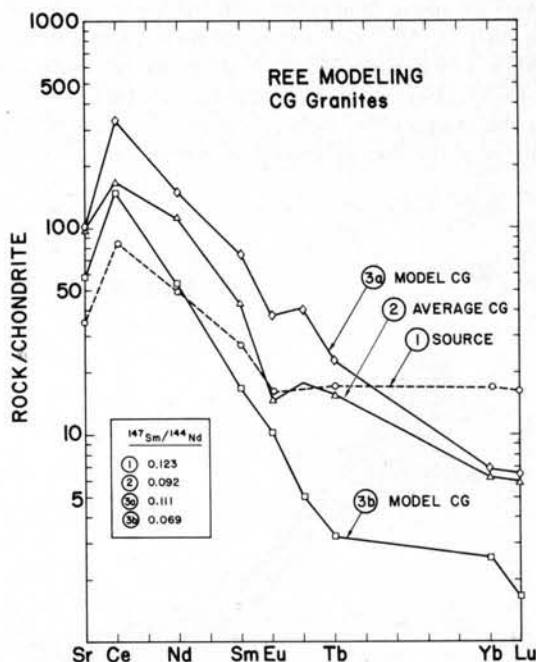


Fig. 18b. Modeling of CG REE patterns from melting of granulite facies continental crust. Assumed a crustal source with PAAS REE abundances but with Sm and Nd abundances shifted to produce a  $^{147}Sm/^{144}Nd$  ratio equivalent to that calculated for early Proterozoic crust (0.123; calculated assuming a crustal  $\epsilon_{Nd} = -18$ , and a crust formation age of 2.2 b.y.). The two model CG granites are the magmas produced from a 20% modal melt of a crust composed of 73% cpx, 23% gar, and 7% plag, using either the basalt and andesite  $D$  values for the REE (3a) or the rhyolite and dacite values (3b) from Arth [1976].

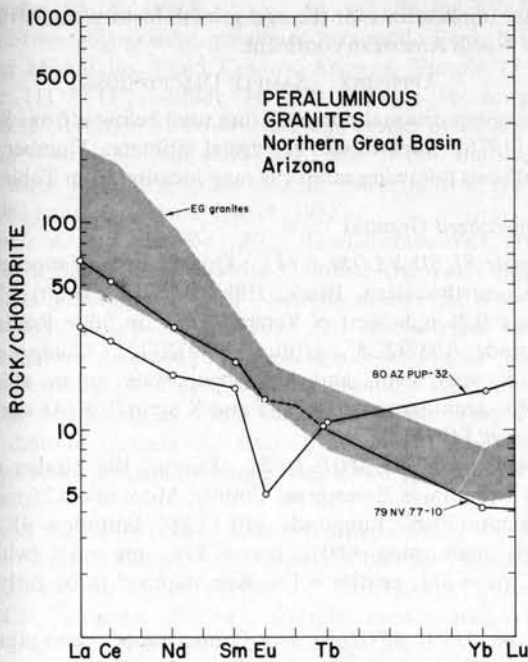


Fig. 19. Chondrite-normalized REE patterns for Tungstia peraluminous granite in the NGB (79 NV 77-10) and Presumido Peak granite (80 AZ PUP-32).

models for the generation of their parental magmas [FD, 1983]. Jurassic granites, including those in the Sierra Nevada, NGB, and southern Arizona, were all the end results of partial melting in the upper mantle induced by the subduction of oceanic lithosphere at the western margin of North America [Dickinson, 1981]. However, Jurassic and Cretaceous batholith granites in the Sierra Nevada are apparently composed primarily of mantle-derived material [DePaolo, 1980, 1981a],

whereas those in southern Arizona are dominantly composed of preexisting crust (Figure 4). The large crustal components in the southern Arizona granites may represent a greater pre-batholithic crustal thickness in this region (relative to the Sierra Nevada) and/or a lower flux of magma into the lower crust farther inland from the subduction zone [FD, 1983].

Late Cretaceous and early Tertiary metaluminous granites also have apparent mantle components, suggesting that most of the magmatism that occurred at this time was linked to partial melting in the upper mantle. However, it is difficult to correlate such partial melting with subduction-related processes, since granites with apparent mantle components were produced at this time as far as 1500 km inland in Colorado and the Black Hills. Changes in the dip angle of subducted oceanic lithosphere [Coney and Reynolds, 1977; Lipman, 1980] or convection and partial melting in the upper mantle induced by subduction [FD, 1983] could have been important in producing the magmatism, but no fully satisfactory model for the great inland extent of Late Cretaceous magmatism in the western United States yet exists.

