Ages of Selected Intrusive Rocks and Associated Ore Deposits in the Colorado Mineral Belt

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By Charles G. Cunningham, Charles W. Naeser, Richard F. Marvin, Robert G. Luedke, and Alan R. Wallace

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Sixty-three fission-track and K-Ar age determinations help understand the temporal and spatial evolution of the Colorado Mineral Belt

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Ages of Selected Intrusive Rocks and Associated Ore Deposits in the Colorado Mineral Belt

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ABSTRACT

The relationships between igneous rocks and temporally and spatially related ore deposits have become better understood with improved geochemical and geochronologic technologies. Sixty-three age determinations, by fission-track and K-Ar techniques, are combined here with the results of recent geochemical, isotopic, geochronologic, and tectonic studies by many authors to better understand the processes that formed the intrusive rocks and related ore deposits that constitute the Colorado Mineral Belt (CMB). The results of this study have helped to (1) document the temporal and spatial evolution of magmatic activity along the CMB, (2) recognize multiple igneous and mineralization events at individual centers, and (3) understand the tectonic-magmatic processes that formed the igneous centers and mineral deposits. These age determinations show that some igneous centers, such as the Ute Mountains and some of the stocks in the northern Sawatch Range, are Laramide (Late Cretaceous and early Tertiary) and have no known associated mineral deposits. Some igneous centers and their associated mineral deposits, such as the La Plata Mountains and some stocks in the northeastern part of the CMB, are also Laramide. Other igneous centers contain Laramide rocks, but spatially associated mineral deposits are of middle Tertiary (Leadville) or late Tertiary (Rico) age and are clearly related to younger intrusions (generally rhyolites) at the center. Some middle Tertiary stocks dated as part of this study (Mount Sopris) have little, or no, associated mineral deposits, whereas others of similar age (Italian Mountain Intrusive Complex) have genetically related mineral deposits.

Other results of this study include (1) recognition of a major paleothermal anomaly "bull's-eye" near the silver-base metal deposits of Rico that helped lead to the discovery of a major molybdenum deposit, (2) documentation of the progression of igneous activity northeastward along the CMB at a rate of about 4 cm/yr, (3) documentation of the existence of a Laramide northwest-trending group of stocks that crosses the CMB, and (4) recognition of 45-Ma igneous activity at Jamestown, the northernmost igneous center in the CMB, that occurred during a generally quiescent period between the Laramide and middle Tertiary igneous activity.

INTRODUCTION

The Colorado Mineral Belt (CMB) is defined by a group of Late Cretaceous and early Tertiary (Laramide), middle Tertiary (approximately Eocene to middle Miocene), and late Tertiary intrusive centers and associated hydrothermal ore deposits that trends northeast across Colorado (fig. 1). The southwestern end is located in the Ute Mountains near the Four Corners area, and the northeastern end is located in the Front Range near Jamestown, about 50 km northwest of Denver. The belt contains most of the major mining districts in Colorado and has produced at least $4 billion in metals, principally molybdenum, gold, silver, copper, lead, and zinc.

Improved fission-track and K-Ar methods have better defined the chronology of CMB igneous and hydrothermal events. The ages reported here have economic as well as tectonic and petrogenetic significance. These data indicate that, in some areas, ages of intrusive and hydrothermal activity are different than previously assumed, thus changing genetic interpretations.

PRESENT STUDY

This report presents the results of 63 age determinations from intrusive rocks in and near the CMB. These determinations began in the 1970's as a part of a study to see if there was a pattern in the spatial distribution or chemical evolution of CMB rocks that might correlate with ore deposits in the belt. The data herein are a combination of information collected for this report as well as data that were previously released in U.S. Geological Survey publications (Cunningham and Naeser, 1975; Naeser and Cunningham, 1976; Cunningham and others, 1977).

Zircon fission-track (ZFT), apatite fission-track (AFT), sphene fission-track (SFT), and K-Ar dates were acquired from the same samples to the extent possible. Fission tracks

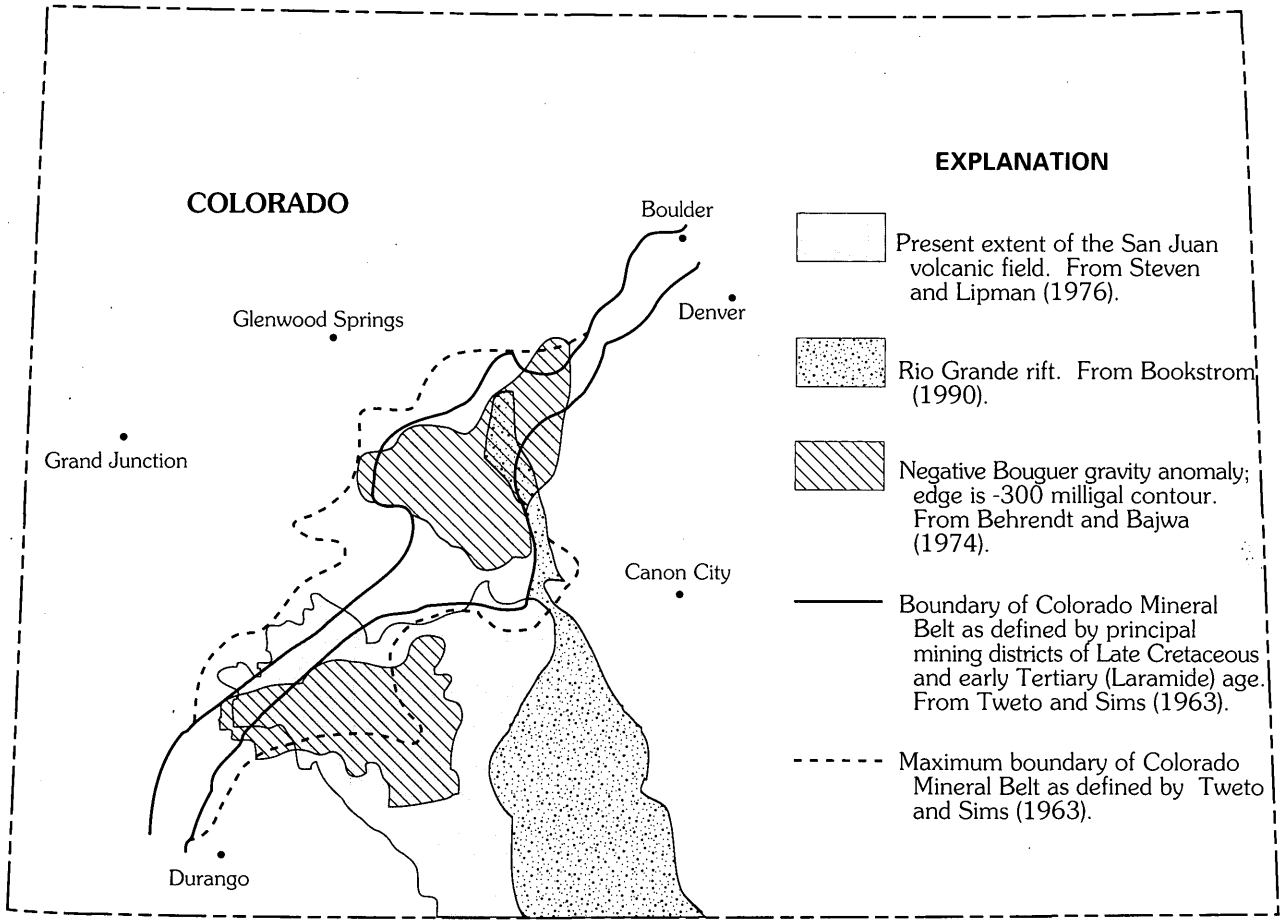


Figure 1. Index map of the Colorado Mineral Belt, showing its relationship to the San Juan volcanic field, Rio Grande rift, and −300 milligal Bouguer gravity anomaly. From Tweto and Sims (1963), Steven and Lipman (1976), Bookstrom (1990), and Behrendt and Bajwa (1974).

are stable over different temperature intervals for different minerals, and, by dating several different minerals from a rock, it is possible to obtain a better understanding of its thermal history. This is especially important for deciphering settings where multiple hydrothermal events have been superimposed upon older rocks. Older fission-track and K-Ar dates were recalculated by using current constants and statistical methods (Dalrymple, 1979; McGee and others, 1985). The data are presented in two tables. Table 1 gives fission-track and K-Ar analytical data for the samples, and table 2 gives sample locations and descriptions. Figures 2, 3, and 4 show the distribution of major Late Cretaceous and early Tertiary (Laramide), middle Tertiary, and late Tertiary intrusive rocks in Colorado and are keyed to the tables by geologic and geographic name and letter symbols.

This report coincides with the publication of a 1:1,000,000-scale map showing the distribution, composition, and age of early and middle Cenozoic volcanic centers in Colorado and Utah (Luedke, 1993). A corresponding map of late Tertiary centers has already been published (Luedke and Smith, 1978). This report complements the comprehensive compilation on Luedke's 1993 map by providing analytical data and further interpretation.

There are many compilations of age determinations for Colorado igneous rocks. Major compilations include Young (1972), Marvin and others (1974), Stein (1985), Mutschler and others (1987), Davis and Streufert (1990), Bookstrom (1990), and Wallace (in press). Luedke's 1993 map is the most recent and comprehensive of the entire CMB.

DATED IGNEOUS CENTERS AND ASSOCIATED MINERAL DEPOSITS

The intrusive rocks of the CMB and vicinity have a distribution pattern related to age of emplacement that provides insight into the evolution of structural settings and magmatic processes. Readers are referred to Tweto's (1979a) geologic map of Colorado and Luedke's (1993) map compilation of ages and compositions for the ensuing discussion. A time boundary between the Late Cretaceous and early Tertiary (Laramide) rocks and the middle Tertiary

Table 1. Fission-track and K-Ar analytical data.

[Numbers in parentheses are number of tracks counted. Values for constants used in calculating ages are as follows: $\lambda_F=7.03\times10^{-17}yr^{-1}$; $^{40}K\lambda_\epsilon=0.581\times10^{-10}yr^{-1}$; $\lambda_\beta=4.962\times10^{-10}yr^{-1}$; $^{40}K/K=1.167\times10^{-4}$. —, no data. Note: The fission-track ages were all determined prior to 1988. The recommendations of Hurford (1990) could not be followed because a zeta calibration was not in place when these ages were determined.]

Sample no.	Lab. no.	Mineral	[1]ρs	[2]ρi	[3]$\phi\times10^{15}$	U (ppm)	K_2O (wt. percent)	[4] $^{*40}Ar$ (10^{10}mol/g)	$^{*40}Ar$ (percent)	Age m.y.±2σ
Apex stock, map symbol A										
A-1	DF-1188	zircon	7.10 (1414)	7.20 (717)	1.05	220	—	—	—	61.7±6.3
A-1	DF-1189	apatite	0.428 (99)	0.700 (162)	1.96	11.4	—	—	—	71.3±18.0
A-2	DF-1190	zircon	8.00 (1926)	8.47 (1020)	1.04	260	—	—	—	58.5±5.2
A-2	DF-1191	apatite	0.285 (594)	0.498 (1037)	1.96	8.1	—	—	—	66.8±7.5
Chicago Basin stock, map symbol CB										
CB-1	DF-908	zircon	1.46 (494)	9.01 (1522)	1.07	270	—	—	—	10.4±1.2
CB-2	DF-907	zircon	1.87 (480)	13.30 (1688)	1.08	390	—	—	—	9.2±1.0
Eldora stock, map symbol E										
E-1	DF-934	zircon	7.49 (1560)	8.50 (885)	1.27	210	—	—	—	66.6±6.4
E-1	DF-1000	zircon	9.31 (1293)	10.67 (741)	1.19	290	—	—	—	61.8±6.3
E-1	DF-942	apatite	0.168 (311)	0.200 (370)	1.17	5.5	—	—	—	58.6±9.4
East Lake Creek stock, map symbol EL										
EL-1	DF-848	sphene	10.30 (2564)	5.50 (687)	0.587	300	—	—	—	65.2±6.3
EL-1	DF-849	zircon	9.87 (777)	8.77 (345)	0.887	320	—	—	—	59.5±8.1
Empire stock, map symbol EM										
EM-1	DF-932	sphene	11.2 (1872)	11.4 (950)	1.16	315	—	—	—	68.0±6.2
EM-1	DF-941	apatite	0.847 (1765)	1.568 (3266)	1.16	43	—	—	—	37.4±2.8
Fulford stock, map symbol F										
F-1	DF-1161	zircon	6.21 (1379)	6.08 (675)	1.07	180	—	—	—	65.1±6.8
F-2	D2498B	biotite	—	—	—	—	8.39 8.38	7.635	94	62.2±1.5
Italian Mountain Intrusive Complex, map symbol I										
I-1	DF-655	zircon	4.31 (694)	8.72 (702)	1.15	240	—	—	—	33.9±3.9

Table 1. Fission-track and K-Ar analytical data—Continued.

Sample no.	Lab. no.	Mineral	[1]ρs	[2]ρi	[3]$\phi \times 10^{15}$	U (ppm)	K_2O (wt. percent)	[4] $^{*40}Ar$ (10^{10}mol/g)	$^{*40}Ar$ (percent)	Age m.y.±2σ
Jamestown stocks, map symbol JS										
JS-1	D2419B	biotite	—	—	—	—	8.55 8.64	7.390	88	58.8±2.0
JS-2A	41FT.	zircon	8.92 (661)	13.06 (484)	1.10	750	—	—	—	44.8±5.7
JS-2B	3361FT.	zircon	7.32 (351)	10.56 (253)	1.09	400	—	—	—	45.1±7.7
JS-3	DF-3177	zircon	4.2 (462)	5.4 (299)	1.05	148	—	—	—	48.4±7.5
JS-3	DF-3178	apatite	0.377 (785)	0.477 (993)	1.00	15	—	—	—	47.1±5.8
Leadville, map symbol L										
L-1	D2642S	sanidine	—	—	—	—	11.34	6.360	91	38.5±0.6
L-2	DF-1445	zircon	13.8 (1343)	20.2 (984)	1.15	510	—	—	—	46.8±4.4
L-3	DF-4151	zircon	4.82 (491)	8.21 (418)	0.993	260	—	—	—	34.8±4.9
La Plata Mountains, map symbol LP										
LP-2	DF-993	zircon	12.90 (2508)	12.2 (1188)	1.09	360	—	—	—	68.5±5.7
LP-3	DF-994	zircon	8.81 (1916)	8.57 (932)	1.09	250	—	—	—	66.7±6.1
LP-3	DF-995	apatite	1.58 (1466)	1.36 (1240)	1.05	41	—	—	—	73.9±6.6
LP-3	D2541B	biotite	—	—	—	—	8.94 8.98	8.915	92	67.8±1.6
LP-4	DF-996	zircon	6.52 (1238)	7.08 (672)	1.09	210	—	—	—	59.8±6.3
LP-4	DF-997	apatite	0.139 (129)	0.110 (102)	1.05	3.3	—	—	—	79.0±21.0
LP-5	DF-998	zircon	18.70 (1040)	17.50 (487)	1.09	510	—	—	—	69.3±8.2
LP-5	DF-999	apatite	1.06 (978)	1.31 (1217)	1.05	40	—	—	—	50.3±4.9
LP-5	D2542B	biotite	—	—	—	—	8.79 8.76	8.682	94	67.5±1.6
Montezuma stock, map symbol M										
M-1	DF-674	zircon	7.85 (1235)	16.76 (1319)	1.25	430	—	—	—	35.0±3.2
Mount Sopris stock, map symbol MS										
MS-1	DF-1104	zircon	3.34 (664)	6.50 (647)	1.12	190	—	—	—	34.3±4.1
MS-1	D2552B	biotite	—	—	—	—	8.30 8.25	4.108	87	34.2±0.8

Table 1. Fission-track and K-Ar analytical data—Continued.

