Epithermal Gold Deposits—Part II

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Chapter I

Epithermal Gold Deposits—Part II

Geology and Gold Deposits of the Oatman District, Northwestern Arizona

By ED DEWITT, JON P. THORSON, and ROBERT C. SMITH

Geology and Gold Deposits of the Marysville Mining District, Montana

By JAMES W. WHIPPLE

Gold Deposits of the Boulder County Gold District, Colorado

By JAMES A. SAUNDERS

Part I is Chapter H

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CONTENTS

Geology and gold deposits of the Oatman district, northwestern Arizona

Geology and gold deposits of the Marysville mining district, Montana

Gold deposits of the Boulder County gold district, Colorado

FIGURES

TABLES

Epithermal Gold Deposits—Part II

Geology and Gold Deposits of the Oatman District, Northwestern Arizona

By Ed DeWitt, Jon P. Thorson,[1] *and* Robert C. Smith[2]

Abstract

Mines in the Oatman mineralized district, near Oatman in northwestern Arizona, have produced more than 1.98 million ounces of gold from mid-Tertiary, epithermal, silver-poor veins that cut Early Proterozoic granitic plutons and Oligocene(?) to Miocene volcanic rocks and plutons. Early Miocene volcanic and plutonic rocks that are thought to be cogenetic with mineralization are alkali-calcic to mildly alkalic in composition, have elevated initial strontium isotopic compositions suggestive of derivation from lower crustal materials, and resemble shoshonitic rocks of typical Andean arcs. Ore deposition and associated hydrothermal alteration appear to have been temporally related to emplacement of late rhyolitic dikes and plugs probably 19–17 Ma.

Ore-bearing veins strike between N. 75° W. and N. 15° W., dip from 50° NE. to vertical, and contain electrum and trace amounts of pyrite, chalcopyrite, sphalerite, and galena. Gold:silver ratios average 1.7:1. Gangue includes quartz, vari-colored calcite, adularia, chlorite, and minor fluorite. Gold grades are richest in the center of the district. Dilatant zones along faults and highly fractured rocks in the Oatman Andesite contain the greatest amount and highest grade of ore. Gold grades within individual veins are remarkably constant both laterally and vertically, and ore-grade gold is restricted to a vertical dimension that averages 180 meters.

Propylitic alteration near veins took place throughout the district. Presence of adularia and the low-pH assemblage illite-montmorillonite are the best indicators of ore. Primary fluid inclusions in quartz and calcite reflect homogenization temperatures of 205–255 °C, contain salinities less than 1.5 weight percent NaCl, and retain very little CO_2, suggesting that boiling during ore deposition may have been restricted to the center of the district.

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INTRODUCTION

The Oatman mining district, centered near the town of Oatman in the Black Mountains of Arizona, is about 32 km southwest of Kingman, Ariz., and 38 km northeast of Needles, Calif. (fig. I1). In the past the district has been referred to variously as the Gold Road, Vivian, Boundary Cone, and Oatman district. The Union Pass or Katherine district (Keith, Gest, and others, 1983; Keith, Schnabel, and others, 1983) is 20 km northwest of Oatman and contains deposits similar to those in the Oatman district, but it will not figure in this report. The general area of the Oatman district and its surroundings is referred to herein as the Oatman area.

History

Gold was discovered in the Oatman and Union Pass districts in 1863 by army personnel stationed along the Colorado River west of Oatman at Camp Mohave (Schrader, 1909; Ransome, 1923). The first production from the Oatman district was by John Moss from the Moss vein in 1863–1864. After a nonproductive period beginning about 1870, gold was found in the Gold Road vein during 1902–1903. In 1915 the rich ore body of the United Eastern mine on the Tom Reed vein was located, and it produced

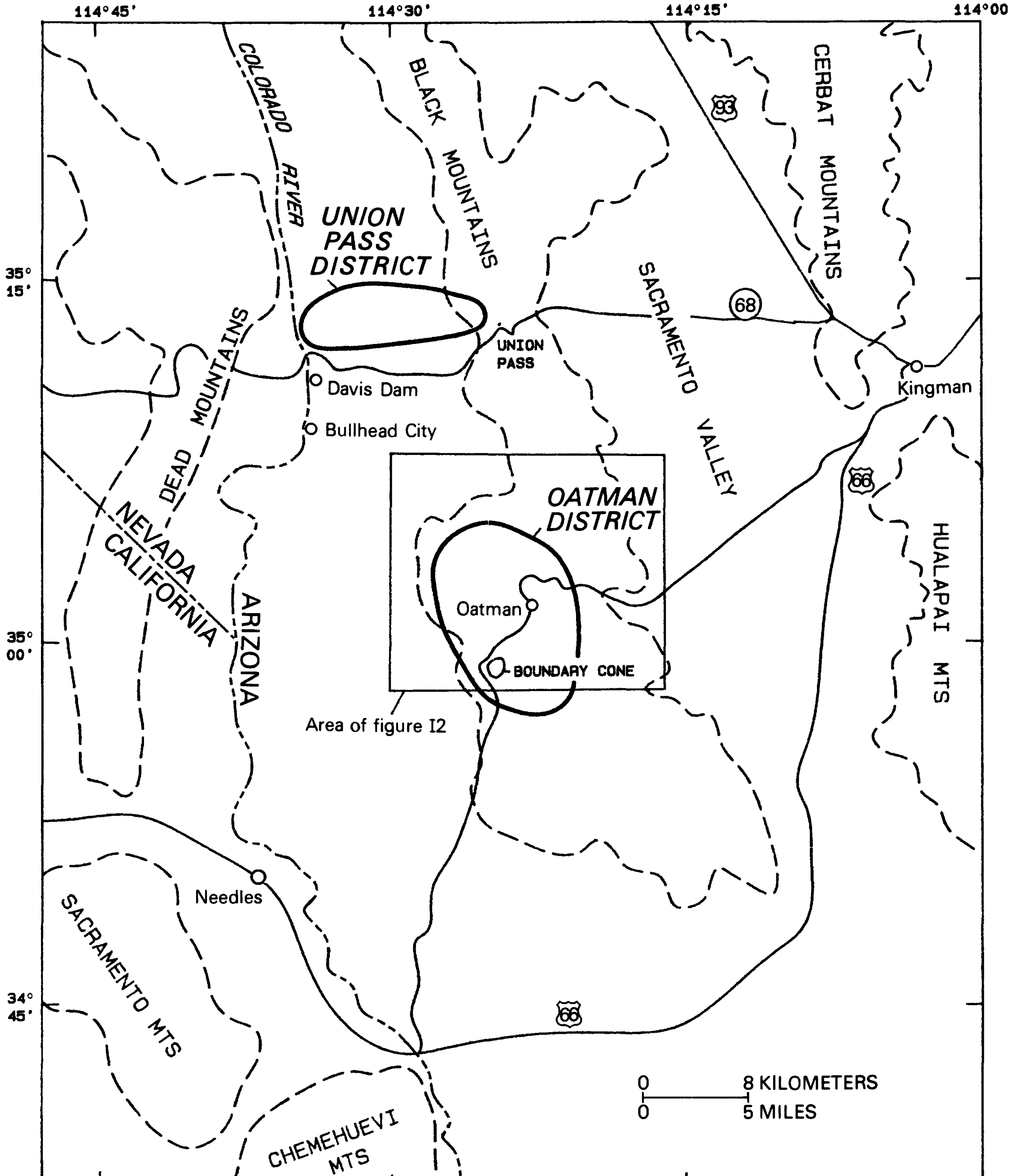


Figure I1. Location map of the Oatman area, northwestern Arizona.

gold ore until 1924 (Clifton and others, 1980). Nearly all production from the Oatman district had ceased by 1943; only sporadic, small-scale leach operations and reprocessing of mine tailings have continued to the present.

Production

Schrader (1909) and Ransome (1923) listed more than 85 mines in the Oatman district. The largest and most famous of these have been the Gold Road, Tom Reed, and United Eastern mines. Total production from the district, based on data of Wilson and others (1967) and unpublished yearly totals, has been estimated by Clifton and others (1980) at 3.8 million tons of ore that yielded 2.2 million troy oz of gold and 0.8 million troy oz of silver. Unpublished data from the Arizona Bureau of Geology and Mineral Technology credit the Oatman district with 3.9 million tons of ore that yielded 1.98 million oz of gold and 1.15 million oz of silver. If production data from the Union Pass district are included with those from the Oatman district, the Oatman area has produced 4.5 million tons of ore containing 2.07 million oz of gold and 1.51 million oz of silver. Only very minor amounts of base metals, chiefly copper, have been recovered from the gold-silver deposits of the Oatman district.

Reserves

Large-scale gold mining ceased in the Oatman area in 1943, due partly to exhaustion of ore and partly to government restrictions on gold mining during World War II. Despite past exploration in the area by numerous companies, no major production has come from the Oatman or Union Pass districts since 1943. However, reserves calculated from drill hole data are 200,000 tons averaging 0.2 oz Au/ton at the United Eastern mine in the Oatman district, and 300,000 tons averaging 0.1 oz Au/ton at the Tyro mine and 20,000 tons averaging 0.2 oz Au/ton at the Frisco mine in the Union Pass district (P.W. Durning, Fischer-Watt Mining Co., and L.H. Knight, Hecla Mining Co., written commun., 1983).