After about 60 Ma ago only peraluminous granites were emplaced in southern Arizona, suggesting that crustal, but not necessarily mantle, melts were being produced at this time (Figure 7). Crustal melting in early Tertiary time has been linked to shallow subduction of oceanic lithosphere and melting in the lower crust [Keith and Reynolds, 1981; Miller, 1982]. However, the lower crust in southern Arizona is likely to have  $\epsilon_{Sr}$  values too low to have been the primary source of the peraluminous granites (Figure 8). Melting in higher  $\epsilon_{Sr}$  midcrustal levels, as a result of crustal thickening in the Late Cretaceous, combined with a steep geothermal gradient induced by emplacement of hot mantle beneath the continent during subduction, may be a more viable mechanism for producing the peraluminous granites [Haxel et al., 1984; FD, 1983].

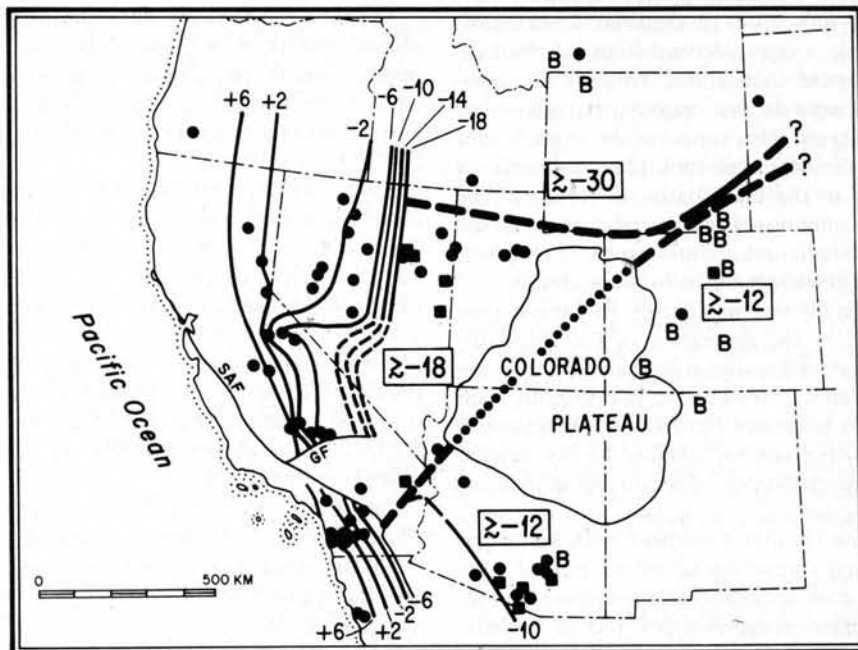


Fig. 20. Nd isotopic provinces in the western United States. The lower limit for the  $\epsilon_{Nd}$  values of the continental interior granites varies on a regional scale, but within any given " $\epsilon_{Nd}$ " province, the granite  $\epsilon_{Nd}$  vary randomly with position. Batholith granites show a distinct west to east decrease in  $\epsilon_{Nd}$  values along the entire length of the continental margin [DePaolo, 1980, 1981a; FD, 1983]. The closely spaced  $\epsilon_{Nd} = -6$  to  $-18$  contours in the NGB define the western edge of Precambrian basement. Sample localities labeled "B" are basement samples from this study and DePaolo [1981b].

The few mid-Tertiary granites analyzed also appear to contain mantle components (Figure 4, 7, and 8). However, by the mid-Tertiary time much of the lower crust of the western United States may have been modified by injection of mantle melts generated during Jurassic, Late Cretaceous, or early Tertiary time. As a result, melting in the lower crust alone may have been sufficient to produce apparent mantle components in the mid-Tertiary rocks. Any mechanism which increased the temperature of the lower crust sufficiently to produce melting would then be sufficient to produce the mid-Tertiary granites, as pointed out by FD [1983].