Sample no.	Lab. no.	Mineral	[1]ρs	[2]ρi	[3]$\phi \times 10^{15}$	U (ppm)	K_2O (wt. percent)	[4] $^{*40}Ar$ (10^{10}mol/g)	$^{*40}Ar$ (percent)	Age m.y.±2σ
Ouray, map symbol O										
O-1	DF-1149	zircon	3.25 (346)	5.05 (269)	1.06	150	—	—	—	40.7±6.9
O-1	DF-1148	apatite	0.011 (22)	0.093 (193)	1.14	2.6	—	—	—	7.8±3.5
O-2	DF-1116	zircon	8.06 (1865)	9.81 (1135)	1.10	280	—	—	—	54.1±4.0
O-2	DF-1117	apatite	0.017 (35)	0.060 (125)	0.89	2.1	—	—	—	14.9±5.7
Porphyry Creek stock, map symbol PC										
PC-1	DF-1152	zircon	4.19 (911)	7.45 (810)	1.05	230	—	—	—	35.3±3.3
PC-1	D2569B	biotite	—	—	—	—	8.92 8.86	4.961	84	38.4±0.9
Rico, map symbol R										
R-1	DF-1166	zircon	4.78 (1174)	4.86 (596)	1.04	150	—	—	—	61.0±6.7
R-1	DF-1168	apatite	0.016 (34)	0.169 (353)	1.14	4.8	—	—	—	6.6±2.4
R-1	DF-1167	sphene	8.46 (1645)	12.15 (1181)	1.89	210	—	—	—	78.3±6.9
R-1	D2573PY	pyroxene	—	—	—	—	0.118 0.116	0.1917	68	[5]110±2
R-2	DF-1146	zircon	9.89 (2151)	9.72 (1058)	1.07	290	—	—	—	64.8±5.6
R-2	DF-1145	apatite	0.017 (36)	0.038 (121)	1.14	1.6	—	—	—	20.3±7.4
Round Mountain stock, map symbol RM										
RM-1	DF-1160	zircon	2.16 (489)	11.74 (1332)	1.05	360	—	—	—	11.5±1.3
RM-1	DF-1147	apatite	0.025 (52)	0.173 (361)	1.14	4.9	—	—	—	9.8±2.9
RM-1	D2567B	biotite	—	—	—	—	8.66 8.62	1.736	62	13.9±0.3
Tincup stock, map symbol T										
T-1	DF-1150	zircon	5.67 (1208)	10.44 (1112)	1.06	310	—	—	—	34.4±3.2
T-1	DF-1151	epidote	0.708 (177)	3.91 (489)	3.46	36	—	—	—	37.4±6.8
Tomichi Creek stock, map symbol TC										
TC-1	DF-1159	zircon	4.85 (1213)	10.36 (1295)	1.06	310	—	—	—	29.6±2.7

Table 1. Fission-track and K-Ar analytical data—Continued.

Sample no.	Lab. no.	Mineral	1ρs	2ρi	3$\phi \times 10^{15}$	U (ppm)	K_2O (wt. percent)	4 *40Ar (10^{10}mol/g)	*40Ar (percent)	Age m.y.±2σ
Ute Mountains, map symbol U										
U-1	DF-1073	zircon	10.3 (2377)	8.26 (956)	0.867	300	—	—	—	64.2±5.7
U-2	DF-1076	zircon	6.18 (1258)	4.49 (456)	0.862	170	—	—	—	70.7±8.3
U-2	DF-1075	apatite	1.96 (490)	7.19 (899)	4.12	50	—	—	—	66.8±8.1
U-3	DF-1077	zircon	7.60 (1232)	5.34 (433)	0.852	200	—	—	—	72.1±8.6
U-3	D2548B	biotite	—	—	—	—	8.41 8.41	8.898	76	72.0±1.7
West Cross Creek stock, map symbol WC										
WC-1	DF-850	zircon	4.36 (1130)	3.89 (504)	0.887	140	—	—	—	59.2±6.9
WC-1	D2499B	biotite	—	—	—	—	8.45 8.51	7.668	95	61.8±1.4
West Tennessee Creek stock, map symbol WT										
WT-1	DF-1164	apatite	0.06 (143)	0.100 (209)	1.14	2.8	—	—	—	46.5±10.3
WT-1	D2568B	biotite	—	—	—	—	8.55 8.54	8.319	87	66.4±2.2

1ρs = tracks/cm^2 fossil, ×10^6.
2ρi = tracks/cm^2 induced, ×10^6.
3 ϕ = neutrons/cm^2.
4 *40Ar= radiogenic argon.
5 K-Ar age is too old.

rocks is placed at 40 Ma by Tweto and 58 Ma by Luedke; the latter, being the Paleocene-Eocene boundary, was selected for the boundary between intrusions shown on figures 2 and 3, and 16 Ma was selected for the corresponding boundary between figures 3 and 4.

The general northeast trend of igneous rocks and associated ore deposits of the CMB has been described by many, especially Burbank and Lovering (1933), Lovering and Goddard (1938, 1950), Tweto and Sims (1963), and Tweto (1968). The Precambrian ancestry of the belt was documented by Tweto and Sims (1963), and Warner (1978) showed that the belt was part of a larger northeast-trending Precambrian wrench fault system he called the Colorado lineament. In the central part of the State, a northwest-trending group of Laramide stocks crosses the CMB. This group extends for a distance of about 30 km from the West Tennessee Creek stock, 15 km northwest of Leadville, across the northern end of the Sawatch Range, and ends at the Fulford stock. Wallace and Naeser (1986) noted that part of this trend may be related to Laramide uplift.

Some of the igneous centers in the CMB have only one age of igneous and hydrothermal activity. Other centers, however, have superimposed igneous and hydrothermal events as recorded by partly reset ages. In this report, the centers are discussed geographically to emphasize the effect and importance of the overprinting of younger Tertiary events on igneous centers that were previously considered to be older, mainly Laramide. We will sequentially describe the CMB from the southwest to the northeast, including the northwest-trending group of stocks at the point it crosses the main trend. Figures 2, 3, and 4 present the data in geochronological sequence.

UTE MOUNTAINS

The Ute Mountains (fig. 2) are underlain by stocks, laccoliths, and sills emplaced mostly into the Upper Cretaceous Mancos Shale. They range in composition and texture from microgabbro to quartz monzonite porphyry and have recently been mapped by Condon (1991). All major igneous rock units, dated for this study, range from 72.1±8.6 Ma to 64.2±5.7 Ma; the geologically reasonable ages, based on field relationships and annealing characteristics of the

Table 2. Sample locations and descriptions.

Map symbol		
A	*Apex stock*	
	A-1:	39°52'03"N., 105°33'18"W.; collected by Robert Barker (sample no. R-138) from trench that cuts the Indianapolis quartz-Mo vein, Central City quadrangle, Gilpin County, Colo. Fine-grained hornblende-biotite quartz monzonite that crops out over a wide area.
	A-2:	39°52'03"N., 105°33'18"W.; same location as A-1. Collected by Robert Barker (sample no. R-139). Medium-grained hornblende-biotite quartz monzonite present as dikes that intrude A-1 in the vicinity of the Nye Metals adit.
CB	*Chicago Basin stock*	
	CB-1:	37°36'13"N., 107°36'43"W.; collected by Peter Holland (sample no. 217) south of Needle Creek, La Plata County, Colo. Quartz-sanidine granite porphyry that forms a composite stock that is spatially related to base- and precious-metal bearing veins.
	CB-2:	37°36'09"N., 107°36'30"W; collected by Peter Holland (sample no. 137). Sanidine-plagioclase-biotite quartz rhyolite porphyry that intrudes center of stock CB-1.
E	*Eldora stock*	
	E-1:	39°57'06"N., 105°35'16"W.; roadcut 0.5 km west of the town of Eldora, Boulder County, Colo. Also called the Bryan Mountain stock. Biotite-hornblende-pyroxene quartz monzonite.
EL	*East Lake Creek stock*	
	EL-1:	39°28'36"N., 106°33'20"W.; collected by Ogden Tweto, 2.8 km east of Gold Dust Peak, Eagle County, Colo. Plagioclase-hornblende granodiorite.
EM	*Empire stock*	
	EM-1:	39°45'48"N., 105°43'20"W.; roadcut along U.S. 40, 3.4 km west of Empire, Clear Creek County, Colo. Hornblende-pyroxene monzonite.
F	*Fulford stock*	
	F-1:	39°31'36"N., 106°39'24"W.; sec. 14, T. 6 N., R. 83 W.; Roadcut 0.8 km east of Triangle Reservoir in southeast part of stock. Eagle County, Colo. Medium-grained, equigranular, quartz monzonite.
	F-2:	39°31'40"N., 106°39'28"W.; Collected by Odgen Tweto, 0.1 km northwest of F-1. Eagle County, Colo. Medium-grained, equigranular quartz monzonite.
I	*Italian Mountain Intrusive Complex*	
	I-1:	38°56'52"N., 106°45'11"W.; 0.4 km north of Italian Mountain near the base of the cirque, Gunnison County, Colo. Same as sample I-368 (Cunningham, 1976). Biotite-sanidine-quartz monzonite that is the youngest intrusion.
JS	*Jamestown stocks*	
	JS-1:	40°07'N., 105°24'W.; sec. 25, T. 2 N., R. 72 W., Boulder County, Colo. Biotite-fluorite vein cutting granodiorite stock.
	JS-2A:	40°07'12"N., 105°23'15"W.; sec. 19, T. 2 N., R. 71 W., Boulder County, Colo. Drill core from vertical hole in sodic granite Porphyry Mountain stock. Sampled 12.5 m below ground surface.
	JS-2B:	40°07'12"N., 105°23'15"W.; same location and drill core as JS-2A. Sampled 1,024 m below ground surface.
	JS-3:	40°06'40"N., 105°23'30"W.; collected by William Lynch. Jamestown granodiorite stock.
L	*Leadville*	
	L-1:	39°15'03"N., 106°14'45"W.; collected by Ogden Tweto from dump of the Big Six mine, Eureka pipe, Lake County, Colo. Rhyolite porphyry intrusion that cuts the ore.
	L-2:	39°15'18"N., 106°14'28"W.; collected by Ogden Tweto from White Cloud mine. Quartz monzonite considered to be Evans Gulch Porphyry by Thompson and Arehart (1990).
	L-3:	39°15'00"N., 106°14'28"W.; collected by Ogden Tweto (sample no. 90T53) from dump of prospect shaft on low spur between Johnson Gulch and Evans Gulch. Johnson Gulch Porphyry. Samples L-1, L-2, and L-3 are all located about 4 km east of the town of Leadville, Colo.
LP	*La Plata Mountains*	
	LP-2:	37°24'15"N., 108°05'26"W.; 0.3 km southwest of the Allard mine, Montezuma County, Colo. Slightly altered syenite of the Allard stock.
	LP-3:	37°23'45"N., 108°04'32"W.; first switchback on road up Bedrock Creek on west side of the La Plata River, La Plata County, Colo. Fresh biotite-syenite of the Allard stock.
	LP-4:	37°26'13"N., 108°00'55"W.; 0.4 km southwest of Snowstorm Peak, Montezuma County, Colo. Monzonite sill.
	LP-5:	37°25'28"N., 108°02'38"W.; roadcut at road fork between Darby Creek and Basin Creek on west side of La Plata River, La Plata County, Colo. Fine-grained biotite-granodiorite.
M	*Montezuma stock*	
	M-1:	39°32'02"N., 105°49'33"W.; collected by George Neuerburg (sample no. H1200) 0.6 km northeast of Webster Pass, Summit County, Colo. Porphyritic quartz monzonite from small stock about 5 km south of the main body of the Montezuma stock.
MS	*Mount Sopris stock*	
	MS-1:	39°16'13"N., 107°08'43"W.; sec. 18, T. 9 S., R. 87 W., 0.3 km southwest of the northernmost Thomas Lakes, Pitkin County, Colo. Medium-grained biotite quartz monzonite.
O	*Ouray*	
	O-1:	37°59'05"N., 107°42'38"W.; roadcut in switchback toward the south on the road to the Camp Bird mine from Ouray, near Senator Gulch, Ouray County, Colo. Slightly propylitically altered porphyritic granodiorite sill.

Table 2. Sample locations and descriptions—Continued.