Similar Deposits

The ore deposits of the Oatman area comprise gold-bearing quartz-calcite veins which occupy fault fissures in Tertiary volcanic rocks. The vein mineralogy (Lausen, 1931), temperatures of formation (Clifton and others, 1980; Smith, 1984), and restricted vertical range of the ore bodies suggest that they are epithermal in nature and resemble Tertiary epithermal gold-bearing deposits at Tonopah, Nev.; Guanajuato, Pachuca Real del Monte, and Tayoltita, Mexico; and Cripple Creek and Creede, Colo. Because of their virtual lack of base-metal minerals, extremely low pyrite content, and simple electrum mineralogy, the veins of the Oatman district most closely resemble those at Goldfield and at Jarbidge, Nev. (Buchanan, 1981; Ashley, 1979).

Acknowledgments

This paper was reviewed by L.J. Buchanan and W.P. Durning of Fischer-Watt Mining Co., who contributed considerable unpublished data to the authors, and by L.H. Knight and Mike Winston of Hecla Mining Company. Conoco Minerals Company contributed unpublished whole rock analyses and strontium isotope data. U-Th-Pb analyses were conducted by Loretta Kwak, U.S. Geological Survey, Denver, Colo.; $^{40}Ar/^{39}Ar$ analyses were conducted by Ed DeWitt at U.S. Geological Survey laboratories in Reston, Va. Mineral separates were prepared by Zeke Rivera, Dave Allerton, Greg Cavallo, and Ed DeWitt. We thank R.E. Zartman and J.F. Sutter for making their U-Th-Pb and $^{40}Ar/^{39}Ar$ laboratories, respectively, available for use in this project. Ralph Christian, George Van Trump, Greg Green, Rebecca Stoneman, David Buscher, and Anna Burack Wilson aided with the computer graphics and analyses. Discussions with R.P. Ashley, S.B. Keith, W.A. Rehrig, D.R. Shawe, R.E. Wilcox, and R.T. Wilson greatly improved the content of the report.

GEOLOGIC SETTING

The gold-bearing veins of the Oatman district (fig. I2) are localized in mid-Tertiary volcanic rocks and associated hypabyssal stocks (Ransome, 1923; Lausen, 1931). Most of the volcanic and plutonic rocks are of late Oligocene(?) to middle Miocene age, about 30 to 15 Ma. Stratigraphic descriptions are from Thorson (1971), slightly modified by Clifton and others (1980) and by this study. Chemical data are from Ransome (1923), Wells (1937), Thorson (1971), and Conoco Minerals Company (unpub. data, 1985). A summary of the major element chemistry is presented in table I1.

Rock names used in this report are based on the chemical classification of De la Roche and others (1980) and are listed in table I2. Even though a rock unit may bear a formal name such as the Esperanza Trachyte (Ransome, 1923), the Esperanza will be referred to as the Esperanza Quartz Latite in the text because of its major element chemistry and position on the De la Roche grid (fig. I3).

The volcanic and plutonic rocks at Oatman, with the exception of the youngest basalt flows, appear to be a cogenetic suite characterized by a unifying chemistry. All units are metaluminous (Shand, 1927) except for a few rocks from the Antelope Rhyolite and the Alcyone Formation. Considered together, the units form an alkali-calcic suite with a Peacock (1931) index of SiO_2=55–58. In terms of combined Na_2O+K_2O (fig. I4*A*) the suite straddles the alkalic/subalkalic boundary used by Anderson (1983). All the units except the youngest basalt are high-potassium rocks (Peccerillo and Taylor, 1976), as shown in figure I4*B*, and resemble shoshonites as defined by Morrison (1980). Most of the subalkalic units have Fe:Fe+Mg typical of magnesium-rich suites (Miyashiro, 1974), and most alkalic units have Fe:Fe+Mg typical of iron-rich suites (table I2).

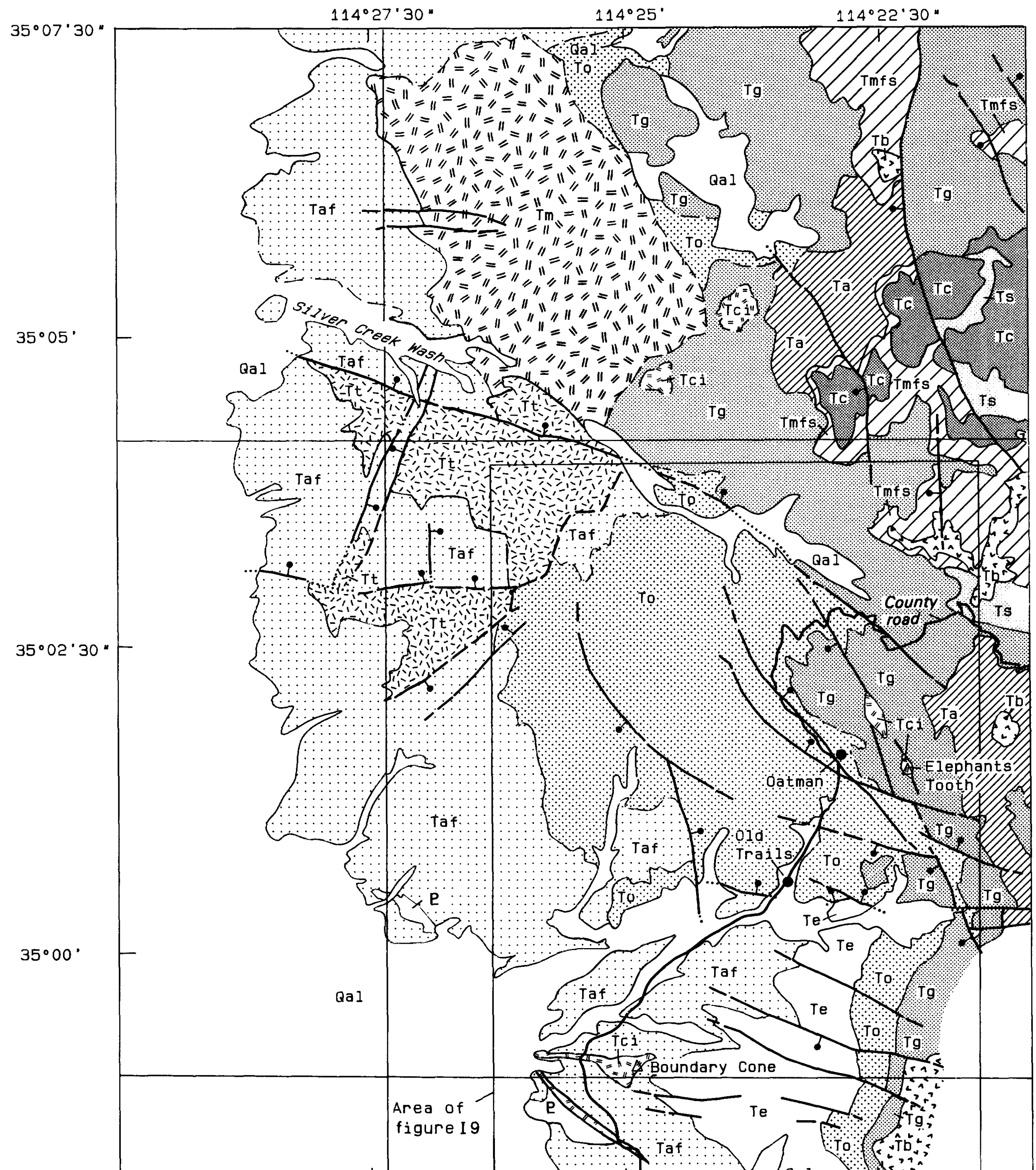
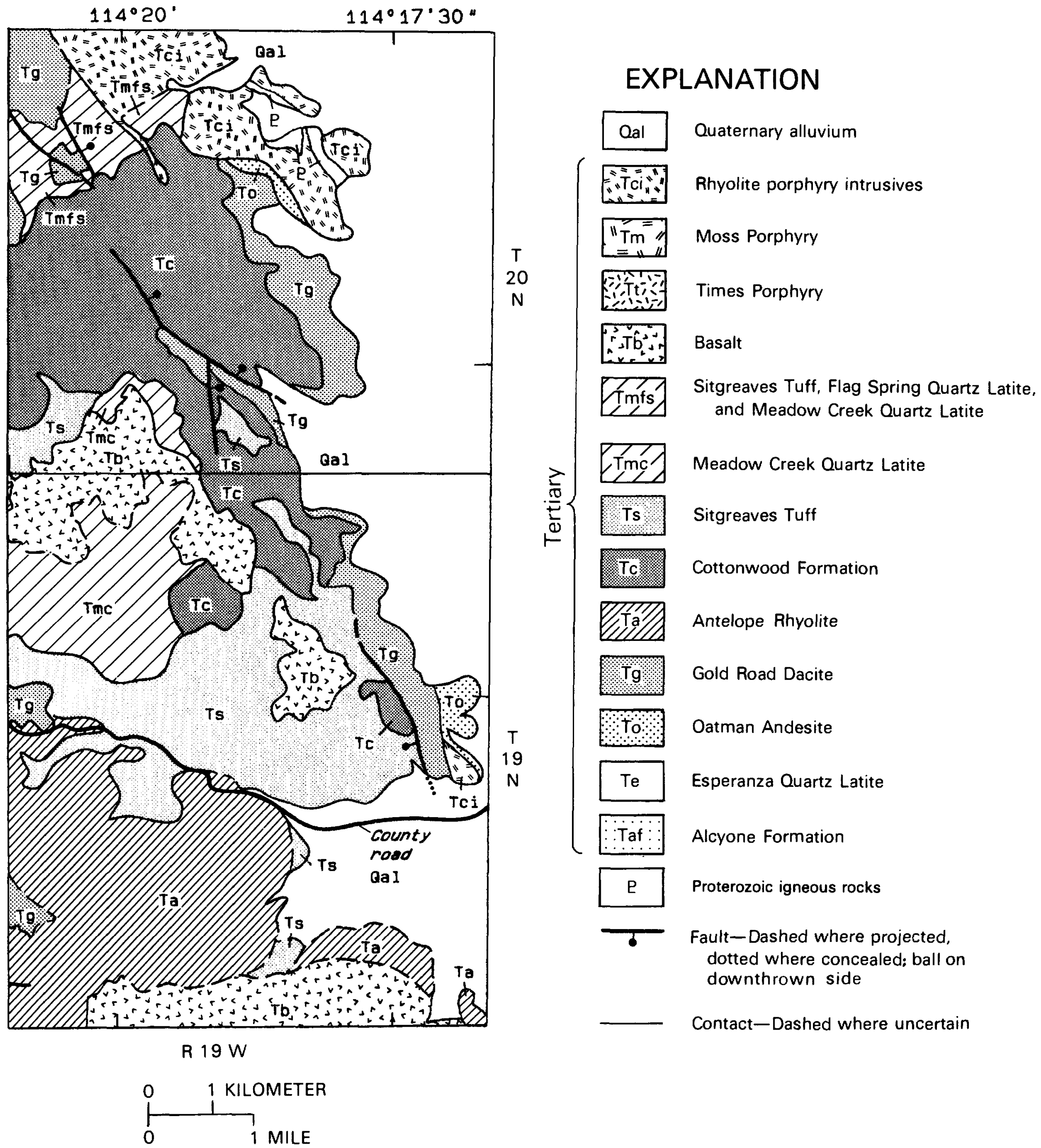