Finally, it should be noted that geographic patterns in the  $K_2O$  contents of granites in the southern Cordillera, for example at 57.5%  $SiO_2$ , have been used as evidence that (1) Late Cretaceous, early Tertiary, and mid-Tertiary magmas were derived from melting from a subducted oceanic slab, and (2) that the dip of the slab beneath the western United States was decreasing in the Late Cretaceous and early Tertiary and increasing in the mid-Tertiary [Keith, 1978, 1982]. Although empirical trends in the  $K_{57.5}$  do exist in the Cordillera granites, it should be emphasized that all these granites were primarily derived from crustal, not mantle, sources. Therefore it is difficult to assert that the chemical compositions of magmas that have undergone extensive interaction with continental crust, as well as subsequent differentiation, are solely functions of the conditions of partial melting in the upper mantle. It is unlikely that the  $K_{57.5}$  values of the Cordilleran granites can be related to the depth at which the parental magmas were produced in the upper mantle.

#### CONCLUSIONS

The results of this study (summarized in Figure 20) support and amplify the conclusions reached regarding continental-interior granite sources reached by FD [1983]. Peraluminous granites throughout the Cordillera, including those in the NGB, apparently have sources exclusively in felsic Precambrian continental crust. Metaluminous granites are either mixtures of mantle magma with felsic, Rb-depleted, lower continental crust, or less likely, magma derived from intermediate to mafic composition lower crust alone. Virtually all continental interior granites were derived entirely or largely from preexisting continental crust. This supports the concept that continental growth in the Mesozoic took place primarily at the continental margin in the main batholith terranes. The small apparent mantle components recognized in many of the continental-interior metaluminous granites probably represent only minor additions of juvenile material to the continent.

Although several different magma sources, in various proportions, were involved in the generation of Cu- and Mo-mineralizing granites, no systematic difference between the sources of mineralized and unmineralized granites has been identified except possibly in eastern Nevada. The data suggest that magma sources do not control whether an ore deposit will form, but only influence the type of metallization that can potentially develop.

The data also indicate (1) that the lower portions of the cratonal basement generally have low  $\epsilon_{Sr}$  values, possibly due to Rb depletion during granulite facies metamorphism, and (2) that Precambrian basement underlying portions of Nevada, western Utah, eastern California, and possibly northwestern Arizona is isotopically distinct from both the Archean and mid-Proterozoic crust exposed elsewhere in the western United States. The distinctive nature of this segment of Proterozoic crust was previously unrecognized and will have im-

portant implications for the age, growth history, and structure of the North American continent.

#### APPENDIX: SAMPLE DESCRIPTIONS

The compositional nomenclature used below is from *Streckeisen* [1976]. Rock modes are visual estimates. Number (5) in parentheses following sample is map location from Table 2.

##### Unmineralized Granites

*Sample 81 SD VLQM-1 (1).* Quartz latite, Vanocker lacolith, northwestern Black Hills, Meade County, South Dakota. 0.25 mile west of Veteran Peak on State Route 135. Longitude  $103^{\circ}32'38''$ , latitude  $= 40^{\circ}20'12''$ . Composed of plag, K spar, biot, and hbl phenocrysts in an alliotriomorphic-granular matrix of qtz and K spar(?). K-Ar age from McDowell [1971].

*Sample 81 MT CMGD-1 (2).* Diorite, Big Timber stock, Crazy Mountains, Sweetgrass County, Montana. 0.25 mile SE of Granite Peak. Longitude  $110^{\circ}17'28''$ , latitude  $= 48^{\circ}2'18''$ . Sample mode: plag = 60%, biot = 30%, cpx = 5% (with hbl rims), qtz = 3%, apatite = 1%. Age assumed to be early Tertiary.

*Sample 81 ID APGD-1 (3).* Granodiorite, Almo pluton, S Albion Mountains, Cassia County, Idaho, Longitude  $113^{\circ}43'00''$ , latitude  $42^{\circ}2'30''$ . Rock descriptions and Rb-Sr age from Armstrong [1968] and Armstrong and Hills [1967], respectively.

*Sample 81 AZ OG-10 (10).* Monzogranite, Oracle granite, N Santa Catalina Mountains, Pinal County, Arizona, 0.5 miles east of Oracle turnoff on State Route 77. Sample mode: qtz = 40%, K spar = 30%, plag = 20%, biot = 10%, musc = 1%. U-Pb age from Shakel *et al.* [1977].