Map symbol		
	O-2:	37°59'40"N., 107°42'14"W.; west side of the canyon wall at elevation 2,840 m on the Weehawken pack trail, 0.4 km west of Thistledown, Ouray County, Colo. Slightly propylitically altered porphyritic granodiorite sill.
PC	*Porphyry Creek stock*	
	PC-1:	38°28'22"N., 106°24'14"W.; sec. 27, T. 49 N., R. 5 E., 0.2 km east of where Porphyry Creek passes under the highway to Whitepine, Gunnison County, Colo. Biotite rhyolite porphyry with beta-morphology quartz phenocrysts.
R	*Rico*	
	R-1:	37°41'40"N., 108°03'37"W.; 0.4 km northwest of Expectation mine, on Expectation Mountain, Dolores County, Colo. Medium-grained augite monzonite stock.
	R-2:	37°38'23"N., 108°03'22"W.; roadcut 0.4 km east-northeast of Montelores Bridge, along the east side of the road, Rico, Dolores County, Colo. Hornblende latite porphyry sill.
RM	*Round Mountain stock*	
	RM-1:	38°46'26"N., 106°51'32"W.; about halfway up Round Mountain, 0.8 km southwest of the summit, Gunnison County, Colo. Biotite rhyolite.
T	*Tincup stock*	
	T-1:	38°40'39"N., 106°30'34"W.; sec. 15, T. 51 N., R. 4 E., 0.2 km west of the summit of Green Mountain, Gunnison County, Colo. Epidote-bearing quartz monzonite porphyry with partly resorbed beta-morphology quartz phenocrysts.
TC	*Tomichi Creek stock*	
	TC-1:	38°27'14"N., 106°24'22"W.; sec. 4, T. 48 N., R. 5 E.; roadcut on road to Whitepine, opposite Cow Creek, Gunnison County, Colo. Medium-grained biotite-augite rhyodacite.
U	*Ute Mountains*	
	U-1:	37°14'25"N., 108°46'35"W.; sec. 36, T. 35 N., R. 18 W.; roadcut alongside Cottonwood Creek, at the east end of the Sun Dance Ground, Montezuma County, Colo. Hornblende diorite porphyry containing amphibolite fragments.
	U-2:	37°16'47"N., 108°46'51"W.; sec. 24, T. 35 N., R. 18 W.; southwest side of Ute Peak, Montezuma County, Colo. Hornblende granodiorite porphyry,
	U-3:	37°15'52"N., 108°48'41"W.; sec. 27, T. 35 N., R. 18 W.; small roadcut at the southwest edge of Ute Peak, Montezuma County, Colo. Biotite quartz monzonite porphyry.
WC	*West Cross Creek stock*	
	WC-1:	39°25'40"N., 106°32'15"W.; collected by Ogden Tweto in unsurveyed sec. 21, T. 75 N., R. 82 W., from the ridge between West Cross Creek and Cross Creek, Eagle County, Colo. Biotite monzogranite.
WT	*West Tennessee Creek stock*	
	WT-1:	39°20'48"N., 106°25'05"W.; 0.5 km southeast of the Homestake mine, near the south end of the stock, Pitkin County, Colo. Fine-grained biotite quartz monzogranite.

various minerals dated, are about 72 Ma (tables 1 and 2). The diorite porphyry (sample U-1) is the most abundant igneous rock and contains prominent xenoliths of amphibolite, which led to previous, apparently spurious, older dates by K-Ar methods (for example, Armstrong, 1969). An Oligocene group of small, minette stocks and dikes is exposed about 30 km southeast of the Ute Mountains (Condon, 1991). No mineral deposits are known to be associated with igneous rocks in the Ute Mountains.

LA PLATA MOUNTAINS

The La Plata Mountains (fig. 2) contain a wide variety of intrusive rocks, of approximately the same age, that form stocks, sills, and dikes. The most abundant rocks form porphyritic monzonitic sills represented by sample LP-4 (79.0±21.0 Ma, AFT; 59.8±6.3 Ma, ZFT). Nonporphyritic intrusions range in composition from syenite to diorite. Samples LP-2 (68.5±5.7 Ma, ZFT) and LP-3 (73.9±6.6 Ma, AFT; 67.8±1.6 Ma, biotite K-Ar; 66.7±6.1 Ma, ZFT) are from the Allard syenite stock, and LP-5 (69.3±8.2 Ma, ZFT); 67.5±1.6 Ma, biotite K-Ar; 50.3±4.9 Ma, AFT) is from one of the two granodiorite stocks. Detailed reports on the area include Eckel (1949) and Werle and others (1984).

The relatively close agreement of all but one of the dates (table 1) indicates Laramide intrusion of igneous rocks at about 67 Ma. Much of the associated mineralization also appears to have taken place in the Laramide. Sample LP-3 is from a syenite stock that has a chalcopyrite-bearing crackle breccia exposed in Bedrock Creek (Eckel, 1949), which has been extensively explored by the mining industry, and less than 1 km north of this sample location is the Copper Hill glory hole. The nonporphyritic syenites and diorites crosscut the porphyritic sills (Eckel, 1949). The youngest date we obtained (sample LP-5) was from apatite in a diorite stock that yields Laramide ages on zircon and biotite. This reset apatite date may indicate the local presence of younger magmatic and hydrothermal activity rather than regional resetting because apatites in other nearby rocks yield Laramide dates.

About $6 million worth of metals was produced from mines in this area prior to 1937; gold, the most important commodity, was produced from gold- and silver-bearing telluride veins and replacement deposits, but significant quantities of silver, lead, and copper also were recovered. Mines of the La Plata Mountains have produced some unusual ores. In addition to telluride ores, Eckel (1949) reported disseminated platinum-bearing chalcopyrite, gold-bearing contact ore, veins of base-metal sulfides containing silver or native gold, chalcocite veins, and veins of ruby silver. Neubert and others (1991) reported that at least 200 million tons of 0.4-percent copper, plus minor quantities of gold and platinum, are known in deposits at the Allard stock. Additional reserves are known at depth. Recent (1994) mining has been limited to small-scale production along gold-telluride veins in the Bessie G mine.

RICO

The Rico area (fig. 2) contains three principal igneous rock types; two are Laramide, and the third is Pliocene. An augite monzonite stock (sample R-1; 78.3±6.9 Ma, SFT; 61.0±6.7 Ma, ZFT; 6.6±2.4 Ma, AFT) was intruded during the Laramide along the axis of the west-trending Rico structural dome. At about the same time, many subhorizontal hornblende latite sills (sample R-2; 64.8±5.6 Ma, ZFT; 20.3±7.4 Ma, AFT) were intruded throughout the area. The hornblende latite sills principally intrude Lower Permian Cutler Formation and are generally located in the vicinity of the Rico structural dome. These mapped relations are shown in Pratt and others (1969). A third principal igneous rock type in the area is rhyolite, which is present as small dikes and as a small stock at Calico Peak.

The data in table 1 show that age determinations on different minerals from the same sample of Laramide rocks give discordant results. The rocks that were intruded during the Laramide give Laramide dates on sphene and zircon but younger dates on apatite. This difference is due to reheating of the Laramide rocks by a major Pliocene thermal event that caused partial annealing of fission tracks in the apatite (Naeser, 1979; Naeser and others, 1980).

Additional dating of igneous rocks near Rico (Naeser and others, 1980) shows that a major Pliocene paleothermal anomaly, greater than 11 km diameter, is present. Samples collected from Laramide hornblende latite sills give partially reset apatite and zircon dates. When contoured, these data form a concentric, younging inward "bull's-eye" of apparent ages centered on a paleothermal anomaly, east of the town of Rico, that formed at 4 Ma. Naeser and others (1980) also obtained 4-Ma dates on mineralized rhyolites and predicted the presence and location of a young, unexposed stock having the potential for porphyry-related mineral deposits. Subsequent drilling at the site by Anaconda Minerals Company, resulted in discovery of the Silver Creek molybdenum deposit 1,200 m below the surface (Barrett and others, 1985).

Rico was a major silver and base-metal mining camp around the turn of the century; classic reports of the geology and ore deposits include Cross and Spencer (1900), Ransome (1901), Cross and Ransome (1905), and McKnight (1974). The silver- and base-metal vein and replacement deposits form a partial halo surrounding and capping the Silver Creek molybdenum deposit and are genetically related to it. Sericite, associated with a silver-base metal vein along the Blackhawk fault, also gives a K-Ar Pliocene age (Naeser and others, 1980).

The Silver Creek molybdenum deposit is large and high grade. Approximately 44 million tons of 0.31-percent Mo have been indicated by drilling (using a 0.2-percent cutoff), and the deposit has not been totally delineated (Barrett and others, 1985). Detailed studies have focused on the porphyry-molybdenum deposit and the changes in the chemistry, fission tracks, isotopes, and mineralogy of the hornblende latite sills as a result of the mineralizing event (Cunningham and others, 1987; Larson, 1987; Wareham, 1991; Larson and others, 1994a, 1994b).

CHICAGO BASIN STOCK

The Chicago Basin stock (fig. 4) is a composite rhyolite porphyry stock that intruded Precambrian rocks. It is in the center of the Needle Mountains near the southwestern edge of the San Juan volcanic field, approximately 40 km east of Rico. It was investigated by the U.S. Geological Survey as part of the studies of the San Juan Primitive Area (Steven and others, 1969), and studies of the geology and ore deposits were reported in Schmitt and Raymond (1977). Samples of the older, outer stock (sample CB-1; 10.4±1.2 Ma, ZFT) and younger, inner stock (CB-2; 9.2±1.0 Ma, ZFT) give concordant dates of about 10 Ma.

The Chicago Basin stock is near the center of a radial assemblage of veins and a zoned pattern of altered rocks. The veins were mined for base and precious metals and contain molybdenite in thin quartz veinlets. The stock was drilled by Climax Molybdenum Company in the 1970's. If a paleothermal anomaly exists, it may have a well-defined expression in the surrounding Precambrian rocks that could be deciphered by various means (see Cunningham and Barton, 1984).

OURAY

Several groups of igneous rocks are exposed in the vicinity of Ouray (fig. 2), the most prominent and important of which are granodiorite sills, dikes, and laccoliths. Younger volcaniclastic breccias and tuffs and a few dikes are related to the Oligocene San Juan volcanic field (Lipman and others, 1973). The granodiorite sills are generally concordant and intruded Devonian to Cretaceous sedimentary rocks. The laccoliths were intruded primarily at or near

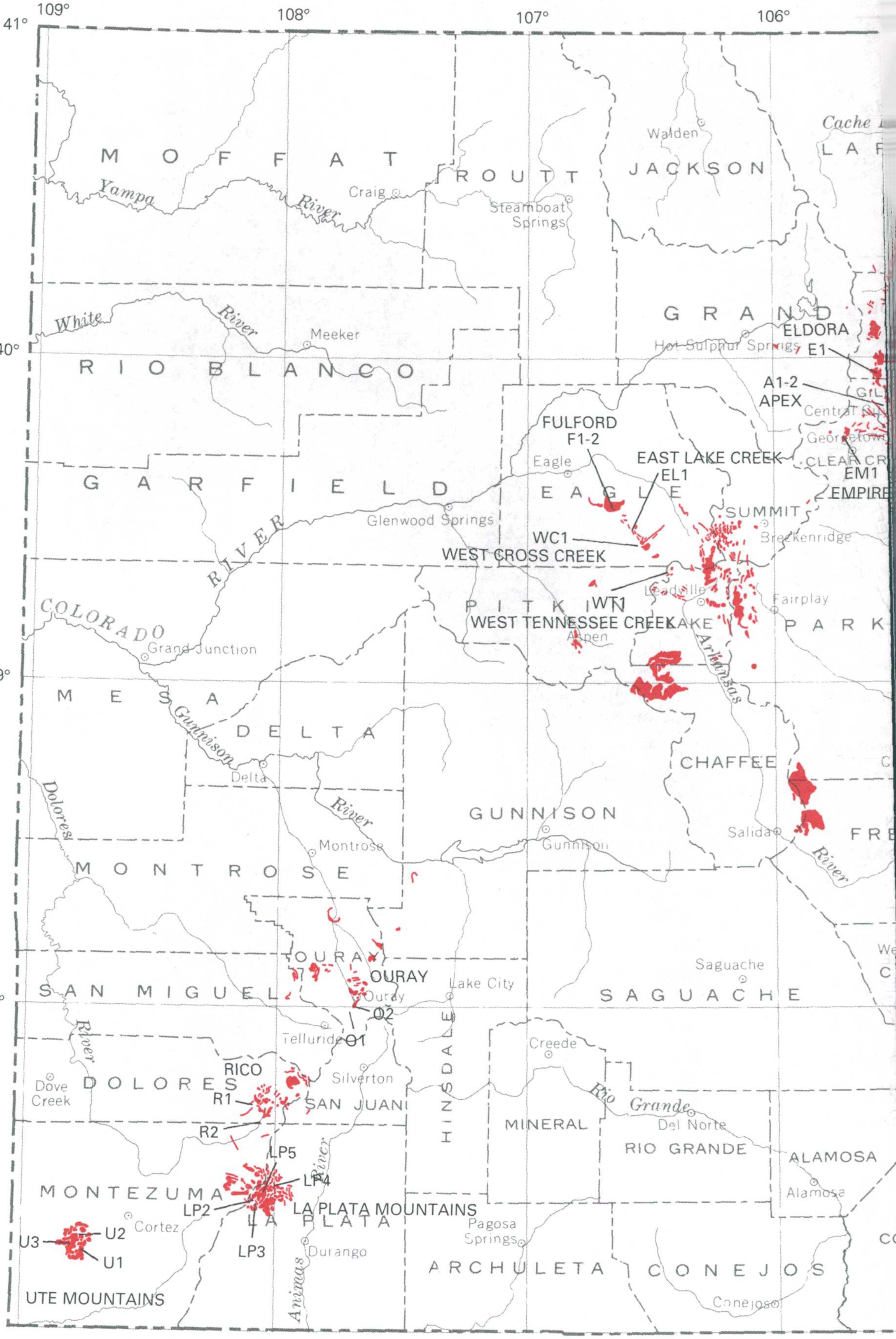
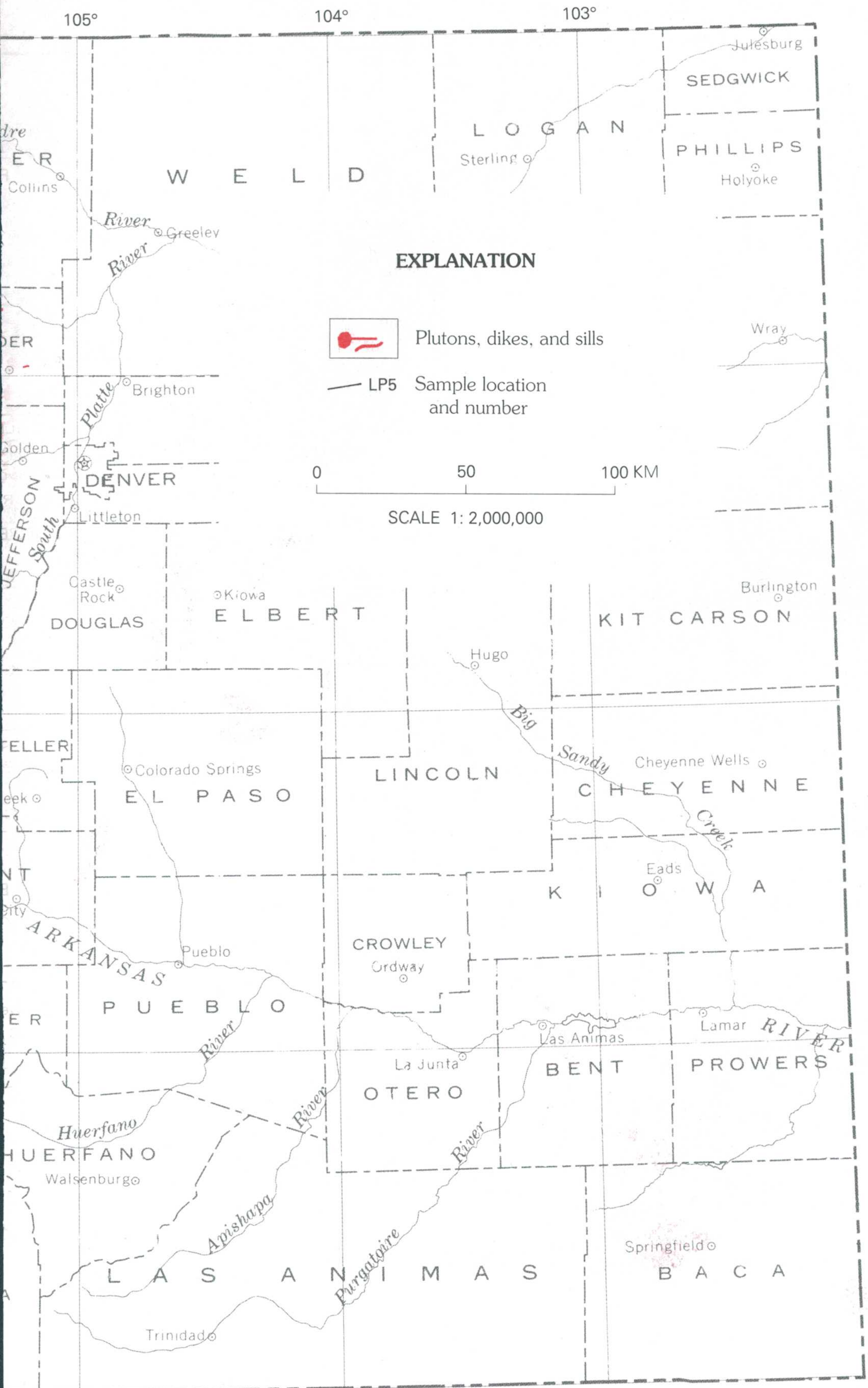