Figure 12 (above and facing page). Geologic map of the Oatman district, Arizona. Compiled from Thorson (1971), Ransome (1923), and Clifton and others (1980). The Sitgreaves Tuff is generally equivalent to the Cottonwood to Antelope rocks.

Stratified Volcanic and Volcaniclastic Rocks

The oldest volcanic rocks of the Oatman area, located south of Boundary Cone, are unnamed basalt flows and basaltic volcaniclastic rocks that unconformably overlie metasedimentary schist and metaplutonic gneiss of Early Proterozoic age and younger coarse-grained granite of the Katherine district of Early and Middle Proterozoic age.



These rocks are included with the Alcyone Formation (fig. I2) because of their limited volume.

The Alcyone Trachyte (Ransome, 1923, p. 13), here referred to as the Alcyone Formation (Thorson, 1971) based on new information on its lithologic content, is a succession of tuffs, flows, sedimentary tuff breccias, welded tuffs, and landslide breccias. It unconformably overlies the unnamed Oligocene(?) basaltic units and is present throughout the western part of the Oatman area. The lower and middle welded tuffs of the Alcyone are iron-rich alkalic quartz trachyte (De la Roche and others, 1980) that has low calcium and high potassium contents, whereas the upper lava flows and plugs are subalkalic quartz latite. The tuffs and flows form distinctly bimodal groups on plots of major element chemistry (figs. I3, I4*A*, and I4*B*) and trace element chemistry (figs. I5*A* and I5*B*). Welded tuffs and flows consist of 65 percent groundmass and 35 percent phenocrysts of sanidine, plagioclase, biotite, and minor pyroxene and quartz. The Alcyone is from 450 to 730 m thick and shows local thickening in an inferred volcanic depression centered about 8 km northwest of Oatman.

A group of three units, the "middle volcanics" of Thorson (1971), unconformably overlies the Alcyone Formation. From bottom to top, these units are the Esperanza

Table 11. Average chemical compositions in percent (Rb, Sr, and Zr in ppm) of Tertiary volcanic and plutonic rocks in the Oatman area

[Data from Ransome (1923), Wells (1937), and Thorson (1971), and from Conoco Minerals Company (unpub. data, 1985); standard deviations of the mean shown in parentheses beneath averages if at least three analyses were available; *n*, number of analyses; leaders (---), no data; 351$^{(2)}$, data available for only two samples]

	Alcyone			Esperanza	Oatman	Gold Road		Antelope		Cottonwood
	#1	#3	#5			lower	upper	flows	intrusives	#1,2,3
n---	(7)	(4)	(7)	(3)	(14)	(12)	(15)	(16)	(8)	(13)
SiO_2	65.17	64.57	61.60	63.75	58.13	60.33	62.87	70.10	69.82	70.73
	(0.76)	(0.90)	(1.46)	(0.53)	(2.77)	(1.92)	(1.08)	(2.69)	(1.38)	(2.25)
TiO_2	0.60	0.62	0.97	0.67	1.11	0.99	0.87	0.41	0.42	0.37
	(0.06)	(0.01)	(0.10)	(0.10)	(0.16)	(0.10)	(0.10)	(0.12)	(0.07)	(0.11)
Al_2O_3	16.27	17.10	16.00	16.26	14.52	15.51	15.59	13.55	14.19	13.64
	(0.49)	(0.30)	(0.53)	(1.41)	(3.87)	(0.56)	(0.71)	(0.74)	(0.45)	(0.77)
FeO_{total}	2.90	2.80	4.89	3.47	5.91	4.93	4.43	2.41	2.36	2.11
	(0.49)	(0.13)	(0.43)	(0.24)	(0.78)	(0.70)	(0.40)	(0.82)	(0.26)	(0.54)
MgO	0.80	0.90	1.92	0.94	3.20	2.72	1.99	0.79	0.76	0.79
	(0.08)	(0.07)	(0.41)	(0.14)	(0.70)	(1.21)	(0.46)	(0.28)	(0.22)	(0.30)
MnO	0.04$^{(5)}$	0.06$^{(2)}$	0.07$^{(2)}$	0.05$^{(2)}$	0.08$^{(10)}$	0.08$^{(9)}$	0.06$^{(10)}$	0.05$^{(7)}$	---	0.05$^{(4)}$
	(0.01)	---	---	---	(0.03)	(0.03)	(0.01)	(0.01)	---	(0.01)
CaO	1.58	1.51	3.99	2.23	6.19	4.89	3.85	2.16	2.03	2.06
	(0.50)	(0.22)	(0.54)	(0.56)	(1.33)	(1.03)	(0.40)	(0.57)	(0.54)	(0.54)
Na_2O	3.99$^{(5)}$	4.13$^{(2)}$	3.69$^{(5)}$	3.83$^{(2)}$	3.14$^{(11)}$	3.33$^{(5)}$	3.61$^{(10)}$	3.08$^{(7)}$	3.07$^{(4)}$	3.40$^{(6)}$
	(0.26)	---	(0.37)	---	(0.43)	(0.32)	(0.24)	(0.45)	(0.35)	(0.44)
K_2O	6.90	6.98	4.36	5.25	3.56	4.05	4.47	5.00	5.06	4.90
	(0.37)	(0.12)	(0.23)	(0.23)	(0.70)	(0.58)	(0.40)	(0.59)	(0.69)	(0.39)
LOI	1.13	1.20	2.70	2.94	3.52$^{(12)}$	2.97	2.02$^{(13)}$	2.03	1.77	1.93
	(0.27)	(0.31)	(1.83)	(1.16)	(1.53)	(0.78)	(0.72)	(1.20)	(1.61)	(1.10)
CO_2	0.45$^{(2)}$	---	0.02$^{(1)}$	1.59$^{(3)}$	---	---	---	---	---	---
	(0.28)	---	---	(0.52)	---	---	---	---	---	---
P_2O_5	0.23	---	---	0.30$^{(1)}$	0.42$^{(3)}$	---	0.27$^{(3)}$	0.28$^{(2)}$	---	0.04$^{(1)}$
	(0.12)	---	---	---	(0.03)	---	(0.01)	---	---	---
Rb	164$^{(2)}$	177$^{(2)}$	94$^{(2)}$	194$^{(1)}$	84$^{(7)}$	85$^{(7)}$	132$^{(8)}$	185$^{(5)}$	---	187$^{(3)}$
	---	---	---	---	(16)	(33)	(17)	(43)	---	(27)
Sr	351$^{(2)}$	368$^{(2)}$	708$^{(2)}$	792$^{(1)}$	1,024$^{(7)}$	728$^{(7)}$	569$^{(8)}$	310$^{(5)}$	---	383$^{(3)}$
	---	---	---	---	(222)	(45)	(41)	(136)	---	(86)
Zr	---	---	---	---	303$^{(2)}$	---	400$^{(2)}$	---	---	---
	---	---	---	---	---	---	---	---	---	---