*Sample 80 AZ PUP-11 (11).* Granodiorite of Kitt Peak, Quinlan Mountains, Pima County, Arizona. 1 mile southwest of Kitt Peak on State Route 386. Longitude  $111^{\circ}36'25''$ , latitude  $31^{\circ}57'29''$ . Rock description from Haxel *et al.* [1980a]. U-Pb age from J. E. Wright (personal communication, 1981).

*Sample 82 AZ ST-4 (12).* Monzogranite, Harris Ranch pluton, Sierrita Mine, Pima County, Arizona. From 3950-foot bench, Sierrita pit. Sample powder provided by J. Kurtz. Sample has undergone potassic and propylitic alteration (J. Kurtz, personal communication, 1982). K-Ar age from Cooper [1973].

*Sample 81 AZ PR-363 (13).* Quartz syenite of Mount Devine, Ko Vaya plutonic complex, N Comobabi Mountains, Pima County, Arizona. Longitude  $111^{\circ}48'37''$ , latitude  $32^{\circ}7'29''$ . Rock description and modes from Haxel *et al.* [1978]. U-Pb age from J. E. Wright (personal communication, 1981).

*Sample 81 AZ LW-1 (14).* Quartz diorite, Leatherwood pluton, N Santa Catalina Mountains, Pima county, Arizona. 1 mile east of Mount Lemmon Ski Area on Mount Lemmon Highway. Rock description and Rb-Sr age from Keith *et al.* [1980].

*Sample 80 AZ PUP-9 (15).* Quartz diorite, Cimar Hills, Pima County, Arizona. Longitude  $112^{\circ}6'19''$ , latitude  $32^{\circ}26'50''$ . Rock description (unit Tkgd) and mode from Briskey *et al.* [1978]. U-Pb age from J. E. Wright (personal communication, 1981).

*Sample 81 AZ WG-1 (16).* Peraluminous granite, Wilderness stock, Santa Catalina Mountains, Pima County, Arizona, General Hitchcock picnic area, Mount Lemmon Highway. Rock description, mode, and Rb-Sr age from Keith *et al.* [1980].

*Samples 80 AZ PUP-32 and 81 AZ PUP-22 (17-18).* Garnet-two-mica-granite, granite of Presumido Peak, S Baboquivari Mountains, Pima County, Arizona. Sample 17; longitude 111°37'11", latitude 31°36'2". Sample 18; longitude 111°38'51", latitude 31°36'44". Average mode: qtz = 40-45%, K spar = 40-45%, plag = 15-20%, biot = 1%, musc = 1%, gar = trace. Rock description and age estimate from Haxel *et al.* [1982] and Wright and Haxel [1982].

*Sample 81 AZ PR-364 (19).* Garnet-muscovite granite, granite of Sierra Blanca, Pima County, Arizona. Longitude 112°14'23", latitude 32°11'50". Sample mode: qtz = 40%, K spar = 40%, plag = 10%, musc = 10%, gar = trace. No age determination; assumed to be same age as samples 17-18.

*Sample 81 AZ CG-1 (20).* Monzogranite, Catalina pluton, N Catalina Mountains, Pima County, Arizona. Sample from earth dam in Canada del Oro, 1 mile west of Rancheria Springs. Rock description, mode, and Rb-Sr age from Keith *et al.* [1980].

*Sample 81 CO TLGD-1 (28).* Granodiorite, Twin Lakes pluton, Sawatch Range, Lake County, Colorado. Roadcut on State Route 82, 1.5 miles west of Twin Lakes. Longitude 106°24'3", latitude 39°3'54". Sample mode: plag = 60%, qtz = 25%, K spar = 10%, hbl = 5%, biot = 1%. Age assumed to be early Tertiary.

*Sample 81 CO MGD-1 (29).* Monzogranite, Montezuma stock, Front Range, Summit County, Colorado. 1 mile east of State Route 6 on Montezuma Road. Longitude 105°55'10", latitude = 39°36'25". Sample mode: K spar = 40%, qtz = 30%, plag = 25%, biot = 5%. Rb-Sr age from Simmons and Hedge [1978].

*Sample A80-8 (33).* Monzogranite, Emerson Lake, San Bernardino County, California. Longitude 116°25'12", latitude 34°24'11". Sample A80-8 from Knauer [1983]. Rb-Sr age from G. L. Farmer (unpublished data, 1981)].