Figure 2. Late Cretaceous and early Tertiary (Laramide) intrusions, Colorado.


105°
104°
103°
EXPLANATION
Plutons, dikes, and sills
LP5 Sample location and number
0
50
100 KM
SCALE 1: 2,000,000
Julesburg
SEDGWICK
LOGAN
Sterling
PHILLIPS
Holyoke
WELD
Collins
River
Greeley
River
Wray
Brighton
Platte
Golden
DENVER
Littleton
JEFFERSON
South
Castle Rock
DOUGLAS
Kiowa
ELBERT
Burlington
KIT CARSON
Hugo
Big
Sandy
Cheyenne Wells
CHEYENNE
Creek
ELLER
Colorado Springs
EL PASO
LINCOLN
Eads
KIOWA
ARKANSAS
Pueblo
CROWLEY
Ordway
PUEBLO
River
Las Animas
Lamar
RIVER
La Junta
OTERO
BENT
PROWERS
Huerfano
River
HUERFANO
Walsenburg
River
Apishapa
Purgatoire
LAS ANIMAS
Springfield
BACA
Trinidad

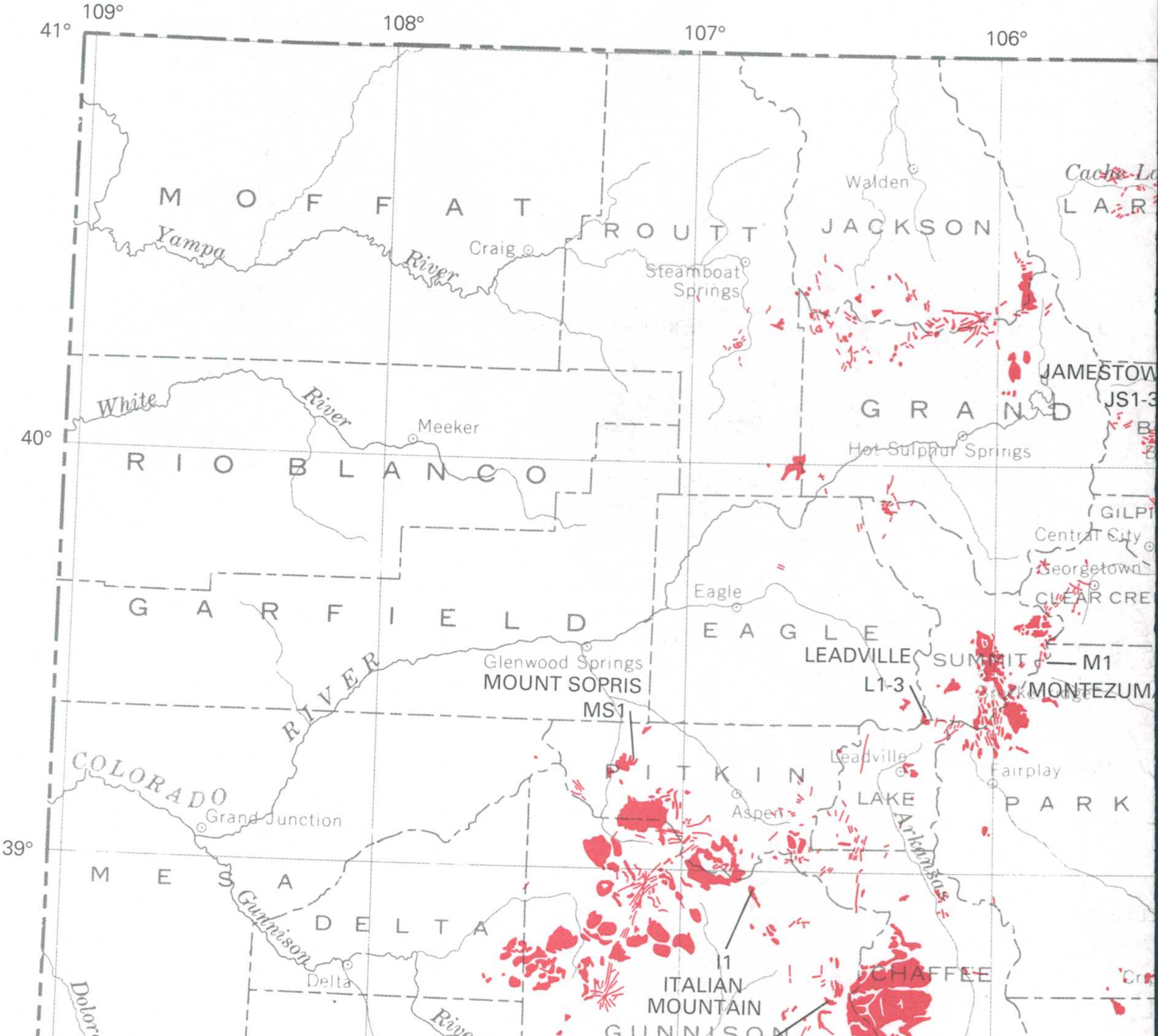
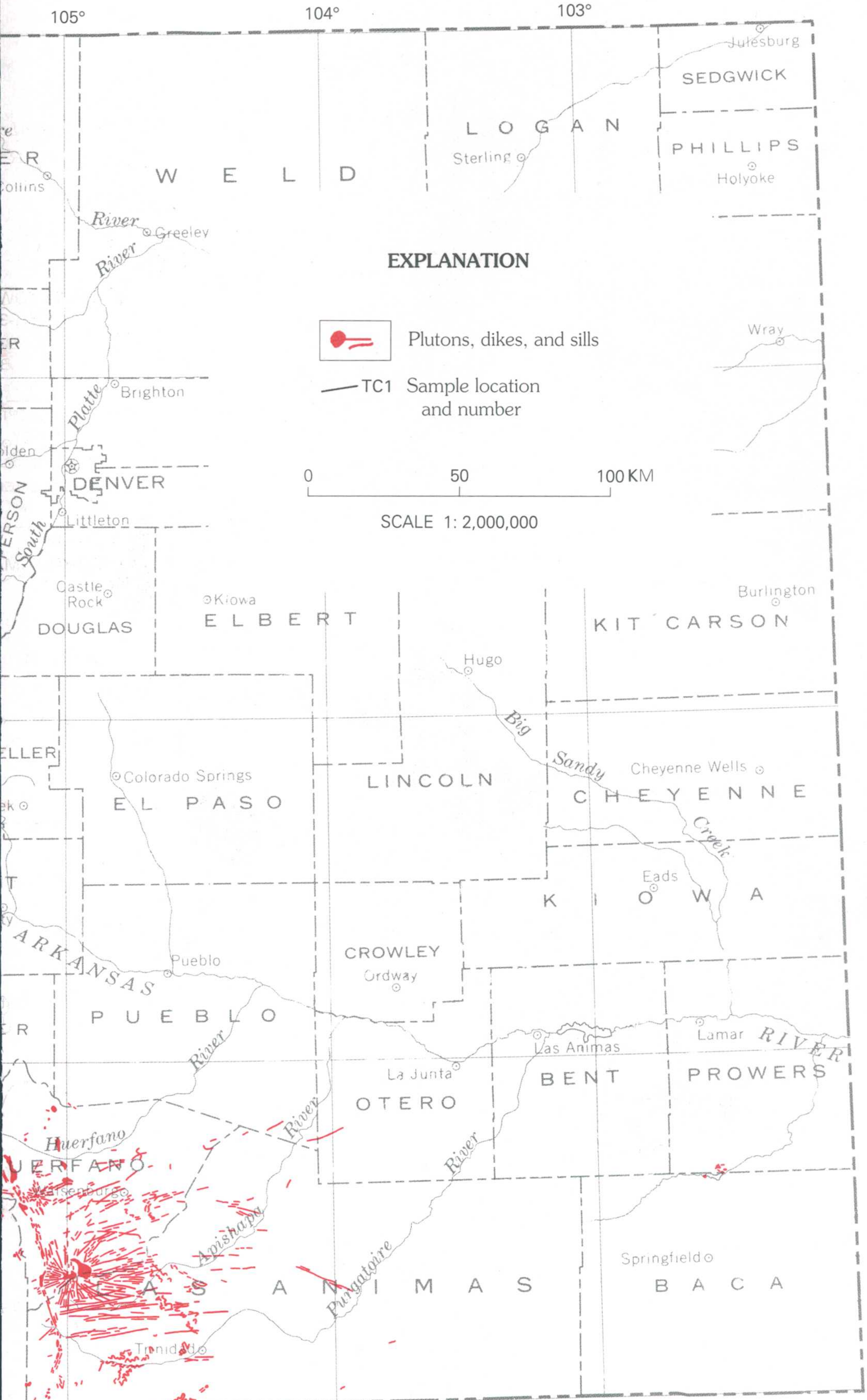


Figure 3. Middle Tertiary intrusions, Colorado.



105°
104°
103°
EXPLANATION
Plutons, dikes, and sills
TC1 Sample location and number
0
50
100 KM
SCALE 1: 2,000,000
W E L D
L O G A N
SEDGWICK
PHILLIPS
Julesburg
Sterling
Holyoke
Greeley
River
River
Wray
Brighton
Platte
DENVER
Littleton
South
Castle Rock
DOUGLAS
Kiowa
E L B E R T
Burlington
KIT CARSON
Hugo
Big
Sandy
Creek
Cheyenne Wells
C H E Y E N N E
LINCOLN
Colorado Springs
E L P A S O
Eads
K I O W A
CROWLEY
Ordway
Pueblo
ARKANSAS
P U E B L O
River
Las Animas
Lamar
RIVER
La Junta
O T E R O
B E N T
PROWERS
River
Huerfano
HUERFANO
Walsenburg
River
Apishapa
Purgatoire
L A S A N I M A S
Trinidad
Springfield
B A C A