	Cottonwood		Flag Spring	Meadow Creek	Times Porphyry		Moss Porphyry			Rhyolites
	#4,5	#6			border	core	border	porphyry	main	
n---	(4)	(4)	(6)	(5)	(5)	(6)	(4)	(7)	(17)	(2)
SiO_2	66.49	75.34	66.71	64.91	75.81	73.09	59.43	64.62	65.47	77.80
	(1.49)	(1.57)	(1.59)	(0.69)	(0.52)	(1.96)	(1.54)	(2.40)	(1.72)	---
TiO_2	0.48	0.10	0.46	0.60	0.15	0.32	1.06	0.69	0.70	0.11
	(0.08)	(0.04)	(0.12)	(0.01)	(0.04)	(0.09)	(0.07)	(0.12)	(0.13)	---
Al_2O_3	15.43	12.53	16.25	16.51	11.98	13.39	15.11	15.02	15.05	12.05
	(0.54)	(1.06)	(0.58)	(0.28)	(0.57)	(0.88)	(0.16)	(0.58)	(0.68)	---
FeO_{total}	2.85	0.64	2.56	3.71	0.83	1.55	5.88	3.85	3.64	0.88
	(0.58)	(0.17)	(0.64)	(0.33)	(0.18)	(0.46)	(0.45)	(0.80)	(0.69)	---
MgO	0.96	0.18	0.55	0.79	0.17	0.37	3.20	1.97	1.63	$0.09^{(1)}$
	(0.24)	(0.07)	(0.18)	(0.06)	(0.03)	(0.27)	(0.33)	(0.71)	(0.41)	---
MnO	$0.06^{(1)}$	$0.06^{(1)}$	$0.06^{(2)}$	$0.07^{(1)}$	$0.03^{(2)}$	$0.06^{(3)}$	---	$0.08^{(2)}$	$0.06^{(10)}$	$0.04^{(1)}$
	---	---	---	---	---	(0.01)	---	---	(0.01)	---
CaO	2.83	1.01	2.04	3.13	0.56	0.87	4.12	3.21	2.95	0.39
	(0.31)	(0.43)	(0.39)	(0.12)	(0.09)	(0.36)	(0.50)	(0.75)	(0.60)	---
Na_2O	$3.63^{(2)}$	$3.65^{(2)}$	$4.48^{(4)}$	$4.16^{(3)}$	$3.59^{(2)}$	$4.26^{(3)}$	$3.59^{(3)}$	$3.49^{(5)}$	$3.85^{(11)}$	$0.37^{(1)}$
	---	---	(0.18)	(0.16)	---	(0.32)	(0.24)	(0.29)	(0.18)	---
K_2O	4.70	5.35	5.04	4.79	5.31	5.50	4.34	4.57	4.63	8.77
	(0.09)	(0.29)	(0.32)	(0.11)	(0.05)	(0.46)	(0.47)	(0.77)	(0.40)	---
LOI	2.48	1.61	0.94	0.59	0.74	0.72	1.99	2.39	1.68	$0.70^{(1)}$
	(1.07)	(1.52)	(0.11)	(0.23)	(0.36)	(0.65)	(0.97)	(0.78)	(0.55)	---
CO_2	---	---	---	---	---	---	---	---	$0.07^{(1)}$	$0.04^{(1)}$
	---	---	---	---	---	---	---	---	---	---
P_2O_5	---	---	$0.17^{(1)}$	$0.24^{(1)}$	---	---	---	---	$0.30^{(2)}$	$0.02^{(1)}$
	---	---	---	---	---	---	---	---	---	---
Rb	$127^{(1)}$	---	$124^{(1)}$	$118^{(1)}$	$308^{(2)}$	$229^{(2)}$	---	$165^{(2)}$	$141^{(11)}$	---
	---	---	---	---	---	---	---	---	26	---
Sr	$1,113^{(1)}$	---	$901^{(1)}$	$1,625^{(1)}$	---	$178^{(1)}$	---	$338^{(2)}$	$556^{(11)}$	---
	---	---	---	---	---	---	---	---	---	---
Zr	---	---	---	---	---	---	---	---	81	---
	---	---	---	---	---	---	---	---	---	---

Table I2. Chemical and modal classifications and range of SiO_2 content for Tertiary volcanic and plutonic rocks of the Oatman area

[Rock unit names from Thorson (1971); FE, iron-rich; MG, magnesium-rich; SUB, subalkalic; ALK, alkalic]

Rock unit	Chemical classification (De la Roche and others, 1980)	Modal classification (Streckeisen, 1973)	Fe:Fe+Mg classification (Miyashiro, 1974)	Alkali classification (Anderson, 1983)	SiO_2 range[1]
Times Porphyry					
core	granite	syenogranite	MG-FE	SUB	71–76
border	alkali granite	syenogranite	MG-FE	SUB	75–77
Moss Porphyry					
main phase	tonalite-granodiorite	monzogranite	MG	SUB/ALK	62–67
border	monzodiorite		MG	SUB/ALK	58–62
Flag Spring Quartz Latite	quartz latite		FE	ALK	65–68
Meadow Creek Quartz Latite	quartz latite		FE	ALK/SUB	64–65
Cottonwood Formation	rhyolite		MG	SUB	64–77
Antelope Rhyolite	rhyodacite-rhyolite		MG	SUB	65–75
Gold Road Dacite					
upper	dacite		MG	SUB/ALK	62–65
lower	latitic andesite-dacite		MG	SUB/ALK	58–63
Oatman Andesite	latitic andesite		MG	SUB	56–63
Esperanza Quartz Latite	quartz latite		FE-MG	ALK	63–64
Alcyone Formation					
#5, quartz latite	quartz latite		MG-FE	SUB/ALK	60–64
#1, 3, trachyte	quartz trachyte		FE	ALK	64–66

[1]Data uncorrected for water content.

Trachyte, referred to here as the Esperanza Quartz Latite (Ransome, 1923, p. 14), Oatman Andesite (Thorson, 1971; Ransome, 1923, p. 14; Lausen, 1931), and Gold Road Latite (Ransome, 1923, p. 15), referred to here as Gold Road Dacite. The Esperanza Quartz Latite is a lava flow, or flows, of alkalic quartz latite that contains an average of 10 percent phenocrysts, predominantly plagioclase and biotite. The Esperanza is found only to the south of Oatman, from near the ghost town of Old Trails to south of Boundary Cone (fig. I2), and ranges in thickness from 60 to 300 m.

The Oatman Andesite is perhaps the best known rock unit in the area, as it hosts many of the gold-bearing veins of the district. The Oatman ranges in composition from dacite to andesitic basalt (fig. I3), but averages in the subalkalic latitic andesite range (table I2). The unit is composed of flows, tuffs, and flow breccias. A typical rock consists of 55 percent groundmass and 45 percent phenocrysts of plagioclase (An_{44-47}), orthopyroxene, and clinopyroxene. The Oatman overlies the Alcyone north of Old Trails, and thins markedly to the south away from the Tom Reed and Gold Road mines (fig. I2), at which it is estimated to be 300 m thick (Clifton and others, 1980).

The Gold Road Dacite conformably overlies the Oatman Andesite and is composed of lithic ash beds, vent breccias, and flows. Most of the productive mines not in the Oatman Andesite are in the Gold Road Dacite. The Gold Road ranges from subalkalic to alkalic dacite. The lower part contains 30 percent phenocrysts of plagioclase (An_{40-47}), clinopyroxene, orthopyroxene, and minor amounts of quartz, biotite, and potassium feldspar; the upper part averages 40 percent of the same phenocrysts, but no quartz is present. The Gold Road attains a maximum thickness of 240 m, although Thorson (1971) suggested that it may have been as much as 900 m thick before its erosion and the subsequent deposition of the upper volcanics.

Considered as a comagmatic group, the middle volcanics have a Peacock index of 57 and are magnesium rich (table I2). They have anomalously high strontium and rubidium concentrations as compared to high-potassium, calc-alkalic andesites and dacites (Gill, 1981).

The upper volcanics of Thorson (1971) unconformably overlie the middle volcanics and contain vein and fault-vein systems similar to the middle volcanics, but do not host any gold deposits in the Oatman area. From bottom to top, the upper volcanics consist of the dominantly volcanic Antelope Rhyolite, Cottonwood Rhyolite (Ransome, 1923, p. 16) referred to here as the Cottonwood Formation (Thorson, 1971), Flag Spring Trachyte

(Ransome, 1923, p. 16), referred to here as Flag Spring Quartz Latite, and Meadow Creek Trachyte (Ransome, 1923, p. 16), referred to here as Meadow Creek Quartz Latite, and the dominantly volcaniclastic Sitgreaves Tuff (Ransome, 1923, p. 16), which is temporally equivalent to all the upper volcanic units.

The Antelope Rhyolite and Cottonwood Formation are flows and domes of subalkalic rhyodacite to rhyolite, and rhyolite to alkali rhyolite, respectively. Both the Antelope and Cottonwood contain approximately 70 percent groundmass and 30 percent phenocrysts, the phenocrysts being dominantly plagioclase (An_{29-34} in the Antelope), biotite, potassium feldspar, quartz, hornblende, and minor clinopyroxene and orthopyroxene. Both formations have high rubidium contents; the Cottonwood has anomalously high strontium contents (fig. I5).

The Flag Spring and Meadow Creek Quartz Latites are iron-rich, alkalic to subalkalic quartz latite flows, agglomerates, and flow breccias that compositionally resemble the Esperanza Quartz Latite (figs. I3, I4*A* and *B*). The Flag Spring and Meadow Creek both contain 15–25 percent phenocrysts of plagioclase, biotite, and minor hornblende. Both units have very high strontium contents and appear to be transitional in chemistry between the middle volcanics and the Antelope and Cottonwood.

The Sitgreaves Tuff is one of the few dominantly volcaniclastic units in the area. It contains much conglomerate and air-fall tuff, and many lithic fragments from the upper volcanics.

The upper volcanics are unconformably overlain by flat-lying to very gently east dipping basalt flows and interbedded white conglomerate and rhyolitic ash. The entire sequence is as thick as 300 m. Phenocrysts in the basalt are plagioclase, olivine, and clinopyroxene. The basalt and rhyolite belong to a low-potassium suite that is probably younger and unrelated to the underlying high-potassium suite.