#### Mineralized Granites

*Sample 79 NV CUC-1 (4).* Granodiorite porphyry, Copper Canyon intrusion, Battle Mountain, Lander County, Nevada. Fresh drill core sample (hole DDH-994, 671.9 feet). Sample provided by T. G. Theodore. Rock descriptions and K-Ar from Theodore *et al.* [1973].

*Sample 79 NV BMMO-1 (5).* "Granite aplite," Buckingham Mo deposit, Battle Mountain, Lander County, Nevada. From Climax Molybdenum Company drill hole B-29, 618 feet. Sample provided by T. G. Theodore. K-Ar age from Theodore and McKee [1983].

*Sample 79 UT BM-5b (6).* Monzogranite porphyry, Bingham stock, Oquirrh Mountains, Salt Lake County, Utah. From Bingham pit bottom, spring 1979. Sample is potassically altered; contains minor MoS<sub>2</sub>. Rock description from Lanier *et al.* [1978]. K-Ar age from Warnaars *et al.* [1978].

*Sample 79 NV TPE-1 (7).* Monzogranite porphyry, Tripp pit, Ely mining district, White Pine County, Nevada. Sample shows potassic (K spar-biot) and phyllic alteration. Rock description from James [1976]. K-Ar age from McDowell and Kulp [1967].

*Sample 80 AZ MP-10 (8).* Monzogranite porphyry, Ithaca Peak stock, Mineral Park mine, Cerbat Mountains, Mohave County, Arizona. Sample MP-10 from Laine [1974]. Sample shows potassic and phyllic alteration. K-Ar age from Mauger and Damon [1965].

*Sample 81 AZ B-1 (9).* Monzogranite porphyry, Bagdad mine, Yavapai County, Arizona. Collected at pit bottom in

1981 by D. J. DePaolo. Sample potassically altered (K spar-biot-albite) with minor sericite. K-Ar age reported by Livingston [1973].

*Sample 80 AZ QDP-1 (21).* Monzogranite porphyry, San Manuel, Pinal County, Arizona. Sample potassically altered. K-Ar age reported by Livingston [1973].

*Sample 81 AZ PUP-62 (22).* Monzogranite, New Cornelia stock, Cardigan Peak, Little Ajo Mountains, Pima County, Arizona. Sampled at Cardigan Peak. Rock description and modes from Wadsworth [1968]. K-Ar age reported by Livingston [1973].

*Sample 81 AZ PR-350 (23).* Monzogranite porphyry, New Cornelia mine, Ajo, Pima County, Arizona. Sampled at pit bottom in 1981 by G. Haxel. Sample shows propylitic and phyllic alteration. Rock descriptions from Gilluly [1946]. K-Ar age reported by Livingston [1973].

*Sample 82 AZ 2B-2A (24).* Monzonite, Silver Bell Mountains, Pima County, Arizona. From south of El Tiro open pit. Sample powder provided by J. Kurtz. K-Ar ages summarized by Richard and Courtright [1966].

*Sample 82 AZ ST-2 (25).* "Ruby Star" monzogranite porphyry, Sierrita-Esperanza mine, Pima County, Arizona. From 3865-foot bench in Esperanza pit. Sample shows potassic, phyllic, and propylitic alteration. Sample powder provided by J. Kurtz. K-Ar ages summarized by West and Aiken [1982].

*Sample 81 AZ PR-328 (26).* Monzogranite, Lakeshore stock, Pinal County, Arizona. From just north of Lakeshore mine; collected by G. Haxel. Sample mode: qtz = 40%, K spar = 35%, plag = 25%, biot = 1%, gar = trace. K-Ar age from Huyck [1982].

*Sample 80 AZ M-10 (27).* Monzogranite porphyry, Morenci mine, Greenlee County, Arizona. Sample M-10 from Laine [1974]. Sample shows potassic and phyllic alteration. K-Ar age reported by Livingston [1973].

*Samples UGP-1, DG-1, and SG-1 (30-32).* Syenogranite to syenogranite porphyry, Henderson mine, Clear Creek County, Colorado. Samples are from Urad, Dailey, and Seriate stocks (Climax Molybdenum Company samples CX-122, 4820; H434, 1046; and H2480, 1040). Samples are generally fresh, but weak argillization and sericitization of feldspars and chloritization of biot is present. Typical rock modes given by White *et al.* [1981]. All stocks considered to be about 25 m.y. old [cf. Naeser *et al.*, 1973]. Samples provided by R. Carten (Climax Molybdenum Company).

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