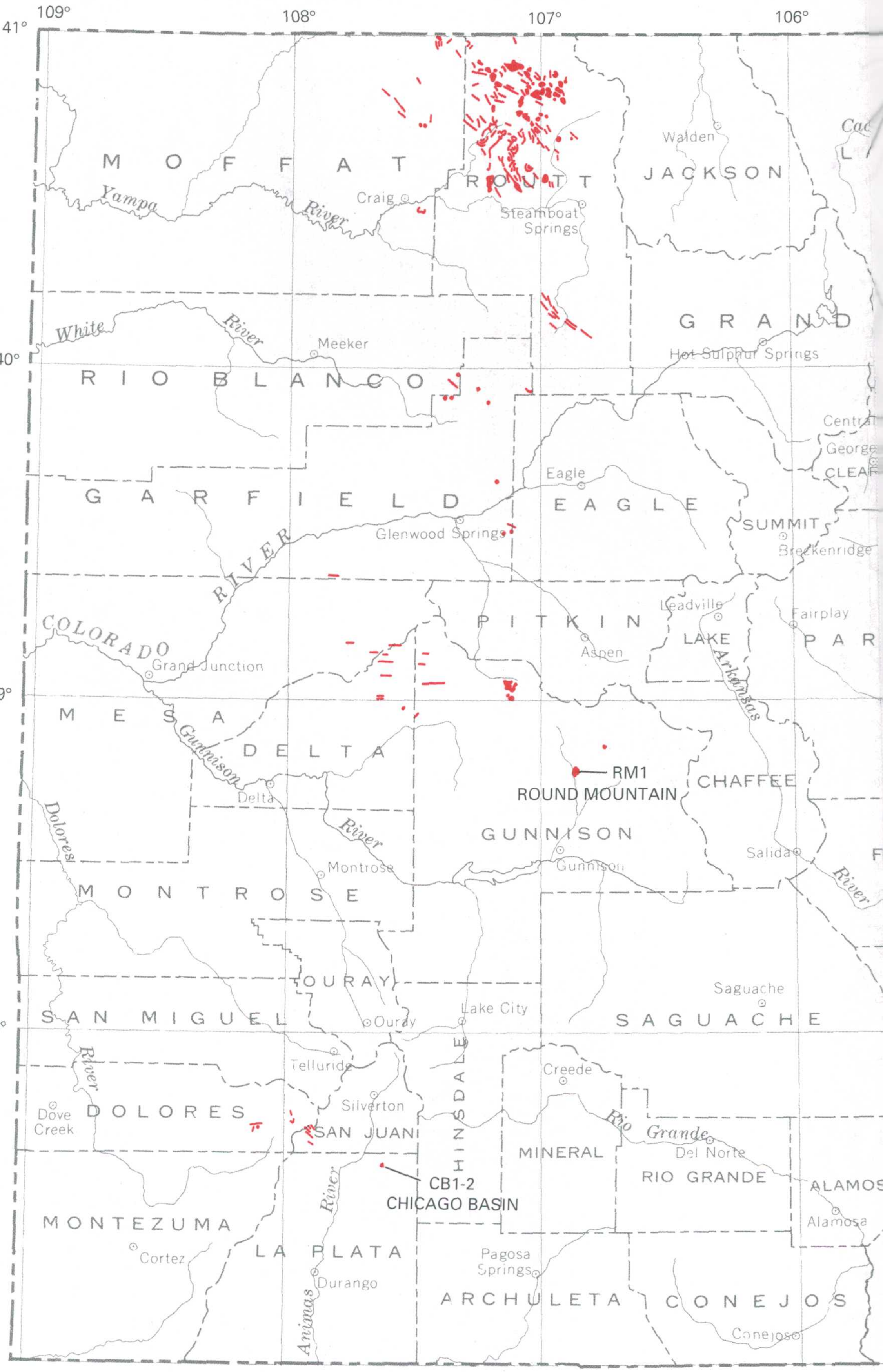
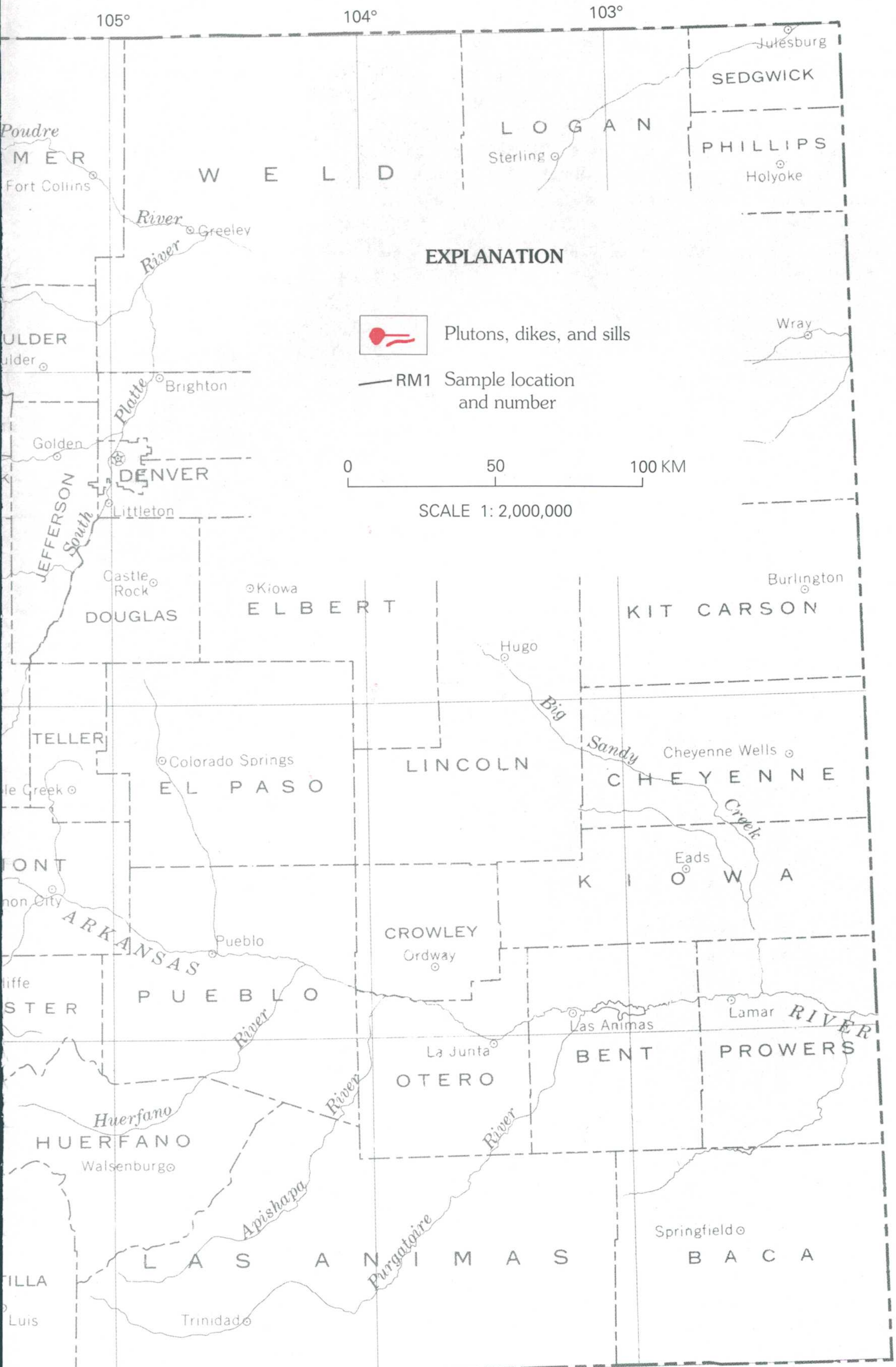


Figure 4. Late Tertiary intrusions, Colorado.



105°
104°
103°
Julesburg
SEDGWICK
LOGAN
Sterling
PHILLIPS
Holyoke
Poudre
Fort Collins
WELD
River
Greeley
River
EXPLANATION
Plutons, dikes, and sills
RM1 Sample location and number
0
50
100 KM
SCALE 1: 2,000,000
Wray
Brighton
Platte
Golden
DENVER
JEFFERSON
South
Littleton
Castle Rock
DOUGLAS
Kiowa
ELBERT
Burlington
KIT CARSON
Hugo
Big
Sandy
TELLER
Colorado Springs
EL PASO
LINCOLN
Cheyenne Wells
CHEYENNE
Creek
Eads
KIOWA
ARKANSAS
Pueblo
CROWLEY
Ordway
PUEBLO
River
Las Animas
Lamar
RIVER
La Junta
BENT
PROWERS
OTERO
River
Huerfano
HUERFANO
Walsenburg
River
Apishapa
Purgatoire
LAS ANIMAS
Springfield
BACA
Trinidad

the base of the Cretaceous Mancos Shale, and they form prominent cliffs on either side of the canyon walls above Ouray (Burbank and Luedke, 1964). The sills are Laramide in age; zircon from sample O-2 (table 1) gave a 54.1±4.0 Ma date, which is a minimum age because apatite in the same sample shows the rock was reheated. Burbank (1930) notes that the sills and laccoliths are overlain by the Eocene Telluride Conglomerate, and Luedke and Burbank (1962) describe porphyritic granodiorite clasts in the formation. Both relations indicate that the igneous rocks are no younger than Eocene.

Geochronology reported by Billings (1980) indicates the approximate timing of three hydrothermal events in the vicinity of Ouray: (1) 27.5 Ma (Lipman and others, 1976) following the collapse of the Silverton caldera, (2) approximately 15 Ma, related to the rhyolite at Stoney Mountain, and (3) approximately 10 Ma, related to the Camp Bird system. Fission-track ages in both zircon and apatite were reset by a large paleothermal anomaly that appears to be related to mineralization at the Camp Bird mine. A ZFT date of 54.1 Ma from sample O-2 may be partly reset, and the zircon date from O-1 was even more reset to 40.7±6.9 Ma (table 1). Apatites in both of the same samples give discordant, younger dates because of their lower annealing temperatures (Naeser, 1979). The apatite in sample O-2 gives a 14.9±5.7-Ma date, and apatite in O-1, which is closer than O-2 to the Camp Bird mine, was apparently completely reset to 7.8±3.5 Ma, which approximates the age of mineralization of 10.5±0.5 Ma at the Camp Bird mine (Lipman and others, 1976).

PORPHYRY CREEK AND TOMICHI CREEK STOCKS

The Porphyry Creek rhyolite porphyry stock is an elongate 1 by 3 km pluton that adjoins the northern edge of the Tomichi Creek stock (fig. 3). It was mapped by Raines (1971) and Tweto and others (1976). The stock is closely associated with and located approximately 6 km south of the Mount Princeton batholith, which is the largest of the exposed middle Tertiary plutons in the CMB (fig. 3).

Both the Porphyry Creek stock and adjoining Tomichi Creek stock have ages similar to those of the Mount Aetna cauldron complex. The Mount Aetna complex includes the Mount Princeton batholith, which forms a large subcircular pluton about 24 by 34 km in diameter and is composed mainly of medium-grained quartz monzonite. Principal studies of the batholith include those by Crawford (1913), Dings and Robinson (1957), Shannon (1988), and Toulmin and Hammarstrom (1990). The Mount Aetna volcanic center is located in the southwestern part of the batholith; isotopic dates for this volcanic center indicate igneous activity beginning at 40–37 Ma (Toulmin and Hammarstrom, 1990). In a detailed study of the Mount Aetna cauldron complex, Shannon (1988) showed three major magmatic events in the south-central Sawatch Range: (1) the emplacement of the Mount Princeton pluton at 36.6 Ma; (2) the formation of the Mount Aetna cauldron at 34.4 Ma; and (3) chemically evolved granites at 29.8 Ma. A date on biotite from the Mount Antero Granite, the youngest of seven separate intrusions that make up the Mount Princeton batholith, is 31.6±1.1 Ma (Thompson and Pulfrey, 1973). Significant ore deposits are not associated with the main batholith intrusion; however, molybdenite and beryllium minerals associated with the Mount Antero Granite have been known for many years (Adams, 1953; Sharp, 1976).

Dates on sample PC-1 (tables 1 and 2) from the Porphyry Creek stock are 38.4±0.9 Ma (K-Ar, biotite) and 35.3±3.3 Ma (ZFT). They are concordant and similar to the age of the main quartz monzonite phase of the Mount Princeton batholith. The slightly younger date on the zircon may reflect partial resetting by the adjacent, younger Tomichi Creek stock or the effect of cooling and uplift time.

The Tomichi Creek rhyodacite stock, about 2 km in diameter and adjoining the southern margin of the Porphyry Creek stock, is approximately 8 km south of the Mount Princeton batholith. The zircon date of 29.6±2.7 Ma (sample TC-1, table 1) is similar to the age of the chemically evolved granites of 29.8 Ma, the youngest intrusions in the Mount Aetna cauldron complex.

TINCUP STOCK

The Tincup stock (fig. 3) is one of several plutons of quartz monzonite porphyry mapped by Dings and Robinson (1957) in and around the Tincup mining district. Sample T-1 (tables 1 and 2), collected from a west-trending stock about 1 km south of Cumberland pass, contains prominent epidote crystals. Table 1 shows that epidote and zircon give concordant fission-track dates of 37.4±6.8 Ma and 34.4±3.2 Ma, respectively. This indicates that the age of the Tincup stock is similar to the Porphyry Creek stock (table 1; sample PC-1, 38.4±0.9 Ma, biotite K-Ar; 35.3±3.3 Ma, ZFT) and also to the main quartz monzonite phase of the Mount Princeton batholith, located about 6 km east of sample T-1. Another related, north-trending stock of similar composition, mapped as Tincup quartz monzonite porphyry by Dings and Robinson (1957), is about 4 km northeast of sample T-1. This stock intruded along the Precambrian-Paleozoic contact, and nearby mineral deposits are present in the Mississippian Leadville Limestone.

A series of metal-bearing veins are located about 1 km north of the Tincup stock in the vicinity of Cumberland pass, and at least one vein cuts the stock (Dings and Robinson, 1957). The Bon Ton mine is located 0.6 km north of the stock contact in a vein that cuts Precambrian gneissic granite. The Bon Ton mine produced gold, silver, copper, and lead and some molybdenum and tungsten ore (Dings and

Robinson, 1957). The spatial association and concordant ages of the dated minerals suggest that these metal deposits are genetically associated with the Tincup stock.

ROUND MOUNTAIN STOCK

The Round Mountain stock (fig. 4) is a fine-grained biotite rhyolite stock about 2 km in diameter. It is situated at the eastern end of the West Elk volcanic field about 15 km southeast of Crested Butte. Cross (1894) noted that it was different from the quartz monzonite that comprises the West Elk laccoliths and that it was probably younger in age. Our dating studies support his observations; sample RM-1 (tables 1 and 2) gives concordant zircon (11.5±1.3 Ma) and apatite (9.8±2.9 Ma) dates and a slightly older biotite date (13.9±0.3 Ma). This is essentially the same age as the Crystal pluton of the Treasure Mountain dome dated at 12.7 Ma, located 35 km to the northwest (Obradovich and others, 1969). There are no known mineral deposits associated with the Round Mountain stock.

ITALIAN MOUNTAIN INTRUSIVE COMPLEX

The Italian Mountain Intrusive Complex (fig. 3) is a heterogeneous assemblage of intrusive rocks in the eastern Elk Mountains. It includes three intrusive centers and associated plutons of quartz diorite, granodiorite, and quartz monzonite composition (Cunningham, 1976). The ZFT age published in Cunningham and Naeser (1975) is here revised to 33.9±3.9 Ma using a recalibrated thermal neutron dose of 1.15×10^{15} and a decay constant of 7.03×10^{-15} yr^{-1}. The Italian Mountain Intrusive Complex is similar in age and composition to other stocks in the eastern Elk Mountains, including the Whiterock and Snowmass stocks, 34.8±1.0 Ma and 35.0±1.4 Ma, respectively (Gaskill, 1956; Obradovich and others, 1969), and the Mount Sopris stock (34.3±4.1 Ma, ZFT; 34.2±0.8 Ma, biotite K-Ar; sample MS-1, table 1).

Lead-zinc-silver hydrothermal deposits are present in the Leadville Limestone on the east side of the intrusive complex. The deposits are zoned outward from the northernmost, youngest, intrusive center, suggesting that they are genetically related to that youngest center.

MOUNT SOPRIS STOCK

The circular Mount Sopris stock (fig. 3), about 5 km in diameter, is the northernmost of the principal stocks of the eastern Elk Mountains. It is composed mostly of biotite quartz monzonite but grades locally to granodiorite. Aspects of the structure and petrology are described by Pilkington (1954) and Foland (1967). The dates of 34.3±4.1 Ma (ZFT) and 34.2±0.8 Ma (biotite K-Ar) (sample MS-1, tables 1 and 2) show that the Mount Sopris stock is the same age as other small stocks in the Elk Mountains.