Regional Correlations

Thorson (1971) correlated the middle and pre-middle volcanic rocks in the Oatman area to the Patsy Mine Volcanics (Longwell, 1963) in the Eldorado Mountains of Nevada, 85 km northwest of Oatman. The upper volcanics were correlated to the Golden Door Volcanics of Longwell (1963)—a term that has since been abandoned in favor of Patsy Mine Volcanics—in the Eldorado Mountains, and the capping olivine basalt was correlated to the Fortification Basalt Member of the Muddy Creek Formation near Lake Mead (Thorson, 1971). Anderson (1978) slightly modified the correlations and suggested that the middle and pre-middle volcanic rocks in the Oatman area may be temporally equivalent to the lower part of the Patsy Mine Volcanics, and that the upper volcanics were temporal equivalents of the middle part of the Patsy Mine Volcanics. Anderson and others (1972) and Anderson (1978) suggested that the two areas contain no truly correlative rock units, inasmuch as the volcanic suites in the two areas, although chronologically and chemically similar, may have evolved separately. Tertiary volcanic rocks of similar chemistry were noted by Otton (1982) in the Date Creek basin, 130 km southeast of Oatman.

Intrusive Rocks

Two small stocks and a series of dikes intrude the volcanic rocks in the Oatman area. The Moss Porphyry (Ransome, 1923, p. 12) is a north-northwest-elongate stock, 3×6 km, that intrudes the Alcyone Formation, Gold Road Dacite, and Oatman Andesite north of Silver Creek (fig. I2). The Times Porphyry (Ransome, 1923, p. 12) is a roughly triangular shaped laccolith that intrudes the Alcyone and is in fault contact with the Oatman south of Silver Creek and northwest of Oatman. Just north of Silver Creek, fine-grained mafic dikes of the Moss intrude the Times Porphyry (fig. I6). Rhyolite porphyry dikes and small plugs intrude volcanic units as young as the upper flows in the Cottonwood; in the Oatman area they are localized along the same fractures as the northwest-trending gold-bearing veins and fault-veins. Boundary Cone and Elephants Tooth (fig. I2), two prominent landmarks in the Oatman area, are volcanic necks composed of rhyolite porphyry.

The Times Porphyry is a reversely zoned granophyric laccolith having a highly siliceous border and a less siliceous core. Both border and core are subalkalic granite and alkali granite that have a similar mineralogy of potassium feldspar, quartz, plagioclase (An_{21}), biotite, and minor hornblende. Modal averages indicate that the Times is a syenogranite (fig. I2). The Times most closely resembles alkali rhyolite of the Cottonwood in both major and minor element chemistry.

The rhyolite and rhyolite porphyry dikes, sills, and necks such as Boundary Cone and Elephants Tooth have compositions similar to the Times Porphyry, but with extremely high K_2O contents (7–9 percent). This K_2O enrichment is probably the result of hydrothermal alteration associated with quartz-calcite-adularia veins that parallel the rhyolite bodies and locally cut them.

The Moss Porphyry is a concentrically zoned stock with an outer monzodiorite border, an inner porphyritic tonalite to quartz monzonite margin, and a central tonalite-granodiorite core. The modal average of the core phase is monzogranite (Streckeisen's terminology, 1973; table I2). Both porphyritic margin and core have the same mineralogy and are composed of plagioclase (An_{29-32} and An_{40-50} respectively), potassium feldspar, quartz, biotite, and minor amounts of actinolitic hornblende, clinopyroxene, and orthopyroxene. The Moss Porphyry is subalkalic to slightly alkalic, and in terms of Fe:Fe+Mg is magnesium rich. By virtue of its major element composition, the Moss most closely resembles the Gold Road Dacite; its rubidium and

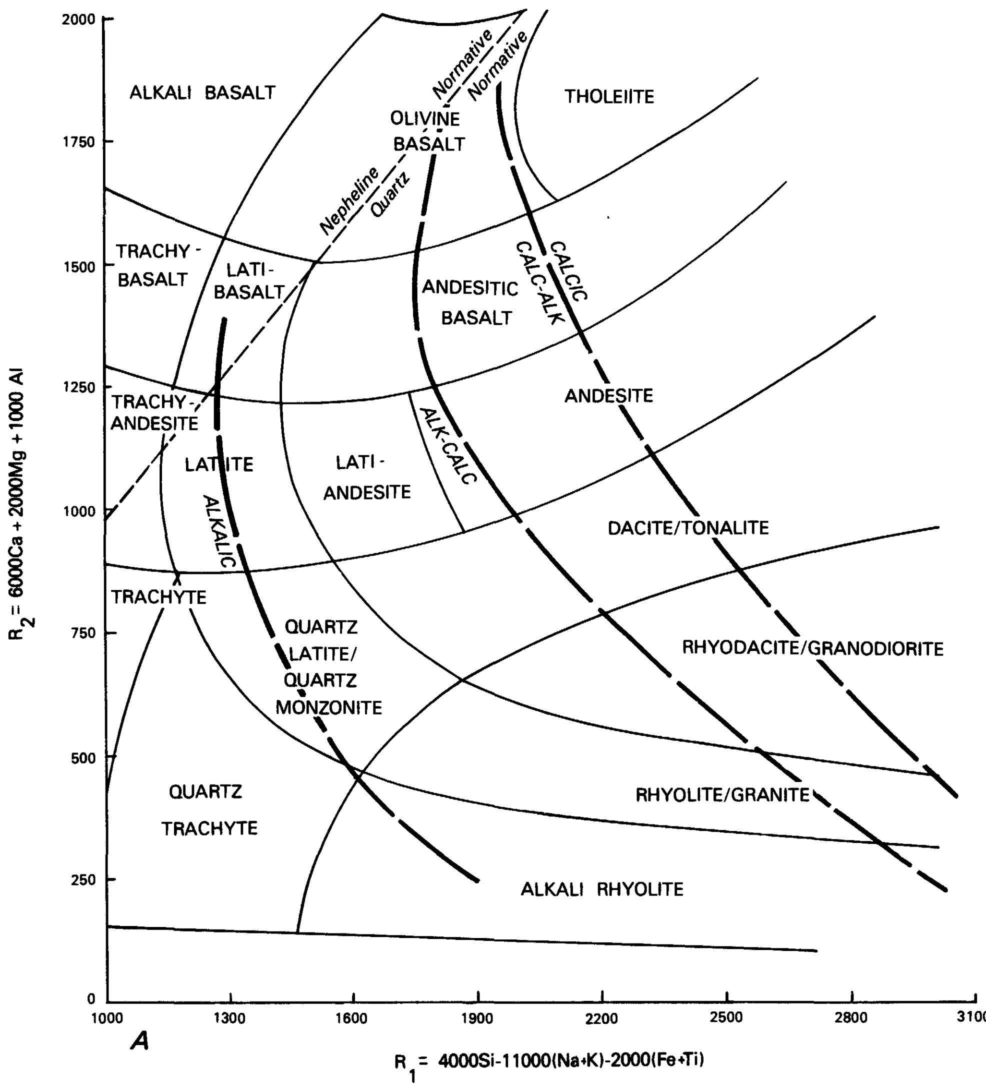
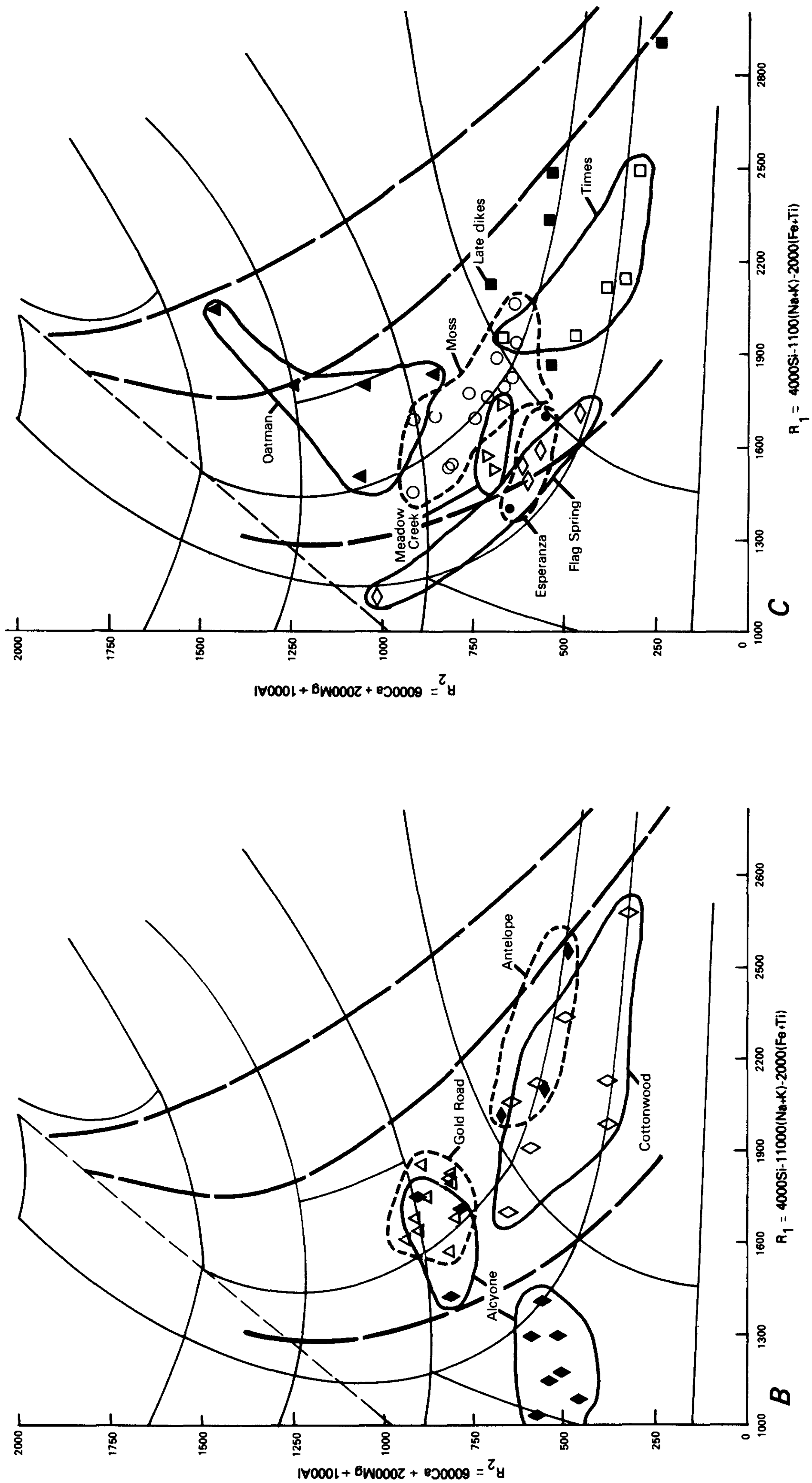