Minor lead and silver deposits are associated with the Mount Sopris stock, primarily in the contact zone (Pilkington, 1954). Schwartz and Park (1930) describe galena with stromeyerite, argentite, covellite, and bornite from these deposits.

LEADVILLE

The Leadville district (fig. 3) is one of the world's most famous mining districts. Despite many studies, the ages of the igneous rocks and ore deposits remain controversial. However, new isotopic and analytical methods, coupled with the detailed records of early investigators such as Emmons (1886), Emmons and others (1927), and Behre (1953), have given new understanding in discerning geologic relationships in this district. Much of the recent information on the Leadville district is synthesized in Beaty and others (1990).

The Leadville district contains at least six different igneous rock units that range in age from Late Cretaceous to middle Tertiary. Five of them are pre-ore (Thompson and Arehart, 1990): Pando Porphyry (71.8 Ma, biotite K-Ar, Pearson and others, 1962); Lincoln Porphyry (66.3 Ma, biotite K-Ar, Pearson and others, 1962); Evans Gulch Porphyry (46.8±4.4 Ma, ZFT, sample L-2, this study); Sacramento Porphyry (43.9±4.3 Ma, ZFT, Thompson and Arehart, 1990); and Johnson Gulch Porphyry (43.1±4.3 Ma, ZFT; 43.1±7.6 Ma, AFT, Thompson and Arehart, 1990). This geochronologic order is in disagreement with Beaty and others (1987) who reported a ZFT age of 53.6±6 Ma for the Sacramento Porphyry and with Tweto (1974) who, on the basis of geologic relations, reported that the Sacramento Porphyry is post-Pando Porphyry and pre-Lincoln Porphyry. Hydrothermal sericite produced during the principal Leadville ore-forming event has been dated by Thompson and Arehart (1990) at 39.6±1.7 Ma. The Leadville ore deposits are cut by younger rhyolite porphyry dikes and plugs and still younger breccias. Sanidine from the postmineralization rhyolite gives a K-Ar age of 38.5±0.6 Ma (sample L-1, tables 1 and 2). Thompson and Arehart (1990), on the basis of annealed fission tracks in apatite and zircon, show thermal events associated with mineralization and alteration extended to 33.8±5.0 Ma. This agrees well with our sample L-3, described as Johnson Gulch Porphyry by Ogden Tweto (U.S. Geological Survey, written commun., 1981), which gives a ZFT date of 34.8±4.9 Ma. These younger dates may also represent annealing caused by a younger intrusion.

The principal ore deposits of the Leadville district are massive replacement sulfide bodies in dolostone that are zoned around the Breece Hill stock, which is composed of Johnson Gulch Porphyry, although the ore is interpreted to be derived from a younger intrusive system centered beneath the stock (Thompson and Arehart, 1990). DeVoto (1983) and Tschauder and others (1990) suggest that some of the silver in the Leadville ores is remobilized from silver-rich ores that formed during a late Paleozoic, Mississippi Valley-type, mineralization event.

Age relationships of igneous rocks and ore deposits at Leadville are similar to those documented at the Gilman district, about 32 km to the northwest. At Gilman, the Pando Porphyry, dated at 71.8 Ma (Pearson and others, 1962), forms large sills in Paleozoic sedimentary rocks, but the oldest determined zircon dates are only 60.1±7.8 Ma (Naeser and others, 1990), indicating they have been partially reset. The main ore deposits are massive sulfide replacement ores in the Mississippian Leadville Limestone. The ore is related to an unexposed, middle Tertiary stock (Beaty and others, 1990) that formed a large dome-shaped paleothermal anomaly in the Pando Porphyry (Naeser and others, 1990). The ores at Gilman formed at 34.5±4.4 Ma; this age is based on an apatite fission-track determination on paragenetically late hydrothermal apatite in the ore assemblage. Fission tracks in apatite and zircon in the nearby Pando Porphyry are partially reset and give anomalously young ages near the ore. The age of 34.5±4.4 Ma from the Gilman ore is similar to the date given by reset zircons of 34.8±4.9 Ma in the Johnson Gulch Porphyry (sample L-3, table 1) from the Leadville district; thus young igneous-hydrothermal events of the same age may have occurred at both districts.

WEST TENNESSEE CREEK STOCK

The West Tennessee Creek stock (fig. 2) is the southernmost of several small monzogranite to granodiorite (Wallace and Blaskowski, 1989) stocks that trend northwest across the northern tip of the Sawatch Range. Elongate and only about 0.5 km in length, the stock is located immediately north of West Tennessee Lakes and has been mapped by Tweto (1974). A date of 66.4±2.2 Ma on biotite (sample WT-1, tables 1 and 2) shows that it was emplaced during the Laramide, but the younger apatite date of 46.5±10.3 Ma (sample WT-1, tables 1 and 2) indicates it was reheated or reflects an uplift age. Leadville is about 14 km southeast of this locality.

WEST CROSS CREEK STOCK

The West Cross Creek stock (fig. 2), roughly circular and about 1.0 km in diameter, is an intrusive complex composed mostly of diorite and granodiorite, which occur together with monzogranite and rhyolite porphyry intrusions. It also is referred to as part of the intrusive rocks of Middle Mountain (Wallace and Blaskowski, 1989). The concordant ages of 61.8±1.4 Ma (biotite K-Ar) and 59.3±6.9 Ma (ZFT) (sample WC-1, tables 1 and 2) indicate emplacement during the Laramide. Insufficient apatite was recovered to obtain a date to investigate possible younger partial annealing as observed in the West Tennessee Creek stock. The monzogranite Treasure Vault stock, located 2 km to the southeast, gives a K-Ar age of 64.0±2.3 Ma on biotite (Wallace and Blaskowski, 1989) and an AFT date of 52 Ma (Wallace, in press).

EAST LAKE CREEK STOCK

The East Lake Creek stock (fig. 2), elongate in plan view and about 0.5 by 1.5 km, is composed of leucocratic syenite that locally grades to granite (Wallace and Blaskowski, 1989). Fission-track dates of 65.2±6.3 Ma on sphene and 59.5±8.1 Ma on zircon (sample EL-1, tables 1 and 2) are concordant and similar to other ages of stocks in the northwest trend.

FULFORD STOCK

The Fulford stock (fig. 2), at the northwestern end of the trend, ranges from quartz diorite to granite but is mostly monzogranite. Two samples (tables 1 and 2) collected close to each other give Laramide dates (65.1±6.8 Ma, ZFT, sample F-1;62.2±1.5 Ma, biotite K-Ar, sample F-2). The Fulford stock has small gold-copper-quartz and lead-silver veins spatially associated with it. These veins cut the stock and surrounding sedimentary rocks in the Fulford mining district (Gableman, 1949). Wallace and others (1989) showed that many of the gold-bearing veins were related to post-Fulford, 62.2- to 61.7-Ma albite syenite intrusions.

MONTEZUMA STOCK

The Montezuma stock (fig. 3) is on the western flank of the Front Range and is a 9 by 5 km east-west elongate biotite quartz monzonite porphyry stock. It intruded Precambrian rocks, primarily gneisses, as well as Cretaceous shales at its western tip (Neuerburg and Botinelly, 1972). Smaller, fine-grained plutonic outliers are present south of the main stock; sample M-1 came from one of these. The stock and its associated ore deposits are described by Lovering and Goddard (1950) and Neuerburg and others (1974). Excellent descriptions of the main stock, where it is penetrated by the northwest-trending Harold D. Roberts water tunnel are given by Wahlstrom and Hornbeck (1962) and Warner and Robinson (1967). Simmons and Hedge (1978) report a Rb-Sr date on biotite of 39 Ma for the Montezuma stock. Bookstrom and others (1987) report an AFT age of 40.2±8.8 Ma and a ZFT age of 39.8±4.2 Ma for the relatively fresh Montezuma stock and a ZFT age of

37.4±3.0 Ma on a sericitized part of the stock. Our ZFT age determination of 35.0±3.2 Ma (sample M-1, tables 1 and 2) is similar to a K-Ar date on biotite of 39.6±1.2 Ma on biotite (McDowell, 1971) and a 37.9±1.4 Ma date on biotite (Marvin and others, 1989) and confirms that the stock is middle Tertiary in age.

The Montezuma district contains argentiferous lead-zinc veins that cut the Montezuma stock (Lovering and Goddard, 1950). Trace amounts of molybdenite are present in the stock (Neuerburg and others, 1974), but much of the base metal and molybdenite appear to be related to younger intrusive rocks (Bookstrom and others, 1987).

EMPIRE STOCK

The subcircular 1-km diameter Empire stock (fig. 2) is within the Front Range and is located about 2 km west of the town of Empire. Many intrusive bodies are exposed in the area, ranging from dikes to small plutons in size and from granodiorite to granite aplite in composition; Braddock (1969) determined relative ages where possible. The principal part of the Empire stock consists of hornblende-pyroxene monzonite. Our fission-track date on sphene of 68.0±6.2 Ma (sample EM-1, tables 1 and 2) and 61.6±2.2 Ma on biotite (Marvin and others, 1989) agree reasonably well with a Rb-Sr date of 65 Ma reported by Simmons and Hedge (1978) and reflect the probable age of emplacement; a date of 37.4±2.8 Ma on apatite from our sample EM-1 indicates there has been some thermal annealing of fission tracks.

The Empire district has a long history of mining, and most of the production in the district was from veins in the vicinity of the town of Empire. Braddock (1969) found only one vein that actually cuts the Empire stock. Ore deposits in the Empire district are mostly gold-pyrite veins, which have a strong northeast trend. The veins are clustered in an area just north of town. A well-defined geochemical anomaly in mull (forest humus layer), which has a central zone of gold, copper, and bismuth encircled by silver, lead, zinc, and molybdenum, is located in the vicinity of a small, hornblende diorite porphyry stock that is located about 2 km north of the town of Empire (Curtin and others, 1971) and has not been dated. The age of the ore deposits has not been directly determined; however, the biotite quartz monzonite porphyritic Mad Creek stock, which cuts the eastern edge of the Empire stock, has a peripheral sericitized explosion breccia containing molybdenite, pyrite, galena, and sphalerite (A. Bookstrom, U.S. Geological Survey, written commun., 1994). The Mad Creek stock and its explosion breccia give concordant ZFT dates of 40.5±6.5 Ma (breccia) and 39.4±4.3 Ma (stock), which are similar to the age of the nearby Montezuma stock (Bookstrom and others, 1987).

APEX STOCK

The next major pluton to the north in the Front Range, the Apex stock (fig. 2), cuts Precambrian rocks, is elongate north-south, and is about 5 km long by 1 km wide. It is composed of hornblende-biotite quartz monzonite and is cut by dikes of similar composition. Rice and others (1982) report K-Ar hornblende dates of 79.3±1.9 Ma and 76.7±3.1 Ma. The main body of the stock gives fission-track dates of 71.3±18.0 Ma (AFT) and 61.7±6.3 Ma (ZFT) (sample A-1, tables 1 and 2). Dates from both minerals are concordant at about 60±5 Ma. Barker (1979) reports dates of 60.1±5.5 Ma and 57.3±4.4 Ma. Sample A-2 (tables 1 and 2), from the same location as A-1, is from one of a series of younger, crosscutting dikes and yields an AFT date of 66.8±7.5 Ma and a ZFT date of 58.5±5.2 Ma. Dates from minerals in A-2 are slightly younger than dates from corresponding minerals in sample A-1. Apparently there are problems either with excess radiogenic argon in the hornblende and the stock formed about 60 Ma, or fission tracks in the zircons and apatites have been reset to about 60 Ma by a thermal event apparently associated with a larger intrusion probably related to the dikes sampled by A-2. The apatite ages from both samples A-1 and A-2 show the same ages as from the zircon in the same sample, indicating there has been no thermal resetting younger than about 60 Ma, in contrast to the thermal history of the nearby Empire stock.

Pyritic gold formed the principal ore in the vicinity of the Apex stock. Most of the veins trend northeast and are located just east of the stock (Lovering and Goddard, 1950); however, two veins cut the stock. Low-grade molybdenite deposits are present in the stock and in associated veins and breccias (Barker, 1979).

ELDORA STOCK

The next pluton north in the Front Range part of the CMB is the Eldora stock (fig. 2), which cuts Precambrian rocks and is subcircular with a diameter of about 3 km. It is composed of biotite-hornblende-pyroxene quartz monzonite. Samples of zircon and apatite from rocks at the same locality give fission-track dates (sample E-1, table 1) of 66.6±6.4 Ma (zircon), 61.8±6.3 Ma (zircon) and 58.6±9.4 Ma (apatite) that are concordant around 60 Ma, indicating a Laramide age for the stock. This agrees with a previous $^{40}Ar/^{39}Ar$ date of 63 Ma on biotite (Berger, 1975) and a K-Ar date of 68.2±4.1 Ma on hornblende (Marvin and others, 1989) for the stock. The concordant apatite age shows there has been little or no thermal resetting. The petrography of the stock has been studied in detail by Cree (1948), the contact zone by Hart (1964) and Berger (1975), and the mapped relationships are in Lovering and Goddard (1950) and Gable (1969).

Only a minor amount of ore was produced from the Eldora district, mostly from gold-telluride ores, and molybdenite is reported to be moderately abundant (Lovering and Goddard, 1950). Some quartz-pyrite veins cut the stock. For perspective, the molybdenum mineralization at Central City is reported to be 59 Ma (Rice and others, 1985).

JAMESTOWN STOCKS

Jamestown (fig. 3), at the northeastern end of the CMB, includes two stocks, an older granodiorite stock and a younger sodic granite pluton that intrudes the northern end of the granodiorite. The sodic granite is called the Porphyry Mountain stock. Hornblende from the granodiorite stock has been dated at 79.6±2.3 Ma and 73.6±2.2 Ma (McDowell, 1971). The younger stock was dated by using two samples from the same drill core from a hole near the summit of Porphyry Mountain. Zircons from the two samples (table 1), one at a depth of 12.5 m (sample JS-2A, 44.8±5.7 Ma) and the other from near the bottom of the drill core at a depth of 1,024.4 m (sample JS-2B, 45.1±7.7 Ma), give concordant dates for the stock at about 45 Ma. Zircon and apatite, collected from the older granodiorite stock but within 1 km of the contact of the Porphyry Mountain stock, give dates of 48.4±7.5 Ma and 47.1±5.8 Ma, respectively; these dates are interpreted to be reset, minimum ages. A K-Ar date on biotite from an unusual vein that contains essentially only biotite and fluorite and cuts the granodiorite was 58.8±2.0 Ma (sample JS-1, table 1). Igneous and hydrothermal events in nearby Four Mile Canyon have been dated at 62.06±0.37 Ma, 54.7±1.0 Ma, 48.19±0.29 Ma, and 46±1.0 Ma (Kane and others, 1988) indicating a complex thermal history in the area in which the last significant event occurred at about 45 Ma.

The Jamestown district is known for its production of gold-telluride ore, fluorspar, pyritic gold ore, and silver-lead ore (Goddard, 1946; Lovering and Goddard, 1950; Kelly and Goddard, 1969). Most of the fluorite is paragenetically older than the base metals, gold, and tellurides (Nash and Cunningham, 1973). The igneous-hydrothermal system related to the Porphyry Mountain stock and its underlying source appears to have been responsible for most of the fluorite mineralization in the district because fluorite is a primary mineral in the stock as well as in adjacent breccia bodies, and fluorite-bearing veins and breccia bodies are cut by granitic dikes that appear to be related to the Porphyry Mountain stock; the genetic relationship of the pyritic gold and gold tellurides to the stock is less certain (Nash and Cunningham, 1973).

DISCUSSION OF THE AGES OF INTRUSIVE ACTIVITY

Igneous rocks and their associated ore deposits in the CMB tend to form three natural groupings by age; they are Late Cretaceous and early Tertiary (Laramide), middle Tertiary, and late Tertiary. With the advent of improved technologies to more precisely date rocks, alteration minerals, and ore minerals and the addition of new data, especially since 1990, this tripartite division has blurred somewhat but remains. These natural age groupings have been recognized by many investigators, and, with minor modifications, we follow suit as shown on figures 2, 3, and 4. The age assignment used is our best interpretation of the age of intrusion of stocks or igneous centers and is based on geochronologic data, thermal annealing characteristics of minerals, and geologic relationships.

LARAMIDE IGNEOUS CENTERS

The oldest group of intrusions formed mainly between 70 and 50 Ma, straddling the Cretaceous-Tertiary boundary, and were emplaced during the Laramide orogeny (Tweto, 1975). These intrusions form a well-defined northeastern trend that constitutes the innermost zone of the CMB and is readily apparent on figure 2. Two northwest-trending zones of intrusive rocks are also present. The most prominent is a series of small stocks that extends northwest from the West Tennessee Creek stock, across the northern Sawatch Range to the Fulford stock. Another smaller group of stocks and dikes extends northwest in the Front Range from the Denver area.

Along the main northeastern trend, igneous activity generally proceeded from the southwest to the northeast; this progression is best documented in the southwestern segment of the CMB. Igneous activity in the Ute Mountain area is well dated at about 72–70 Ma (table 1) by multiple dates, including apatite ages, which indicate there has been no significant resetting of ages. The La Plata Mountains appear to be also well dated, and ages group around 68 Ma. The Laramide rocks at Rico are fairly well dated, especially the hornblende latite sills; when the data of this study are combined with those of Naeser and others (1980), an age of about 65 Ma seems most reasonable. The Laramide sills at Ouray are probably of similar age, a determination based on the proximity, similarity in composition, and style of emplacement; the date of 54 Ma (table 1) is a minimum age due to apparent reheating. The most comprehensive compilations of ages at Leadville are by Thompson and Arehart (1990) and Wallace (in press). Although the ore and some of the rocks are younger than Laramide, two major igneous units, the Pando Porphyry (72 Ma) and the Lincoln Porphyry (64 Ma), give Laramide ages. These rock units are Laramide because the Pando Porphyry appears to have been emplaced contemporaneously with thrusting related to Laramide activity (Thompson and Arehart, 1990). A short distance to the north at Gilman, the Pando Porphyry has been affected by a middle Tertiary thermal event. The oldest zircon ages, the ones that are apparently the least reset and closest to the original age of emplacement, range from 58 to 55 Ma (Naeser and others, 1990).

Northeast of Leadville the age progression picture is not as readily apparent. Scattered stocks, such as Apex, Empire, Eldora, and Caribou appear to have been emplaced about 65–60 Ma. The emplacement age of the older granodiorite stock at Jamestown is not well dated. Ages on hornblende are approximately 80 and 74 Ma (McDowell, 1971) and may be too old due to excess argon and to reset dates on apatite and zircon of 48 Ma (sample JS-3, table 1). The date of 45 Ma on the sodic granite stock is quite different from the well-dated Laramide rocks; other dates of approximately 45 Ma have been documented in the nearby Four Mile Canyon area (Kane and others, 1988) and for a quartz monzonite sill in the central CMB in the Swan Mountain area (Simmons and Hedge, 1978; Marvin and others, 1989).

Lovering and Goddard (1950) proposed a general northeastward progression of intrusive activity in the Front Range; corresponding lithologic types appear earlier in the southwestern part than in the northeastern part. If an age of about 62 Ma for the Apex and Eldora stocks is accepted as the general age of activity near that part of the CMB, a distance of about 400 km from the Ute Mountains, then the rate of northeast progression of igneous activity was about 4 cm/yr. The northeastward progression of igneous activity noted at least in the southwestern part of the CMB parallels the general direction of Laramide tectonic activity; the Laramide orogeny commenced in the southwest before marine deposition ended in the northeast (Tweto, 1975).

MIDDLE TERTIARY IGNEOUS CENTERS

Post-Laramide early to middle Tertiary igneous activity, from about 45–25 Ma, was significantly more widespread in Colorado than was Laramide igneous activity (fig. 3). The middle Tertiary igneous rocks that are relevant to our discussion are present today mostly as volcanic rocks in the San Juan volcanic field of southern Colorado (Steven, 1975; Steven and Lipman, 1976) and as epizonal stocks, laccoliths, and volcanic breccias in the Elk Mountains of central Colorado (Godwin and Gaskill, 1964; Lipman and others, 1969; Obradovich and others, 1969). During the middle Tertiary, these two igneous centers coalesced into a single volcanic field (Steven, 1975). Smaller, local centers existed in northern Colorado (fig. 3). Leucocratic stocks related to major molybdenum deposits were intruded at Red Mountain (Urad-Henderson) and Climax at 33 to 24 Ma (Bookstrom and others, 1988) and Mount Emmons at 18 to 16 Ma (Thomas and Galey, 1982).

The volcanic fields of the San Juan and Elk Mountains coincide with two large (> −300 milligal) gravity lows (fig. 1) that have been interpreted to reflect the location of two shallow batholiths (Tweto and Case, 1972; Plouff and Pakiser, 1972; Behrendt and Bajwa, 1974). The margins of the batholiths have been interpreted to be approximately between the −275 mGal and −300 mGal contour lines along the trends of the steepest gravity gradients along the borders of the gravity lows (Steven, 1975). The central Colorado gravity low has a lobe that extends northeastward along the trend of the CMB, as defined by Laramide plutons. Middle Tertiary stocks coincide with Laramide stocks along this part of the CMB all the way to the Porphyry Mountain stock at Jamestown, thereby leading to the conclusion that a lobe of the northeasternmost of the two batholiths underlying central Colorado extends to the northeast (Steven, 1975). Gravity modeling (Isaacson and Smithson, 1976) indicates that a granitic batholith in central Colorado is present at depths of 8 to 25 km.

LATE TERTIARY IGNEOUS CENTERS

Late Tertiary igneous centers are present over a wide area of Colorado (fig. 4) including the CMB. Dates suggest that most of the igneous intrusive activity in these centers took place between about 15 and about 4 Ma. Several of these centers, or stocks, have been dated in the course of this study (tables 1 and 2). They include Round Mountain (about 14–10 Ma), Chicago Basin (about 10 Ma), and the rhyolites associated with the Silver Creek molybdenum deposit at Rico (about 4 Ma). Other significant igneous centers include Treasure Mountain dome at 12.7 Ma in the Elk Mountains (Obradovich and others, 1969; Mutschler, 1970), the Hahns Peak area at about 10 Ma in northern Colorado (McDowell, 1971; Segerstrom and Young, 1972), Flat Top basalts between about 24 Ma and less than 1 Ma (Marvin and others, 1974; Larson and others, 1975), and several centers about 4 Ma in the vicinity of the San Luis valley (Lipman and others, 1970, 1986).

DISCUSSION OF THE AGES OF MINERALIZATION

Most ore deposits in the CMB previously were considered to be of Laramide age because of their spatial correspondence to intrusive rocks that also were believed to be Laramide (Lovering and Goddard, 1950). Recent studies, including this one, have confirmed the Laramide age of some deposits but have shown also that the majority of ore deposits previously thought to be Laramide are actually of middle Tertiary or late Tertiary age, although they may be superimposed on or spatially associated with Laramide igneous rocks.

LARAMIDE ORE DEPOSITS

Many of the Laramide igneous centers of the CMB contain no significant mineralization, especially in the southwestern part of the belt. These include Laramide rocks in the Ute Mountains, sills in the La Plata Mountains, the augite monzonite stock and the sills at Rico, the Twin Lakes stock in the Sawatch Range (63.8±0.7 Ma $^{40}Ar/^{39}Ar$ on hornblende; Shannon and others, 1987), Leadville, some of the small intrusions in the Front Range, the granodiorite stock at Jamestown, and many of the stocks in the northwestern trend.

However, some Laramide igneous centers demonstrably generated cogenetic mineral deposits. In the La Plata Mountains, the telluride veins and replacement bodies, which have yielded more than 95 percent of the district's production, are generally in structures peripheral to the central core of igneous rocks in the district; the exceptions are those veins related to the diorite stocks (Eckel, 1949). The disseminated chalcopyrite deposits in the La Platas are spatially, and apparently genetically, associated with both syenite stocks, and minor gold veins and replacement bodies are scattered throughout the district. All of our age determinations in the La Platas, with one exception, have produced Laramide dates, including fission-track dates on apatite; the major part of the igneous and hydrothermal activity in the La Platas took place during the Laramide, and apparently no major younger thermal event has been recorded. The one exception is an intriguing date of 50.3±4.9 Ma on apatite (sample LP-5, tables 1 and 2) from the diorite stock at Diorite Peak.

Near the northwestern margin of the San Juan volcanic field, ore was deposited in two or more metallogenetic epochs at Ouray; the bulk of the production came from deposits genetically associated with the Laramide porphyritic granodiorite intrusions. Deposits, which are zoned about a central stock, contain gold, base-metals with gold, gold tellurides, and silver, and lead-zinc silver. The deposits are present as fissure fillings and tabular bodies in sedimentary rocks adjacent to igneous rocks. These earliest formed ore deposits were truncated by early Tertiary erosion and overlain by the early Tertiary Telluride Conglomerate and middle Tertiary volcanic San Juan Formation. The ages of emplacement of the laccoliths and sills at Ouray have not been determined; our dates determined on zircon (samples O-1 and O-2, table 1), as previously stated, must be accepted as minimums and those on apatite as reset dates.

Further north along the CMB are other examples of Laramide mineralization. The Aspen district has Laramide intrusions in which the K-Ar dates cluster about 74–72 Ma (Obradovich and others, 1969). Bryant and others (1990) have demonstrated with zircon dates that there was a cooling event at 52 Ma and with apatite dates that there was a thermal event at 30 Ma, possibly related to igneous activity in the Elk Mountains. These dates furnish no definitive evidence for the age of the mineral deposits, but the reconnaissance study does indicate that large middle Tertiary paleothermal anomalies, such as those present at the Leadville (Thompson and Arehart, 1990), Gilman (Beaty and others, 1990), and Tennessee Pass (Beaty and others, 1987) districts, are not present at Aspen (Bryant and others, 1990).

In the northwestern trend, some of the stocks are associated with mineralization, whereas others are barren. The Fulford stock is spatially associated with small gold-albite-siderite vein deposits; however, although the stock is about 65–62 Ma (tables 1 and 2), the spatially associated deposits have been shown by Wallace and others (1989) to be related to post-Fulford (prior to 61.7 Ma) albite-syenite intrusions. The various methods that have been used for age determinations give generally concordant Laramide ages, indicating that these stocks have not had superimposed upon them significant igneous or hydrothermal events. A notable exception may be the West Cross Creek stock, also called part of the intrusive complex at Middle Mountain by Wallace and others (1989). They mapped a rhyolite porphyry in the glaciated valley floor of West Cross Creek, just north of the stock, that has textural characters similar to those of Oligocene granite complexes known to host stockwork molybdenum deposits of the Climax type.

The Whitehorn stock (Normand, 1968; Wrucke, 1974; Wrucke and Dings, 1979) is a large stock, about 23 by 7 km in extent, and is located about 5 km northeast of Salida. The stock is slightly off the main northeastern trend of the CMB and is approximately on line with a southeastern extension of the line of stocks that trend northwest across the Sawatch Range. It has been dated at about 70 Ma (Wrucke, 1974), and, although it ranges in composition from syenogabbro to quartz monzonite, it is mostly granodiorite. Geophysical studies (Case and Sikora, 1984) show the stock is marked by both positive magnetic and gravity anomalies, and detailed modeling suggests that the northern part is sill- or laccolithlike. Along the western side of the Whitehorn stock, contact metasomatic iron deposits (Behre and others, 1936) formed where the stock came into contact with limestones. Minor gold, silver, and copper veins of the Turret-Calumet district occur in conjunction with the iron deposits (Vanderwilt and others, 1947; Marsh and Queen, 1974).

The Central City district, located approximately 50 km west of Denver, contains uranium, base-metal, and precious-metal mineral deposits that have been studied and dated by Wells (1960), Phair (1979); Rice and others (1982) and Wallace (1989). The base- and precious-metal deposits are complexly zoned, and although they are directly related to the emplacement of a Laramide, alkalic rhyolitic magma, there is some uncertainty about the precise age of mineralization (Wallace, 1989). Rice and others (1982) would place the base-metal deposits at about 60–58 Ma, but the deposits might be as old as 69 Ma (Taylor, 1976; Wallace, 1989). Telluride mineralization postdated the base-metal sulfide stage (Sims and Barton, 1962). The telluride mineralization at Central City has not been directly dated but may be similar to the age of the rest of the mineralization (Rice and others, 1982) or significantly younger (Wallace, 1989). Mineralization related to the Apex stock is apparently Laramide because apatite and zircon from the stock give Laramide dates that have no suggestion of subsequent thermal-mineralization events. The age of mineralization at the Empire stock is more questionable, however. The stock is clearly Laramide, and the gold-pyrite veins are similar in character to those in other Laramide districts, but the anomalously young apatite date (sample EM-1, tables 1 and 2) suggests that a younger thermal event may have produced the mineralization.