Figure 13. R_1–R_2 rock classification diagrams (De la Roche and others, 1980) applied to volcanic and plutonic rocks of the Oatman area. *A*, R_1–R_2 rock classification diagram. *B*, Rocks of the Oatman area: Alcyone Formation (vertical filled diamond), Gold Road Dacite (open triangle), Antelope Rhyolite (horizontal filled diamond), and Cottonwood Formation (vertical open diamond). *C*, Rocks of the Oatman area: Esperanza Quartz Latite (filled circle), Flag Spring Quartz Latite (horizontal open diamond), Meadow Creek Quartz Latite (inverted open triangle), Oatman Andesite (filled triangle), Moss Porphyry (open circle), Times Porphyry (open square), and late dikes and rhyolite plugs (filled square).


B
C
R_1 = 4000Si-11000(Na+K)-2000(Fe+Ti)
R_1 = 4000Si-1100(Na+K)-2000(Fe+Ti)
R_2 = 6000Ca + 2000Mg + 1000Al
1000
1300
1600
1900
2200
2500
2800
0
250
500
750
1000
1250
1500
1750
2000
Alcyone
Gold Road
Antelope
Cottonwood
Oatman
Moss
Late dikes
Times
Meadow Creek
Esperanza
Flag Spring

strontium contents are intermediate between the middle volcanics and part of the upper volcanics.

U-Th-Pb and $^{40}Ar/^{39}Ar$ Ages of the Stratified and Intrusive Units

Conventional K-Ar dates (Thorson, 1971) for two units in the volcanic sequence and the Moss and Times Porphyries (table I3) have been recalculated using the decay constants recommended by Steiger and Jaeger (1977). Biotite from the Gold Road Dacite yields a date of 18.6±0.9 Ma, and biotite from the Antelope dates at 19.2±0.9 Ma. Actinolitic hornblende from the Times has a K-Ar date of 23.1±1.8 Ma, and biotite from the Moss has a date of 10.7±0.5 Ma.

The dates from the Gold Road and Antelope overlap within analytical uncertainty and indicate that the volcanic units beneath the Antelope are older than about 19 Ma. The 10.7 Ma biotite date from the Moss Porphyry should be interpreted only as a minimum age for the Moss, as the retention temperature of argon in biotite (≈225 °C) is much lower than the emplacement temperature of the pluton.

In order to more precisely determine the age of the volcanic and plutonic rocks, zircons from the Times and Moss Porphyries were dated by the U-Th-Pb method (table I4) and actinolitic hornblende from the Moss was analyzed by the $^{40}Ar/^{39}Ar$ method (table I5). Analytical techniques are similar to those in DeWitt and others (1984). Three nonparamagnetic zircon fractions from the Moss have discordant dates and define a discordia (fig. I7) having a lower intercept of 18.5±2.5 Ma and an upper intercept of 1,675 ± 42 Ma (York, Model 1 solution; uncertainties are 95 percent confidence limits). The analyzed zircons contain minute inclusions of dark, rounded zircons of presumed Early Proterozoic age. The discordia is thus interpreted as a mixing line between inherited Early Proterozoic zircon and new early Miocene zircon that crystallized during emplacement of the Moss Porphyry. The 18.5±2.5 Ma crystallization age of the Moss is further substantiated by the $^{208}Pb/^{232}Th$ date of 20.9 Ma for the –400 mesh size fraction. Zircon from this size fraction is thorium rich (U:Th ratio about 0.5) as compared to most zircon (U:Th about 2–4). Therefore the young thorogenic lead overwhelms the inherited Early Proterozoic thorogenic lead and the Th-Pb date approaches the lower intercept age more rapidly than do the U-Pb dates.

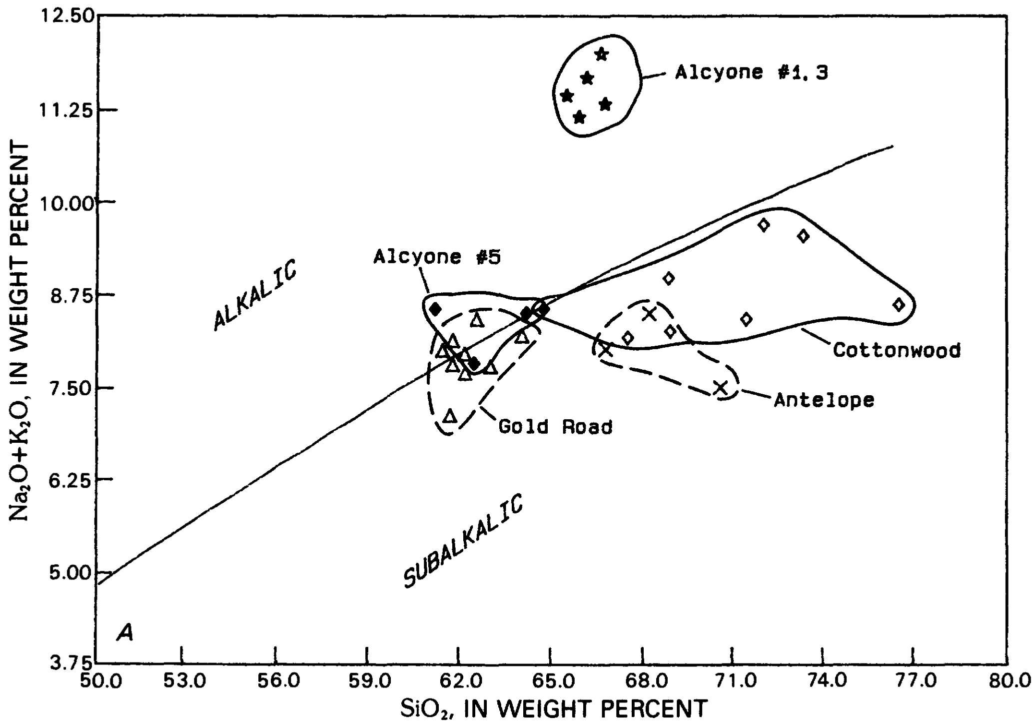
The finest grained zircons available from the Times Porphyry have dates much more discordant than those from the Moss Porphyry. If the 1,675 Ma upper intercept date of the Moss is used and a discordia is projected through the zircon from the Times, the lower intercept is 18.5 Ma. If the data for the Times and Moss Porphyries are combined and regressed as one suite of zircon, the lower intercept obtained is 18.5±0.5 Ma (fig. I7).

Actinolitic hornblende from the Times has a U-shaped $^{40}Ar/^{39}Ar$ spectrum that is probably the result of excess argon present in two phases other than hornblende (fig. I8). The mineral separate from which Thorson (1971) obtained the K-Ar date of 23.1 Ma was used for $^{40}Ar/^{39}Ar$ dating; it contained substantial feldspar adhering to the hornblende and very fine grained magnetite dispersed within the amphibole. The sample was reground to a finer mesh size and separated, but some of the feldspar and much of the magnetite could not be eliminated. Consequently, low-temperature steps between 950 °C and 1,150 °C have K:Ca ratios greater than 0.1, indicating the presence of potassium-rich feldspar. These temperature fractions or steps also have dates older than 19 Ma and suggest that adhering feldspar in the sample contains excess argon. High-temperature steps above 1,275 °C (above the melting temperature of most hornblende) do not show anomalous K:Ca ratios (magnetite contains no potassium or calcium), but do indicate dates older than 20 Ma, the oldest one being 31 Ma. We believe that magnetite, which is degassing at these temperatures, also contains excess argon. Consequently, hornblende as such, as indicated by the constant K:Ca ratio of about 0.08, is present only in the 1,200 and 1,275 °C fractions. These fractions contain 49 percent of the gas and indicate a weighted-average age of 18.83±0.22 Ma (2σ uncertainty), which we interpret to be the crystallization age of the shallowly emplaced Times Porphyry.