MIDDLE TERTIARY ORE DEPOSITS

Middle Tertiary ore deposits are present mainly in the central and northeastern parts of the CMB, especially near the middle Tertiary batholiths and the intersection of the CMB and the north-trending Rio Grande rift system (fig. 1). At Leadville, the water, sulfur, lead, and by inference the rest of the metals of the replacement deposits had a magmatic-hydrothermal origin as determined by stable and radiogenic isotope analyses (Thompson and Beaty, 1990). The age of the replacement ore, 39.6±1.7 Ma, is based on a K-Ar analysis of hydrothermal sericite (Thompson and Arehart, 1990). This age agrees with our postmineralization rhyolite sanidine date of 38.5±0.6 Ma (sample L-1, tables 1 and 2). Assuming that the approximately 39-Ma age for mineralization is valid, the younger zircon and apatite fission-track dates of 34.8±4.9 Ma (ZFT) (sample L-3, tables 1 and 2) and 33.4±5.1 Ma, derived from an average of several samples near the ore (Thompson, 1990), must be annealed samples. The similarity of the fission-track dates of reset apatite and zircon at Leadville to the 34.5±4.4 Ma age on the ore at Gilman suggests the possibility that a thermal event hot enough to partly reset fission tracks may have occurred at Leadville at about the same time as the major mineralizing event at Gilman.

Weakly mineralized middle Tertiary stocks are present throughout the CMB; they occur north of Rico (fig. 3) and, together with unmineralized laccoliths, in the West Elk Mountains (Gaskill and Meeves, 1984). Intrusions of similar age in the Elk Mountains are sparsely mineralized (Bryant, 1971) with the exception of the lead-zinc-silver replacement and vein deposits associated with the Italian Mountain Intrusive Complex dated at 34 Ma (sample I-1, tables 1 and 2). The Montezuma stock, dated at about 40 Ma, is spatially associated with silver-lead-zinc veins and disseminated molybdenum (Neuerburg and others, 1974). A fission-track date on zircon of 37.4±3.0 Ma, from a hydrothermally altered part of the Montezuma stock, is similar to the ages of nearby small intrusions (39–37 Ma) believed to be related to a hidden pluton south of the stock; Bookstrom and others (1987) suggest this hidden pluton is responsible for most of the mineralization and alteration that affected the Montezuma stock.

The thermal events associated with the multiple intrusions and large molybdenum deposits at Red Mountain (Urad and Henderson) spanned from 29.9±0.3 Ma (possibly before 30.38±0.09 Ma) to 26.95±0.08 Ma; the dates were based on a $^{40}Ar/^{39}Ar$ thermochronologic study by Geissman and others (1992). Corresponding activity at Climax occurred between about 33 and 24 Ma (White and others, 1981; Bookstrom and others, 1988; and a recent molybdenite Re-Os date of 26.6 Ma, Suzuki and others, 1993). Biotite from the intrusions at Mount Emmons gives dates of 17.3±0.7 Ma and 16.4±0.7 Ma (Thomas and Galey, 1982). All of these deposits are spatially within the negative 300-mGal Bouguer gravity contour in central Colorado. The Henderson-Red Mountain and Climax deposits are associated with bimodal leucogranite-lamprophyre magmatic suites that are indicative of underplating of the crust by basaltic magmas and consequent melting of felsic source rocks (Bookstrom and others, 1988). Extensive Pb, Sm-Nd, and Rb-Sr isotopic data and rare earth element (REE) data (Stein, 1985; Stein and Crock, 1990) indicate that the Climax-type granites were probably derived from a felsic to intermediate composition lower crustal source.

At Jamestown, fluorite deposits are most probably related to the sodic granite Porphyry Mountain stock, dated at 45 Ma, because fluorite occurs as a primary mineral in a late phase of the stock. The fluorite-biotite veins may reflect an earlier event at about 58 Ma or perhaps an anomalously old age due to argon from the older rocks perhaps concentrated or scavenged by the fluorine. The genetic relationship between pyritic gold, gold telluride veins, and the stock is less certain, but the gold is younger than the fluorite (Nash and Cunningham, 1973); the telluride and molybdenum mineralization most probably was related to the emplacement of the Porphyry Mountain stock (Threlkeld and Gonzalez-Urien, 1985). In the nearby Four Mile canyon area, $^{40}Ar/^{39}Ar$ dating of rocks and vein materials has identified a lead-silver vein at 62.06±0.37 Ma, a syenitic stock at 54.7±1.0Ma, a bostonitic stock at 48.19±0.29 Ma, and a hydrothermal breccia at 46±1.0 Ma, indicating an area of complex magmatic-hydrothermal-metalliferous systems (Kane and others, 1988).

LATE TERTIARY ORE DEPOSITS

Late Tertiary igneous systems, like Laramide and middle Tertiary systems, are characterized by both barren and highly mineralized stocks. At Rico, both lead-zinc-silver vein and replacement deposits and the more recently discovered Silver Creek molybdenum deposit are genetically related to rhyolitic stocks and dikes dated at 4 Ma. These are the youngest known mineralized rhyolites in Colorado.

Sr-Nd-Pb-O isotope and minor element data indicate that the rhyolitic stocks and dikes at Rico are isotopically distinct from the igneous rocks associated with Climax-type porphyry-molybdenum deposits in Colorado and may have contributions from both crust and mantle sources (Wareham, 1991). Chemical analyses of samples from dumps and drill core provide additional trace-element data for the Rico deposit (Neubert and others, 1991). The systems that formed the Chicago Basin molybdenum prospect and the Camp Bird deposits imparted anomalously young dates to Laramide sills near Ouray, at about 10 Ma. In central Colorado, the Round Mountain stock is slightly older (about 14–11 Ma) but contains no known, related mineral deposits. The nearby granite of similar age at Treasure Mountain contains only small, widely separated quartz-pyrite-sericite-fluorite veins, which locally contain minor amounts of molybdenite (Mutschler, 1976). The Hahns Peak (Elkhead Mountains) igneous center, about 30 km north of Steamboat Springs in northwestern Colorado, is about 12 Ma and contains minor amounts of silver, lead, and zinc veins. The vein system and a cone-shaped intrusive breccia containing molybdenite are related to a granitic stock (Casaceli, 1983); spatially associated alluvial gold deposits may or may not be genetically related to the intrusive center (Young and Segerstrom, 1973; Casaceli, 1983).

CONCLUSIONS

The Laramide (Late Cretaceous and early Tertiary) and middle to late Tertiary stocks, dikes, and sills of the CMB tend to be mostly calc-alkaline in composition and range from diorite to rhyolite; granodiorites and quartz monzonite porphyry predominate. At individual centers, intrusions of similar ages, whether Laramide or middle Tertiary, generally increase in silica content and mafic hydrous minerals with time (Ute Mountains, Rico, Leadville, Italian Mountain) or toward alkalic compositions (La Plata Mountains, Jamestown) or both (Central City). Late Tertiary stocks have less compositional range and tend to be rhyolitic.

Rocks of Laramide age in the Front Range are present as two petrographically distinct suites: a silica-oversaturated granodiorite-quartz monzonite suite and a silica-saturated, high alkali monzonite suite (Braddock, 1969). Simmons and Hedge (1978) examined both Laramide and mid-Tertiary plutons in the northeastern part of the CMB. They found that the granodiorite suite was present in rocks of both ages, whereas the monzonite suite was restricted to Laramide rocks. On the basis of Rb-Sr isotopic data, they concluded that both suites were derived from Precambrian source materials.

In general, monzonitic rocks preceded granodioritic rocks during the northeastwardly advance of Laramide magmatic activity between 75–45 Ma and most of the southwestwardly retreat after 45 Ma (Bookstrom, 1990). At Central City, granodiorite of Laramide age predated the sulfide mineralization and slightly younger biotite quartz latite postdated it (Rice and others, 1982). At Leadville, the rocks are generally more silicic, but the same trend persists; quartz latites and quartz monzonites predate the ore deposition, and the slightly younger rhyolite postdate it (Thompson and Arehart, 1990). The same overall change from intermediate composition to alkalic rhyolites also occurs at Rico and Jamestown, although the rocks are of significantly different ages.

Gold-telluride mineralization occurred throughout Colorado but was generally late in the ore-forming sequence at individual centers. In the La Plata Mountains, it is associated with Laramide syenites that are among the latest intrusions. Tellurides formed during the latest of the four stages of mineralization at Central City (Bastin and Hill, 1917; Sims and others, 1963); the gold-telluride mineralization has been related genetically to an alkalic rhyolitic stock and may be younger than 53 Ma (Wallace, 1989). At Jamestown, the telluride mineralization was probably related to the sodic granite stock dated at 45 Ma. The most extensively mined gold-telluride deposits in Colorado are outside of the CMB at Cripple Creek, where they are associated with alkalic rocks (Lovering and Goddard, 1950; Thompson and others, 1985; Thompson, 1992) that have been dated at about 32–28 Ma (Kelley and others, 1993). Lovering and Goddard (1950) noted that in the Front Range, southwest of Georgetown, complex lead-silver-zinc ores predominate and are present with diorite, monzonite, quartz monzonite, and sodic quartz monzonite; in contrast, northwest of Silver Plume, pyritic gold ores are present with alkalic syenite and alkalic trachyte porphyry.

Isotopic data can provide insight into the sources of magmas that formed stocks in the CMB and presumably the sources of metals in ore deposits. Studies of Pb, Rb-Sr, Sm-Nd isotopes, and REE from 52 granitoid intrusive and extrusive rocks indicate a predominantly crustal origin for igneous rocks of the CMB (Stein and Crock, 1990). Data on Climax-type molybdenum systems support magma generation by partial melting of Proterozoic, lower crustal rocks followed by differentiation (Stein and Crock, 1990), but recent Re-Os studies indicate that a mantle component may be part of the process (Stein and others, 1993). These deposits are believed to have formed at the time of incipient rifting related to the development of the Rio Grande rift system (Stein, 1988). Younger molybdenum systems, such as those at Chicago Basin and Rico in southwestern Colorado, may also be related to Rio Grande rifting (Bookstrom, 1981; Stein, 1982).

Documentation of the temporal and spatial evolution of igneous rocks and associated ore deposits in the CMB provides a unique opportunity to gain insight into subcontinental processes during the past 75 million years. Studies of, and references to, the relationship between the igneous-hydrothermal systems in the CMB and plate tectonic settings include Christiansen and Lipman (1972), Lipman and others (1972), Lipman (1980), Bookstrom (1981, 1990), Mutschler and others (1987), and Wallace (1990). Among the earliest to document the relationship between the Laramide tectonic and magmatic processes and subduction of the Farallon plate obliquely beneath the western margin of the American plate was Atwater (1970). Lipman (1980) presented evidence, based on the chemistry of volcanic rocks in a northeast-migrating magmatic arc above the plate, that the plate appeared to have an abrupt hinge between gently and steeply dipping subduction segments. T.A. Steven (U.S. Geological Survey, oral commun., 1976) and Barker and Stein (1990) showed that contoured K_2O–SiO_2 values of volcanic rocks were offset along the CMB, supporting the idea that Laramide igneous activity was related to a leaky transform fault in the subducted slab. Bookstrom (1981, 1990) used time-distance plots to document the northeastern migration of igneous activity along the CMB between 75–60 Ma. This migration was followed successively by tectonism and magmatism in the central part of the belt between 60–45 Ma, post-Laramide tectonic relaxation and southwestern retreat of magmatism between 45–25 Ma, bimodal magmatism with incipient rifting between 35–28 Ma, and rift-related volcanism associated with the Rio Grande rift system after 28 Ma. Alternatively, Mutschler and others (1987) suggested that a subducted plate explanation was not necessary because the igneous activity could be generated by regional compression, crustal thickening, and decompression melting of the mantle during rebound.

The Rio Grande rift system (fig. 1) has had an important role in forming ore deposits within and near the CMB. In Colorado, the north-trending rift is a series of en echelon grabens and horsts that is prominent from the south up to Leadville. The rift continues northward to the Colorado-Wyoming border (Tweto, 1979b), although its surficial expression is much compromised. The Climax and Henderson porphyry molybdenum deposits formed in the zone where the Rio Grande rift and the central Colorado batholith intersect. Bookstrom (1981) and Stein (1982) showed that the younger Mount Emmons (17 Ma), Chicago Basin (10 Ma), and Rico (4 Ma) molybdenum deposits were related to Rio Grande rift-related bimodal volcanism as it progressed outward from the rift axis.

Many studies have investigated the genetic relationship between tectonic processes, igneous centers, and ore-forming hydrothermal systems. They have shown that the CMB formed during processes involving subduction and subsequent rifting; both tectonic regimes produced periods of complex magmatism. Throughout these magmatic processes, ore deposits formed in the CMB.

These data, combined with the results of many authors' studies (especially Tweto and Sims, 1963; Christiansen and Lipman, 1972; Lipman and others, 1972; Steven, 1975; Tweto, 1975; Simmons and Hedge, 1978; Bookstrom, 1981, 1990, 1994; Stein, 1985, 1988; Wallace and Naeser, 1986; Mutschler and others, 1987; Bookstrom and others, 1988; Stein and Crock, 1990; and Wallace, 1990) support the following sequence of events. In the late Mesozoic, the convergence rate of the American plate and Pacific plate increased, resulting in the continued overriding of the intervening Farallon plate and a decrease of the plate's angle of subduction. The effects of this more shallow subduction produced Laramide-style compressional block faulting with basement-cored uplifts and associated deformation as far into the craton as the modern Rocky Mountains. Crustal thickening accompanied the subduction. The subducted plate descended in a northeast direction; within it, several parallel northeast-trending transform faults, being breaks in the slab, probably concentrated volatiles and localized melting of lower crustal Precambrian rocks. Relatively isolated igneous centers developed above these zones during progressive anatexis, and they tended to evolve in composition from monzonite to granodiorite to, locally, alkalic magmas. Magmatic activity progressed from southwest to northeast; associated ore deposits were composed mainly of precious and base metals.

During middle Tertiary time, the subduction rate decreased and the plate angle steepened. Asthenospheric counterflow over the leading edge of the plate occurred; isotherms rose higher into the lower crust, and large volumes of magma were generated. The magma chambers coalesced into two batholiths, one in central Colorado that occupies part of the northeastern trend of the CMB and another beneath the San Juan volcanic field. Progressively more silicic magma was intruded at individual centers. The Rio Grande rift began opening about middle Oligocene time. Silicic igneous rocks and associated major molybdenum deposits were formed by melting lower crustal Precambrian rocks. As the effects of the rifting spread laterally and northward, younger molybdenum-silver-lead deposits formed.

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