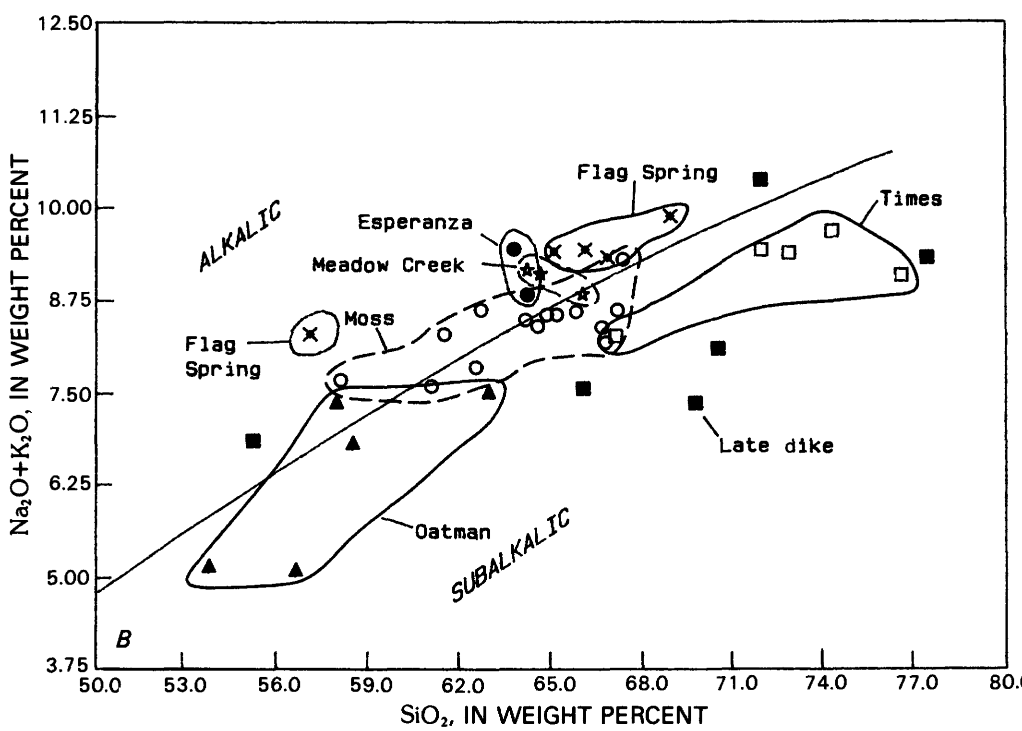
Eruption of the Antelope Rhyolite and volcanic units as old as the Alcyone Formation probably took place between 23 and 19 Ma, as determined from our isotopic investigations and the ages of volcanic rocks in surrounding mountain ranges. Field relations indicate that the Times is older than the Moss Porphyry, but both appear to have been emplaced between 19 and 18 Ma.

Both the Moss Porphyry and the Oatman Andesite have high initial ratios ($^{87}Sr/^{86}Sr_i$) that average 0.7106 (table I3). These ratios suggest a crustal contaminant in the

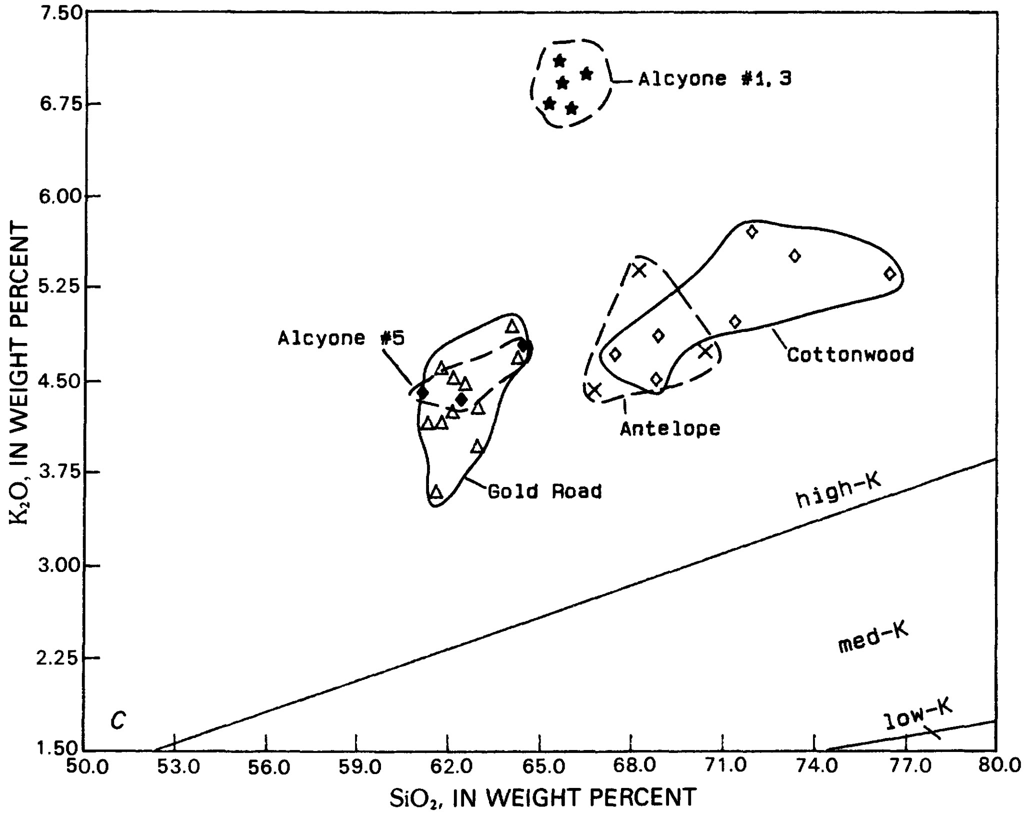
Figure I4 (following pages). (Na_2O+K_2O) vs. SiO_2 and K_2O vs. SiO_2 plots of volcanic and plutonic rocks of the Oatman area. Plotted points represent raw data, uncorrected for water content or loss on ignition. Alkalic-subalkalic field boundary in *A* and *B* from Anderson (1983); high-potassium field boundary in *C* and *D* from Peccerillo and Taylor (1976). *A*, Plot for Alcyone Formation, Gold Road Dacite, Antelope Rhyolite, and Cottonwood Formation. *B*, Plot for Esperanza Quartz Latite, Flag Spring Quartz Latite, Meadow Creek Quartz Latite, Oatman Andesite, Moss Porphyry, Times Porphyry, and late dikes and rhyolite plugs. *C*, Plot for Alcyone Formation, Gold Road Dacite, Antelope Rhyolite, and Cottonwood Formation. *D*, Plot for Esperanza Quartz Latite, Flag Spring Quartz Latite, Meadow Creek Quartz Latite, Oatman Andesite, Moss Porphyry, Times Porphyry, and late dikes and rhyolite plugs.



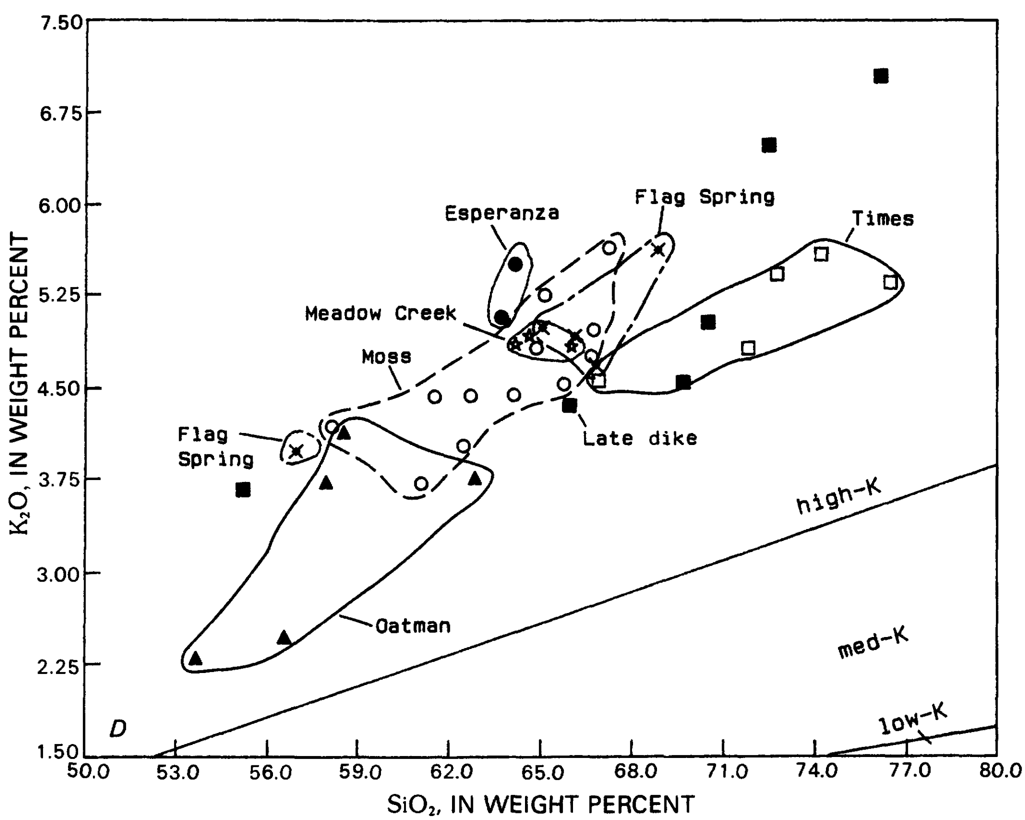
12.50
11.25
10.00
8.75
7.50
6.25
5.00
3.75
50.0
53.0
56.0
59.0
62.0
65.0
68.0
71.0
74.0
77.0
80.0
Na_2O+K_2O, IN WEIGHT PERCENT
SiO_2, IN WEIGHT PERCENT
Alcyone #1, 3
Alcyone #5
ALKALIC
SUBALKALIC
Cottonwood
Antelope
Gold Road
A



12.50
11.25
10.00
8.75
7.50
6.25
5.00
3.75
50.0
53.0
56.0
59.0
62.0
65.0
68.0
71.0
74.0
77.0
80.0
Na_2O+K_2O, IN WEIGHT PERCENT
SiO_2, IN WEIGHT PERCENT
Flag Spring
Times
Esperanza
Meadow Creek
ALKALIC
Moss
Flag Spring
Late dike
Oatman
SUBALKALIC
B



7.50
6.75
6.00
5.25
4.50
3.75
3.00
2.25
1.50
K₂O, IN WEIGHT PERCENT
Alcyone #1, 3
Alcyone #5
Cottonwood
Antelope
Gold Road
high-K
med-K
low-K
C
50.0
53.0
56.0
59.0
62.0
65.0
68.0
71.0
74.0
77.0
80.0
SiO₂, IN WEIGHT PERCENT



7.50
6.75
6.00
5.25
4.50
3.75
3.00
2.25
1.50
K₂O, IN WEIGHT PERCENT
Esperanza
Flag Spring
Times
Meadow Creek
Moss
Flag Spring
Late dike
Oatman
high-K
med-K
low-K
D
50.0
53.0
56.0
59.0
62.0
65.0
68.0
71.0
74.0
77.0
80.0
SiO₂, IN WEIGHT PERCENT

magmas, or derivation of the magmas from Proterozoic crustal material. This contamination or derivation from a source region in the crust is consistent with the pattern of U-Th-Pb zircon inheritance and the shoshonitic geochemistry of the volcanic and plutonic rocks.

Major and minor element chemistry, field relations, and U-Th-Pb and $^{40}Ar/^{39}Ar$ geochronology suggest four major volcanic episodes, as follows: (1) eruption of the subalkalic to alkalic lavas of the Alcyone Formation in a volcanic depression; (2) eruption of the alkalic to subalkalic lavas of the Esperanza, Oatman, and Gold Road; (3) eruption of the subalkalic lavas of the Antelope and Cottonwood followed by emplacement of rhyolite dikes, plugs, and necks; (4) late covering of all older units by olivine basalt and local rhyolite tuff units.

Though spatially associated with rocks of the third episode, the Meadow Creek and Flag Spring Quartz Latites have chemical affinities to the older Esperanza Quartz Latite and are interpreted as the last activity of the second episode. Emplacement of the Times and Moss Porphyries is temporally coincident with volcanic episode 3, but the porphyries appear to be chemically similar to rocks of episodes 3 and 2. Ore deposition appears to have been a late event associated with the third episode, and especially with the emplacement of rhyolite dikes and plugs.

Regional Structure

In general, the oldest Tertiary volcanic rocks in the Black Mountains are exposed west of Oatman and successively younger rocks are exposed to the east. However, the Oatman Andesite and Gold Road Dacite may be exposed on the far east side of the Black Mountains (fig. I2), indicating a synclinal structure paralleling the range crest. All volcanic units have a regional N. 20° W. strike; older units dip 20°–35° E., whereas the youngest units are virtually flat lying. Emplacement of the Times Porphyry has locally domed the Alcyone Formation. Northwest- to north-northwest-trending faults with moderate displacement cut the volcanic units. These faults are closely spaced and numerous in the Oatman area where they contain the gold-bearing vein deposits. A caldera related to the Alcyone volcanism has been proposed by Thorson (1971), but the vein deposits do not appear to be spatially or temporally related to it. Radially and concentrically oriented fracture sets in the Oatman area were noted by Clifton and others (1980); the vein deposits are restricted to the radial set.

ORE DEPOSITS

Structure

The gold-bearing ore bodies in the Oatman district are localized along northwest-trending veins, faults, and combinations of the two (fig. I9). The ore bodies are located in dilatant zones of the vein-fault system that have formed by minor lateral slip along gently curving fault planes (Clifton and others, 1980). The deposits vary from fissure quartz veins with definite walls, through quartz-calcite stringer zones, and faulted and brecciated quartz veins, to gouge zones with only minor quartz-calcite vein filling. Veins in the Gold Road Dacite generally are more distinct, less sheared, and thinner than those in the Oatman Andesite, which commonly are stockworks of veins and country rock. The strikes of the veins and faults range from N. 75° W. to N. 15° W., and the dips range from 50° NE. to vertical, although dip reversals to the southwest are noted on the northwest ends of many veins. Most of the large mines are within a 10×6 km area approximately centered about Oatman, but gold-bearing veins are noted from the Moss mine in the north to south of Boundary Cone, a distance of 19 km (fig. I2). The vein and fault systems cut all the volcanic and plutonic units except those of the youngest basalt, but the majority of large mines are located in the Oatman and Gold Road units.

Deposits in two major structures, the Tom Reed vein and the Gold Road vein, have produced about 90 percent of the gold from the Oatman district. Only two ore bodies were exposed at the surface, one on the Gold Road vein, and one on the Tom Reed vein, but at least a dozen or more major ore bodies were discovered 15–150 m below the surface (Clifton and others, 1980). The Tom Reed vein occupies the Tom Reed fault, which has 120 m of normal displacement within the Oatman Andesite (Ransome, 1923). The vein extends for at least 4.5 km, but major production was from a 3.5-km-long segment centered near Oatman. This segment contained four rather continuously mineralized sections, each separated by barren sections along the vein. From north to south, the mineralized parts were 180 m, 730 m, 570 m, and 240 m long, indicating that half of the 3.5-km-long productive segment was mineralized. Ore bodies within these mineralized parts averaged 130 m along strike, but ranged from 60 to 570 m. The ore bodies varied from 1 to 14 m in width and averaged about 4.5 m. The mined vertical interval ranged from 45 to 390 m and averaged 175 m.

The Gold Road fault is traceable for about 2.9 km, and has a maximum normal displacement of 90–120 m at its northwest end (Lausen, 1931). The fault is within Gold Road Dacite at the surface, but juxtaposes Oatman Andesite and Gold Road Dacite in the subsurface; the fault trends northwest and dips 80°–85° NE. The mineralized part of the Gold Road vein was at least 2 km long, and the ore-grade segment was nearly continuous for a distance of 1.6 km. Ore bodies within the Gold Road Dacite averaged 1–2 m wide, but those in the Oatman Andesite widened to nearly 7 m. Most of the ore bodies were exposed at the surface and extended to less than 370 m depth; their average vertical

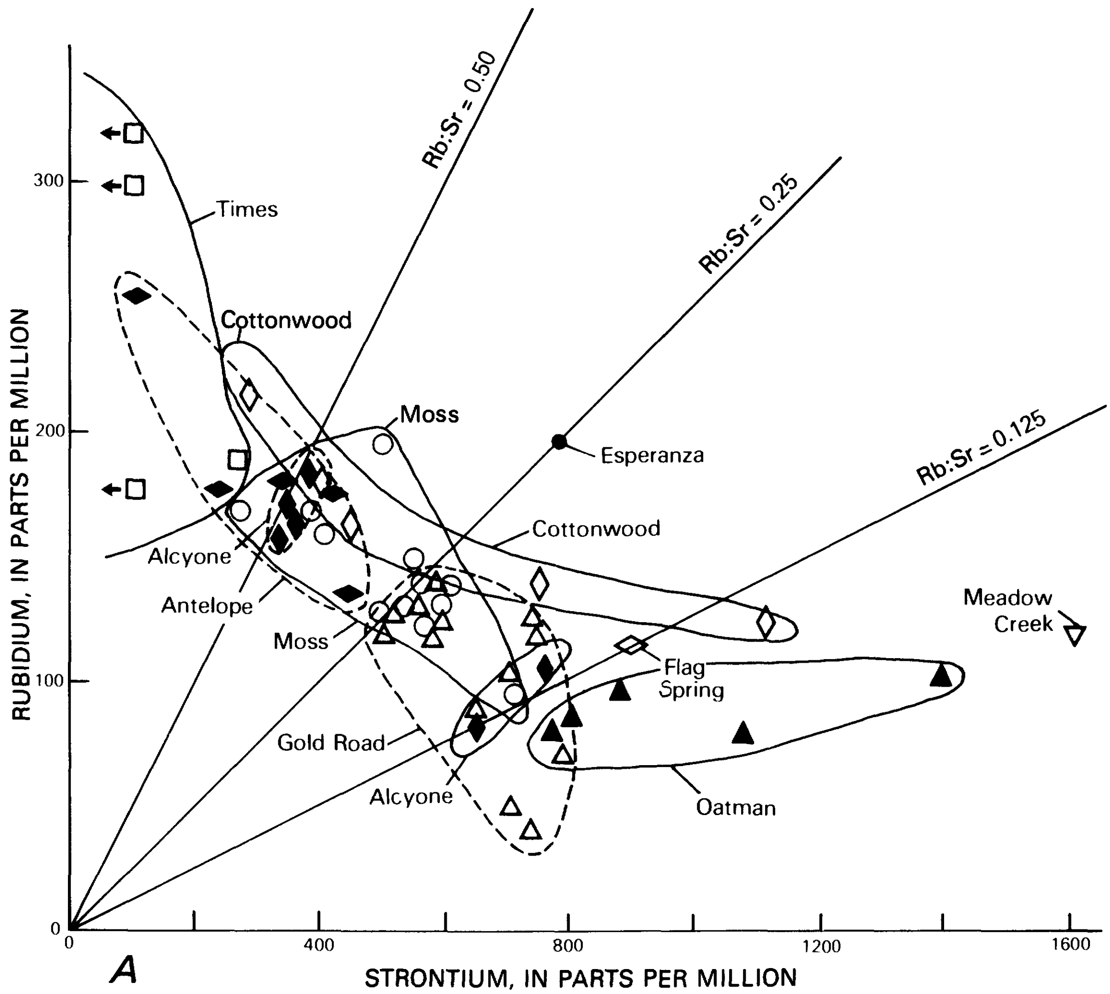


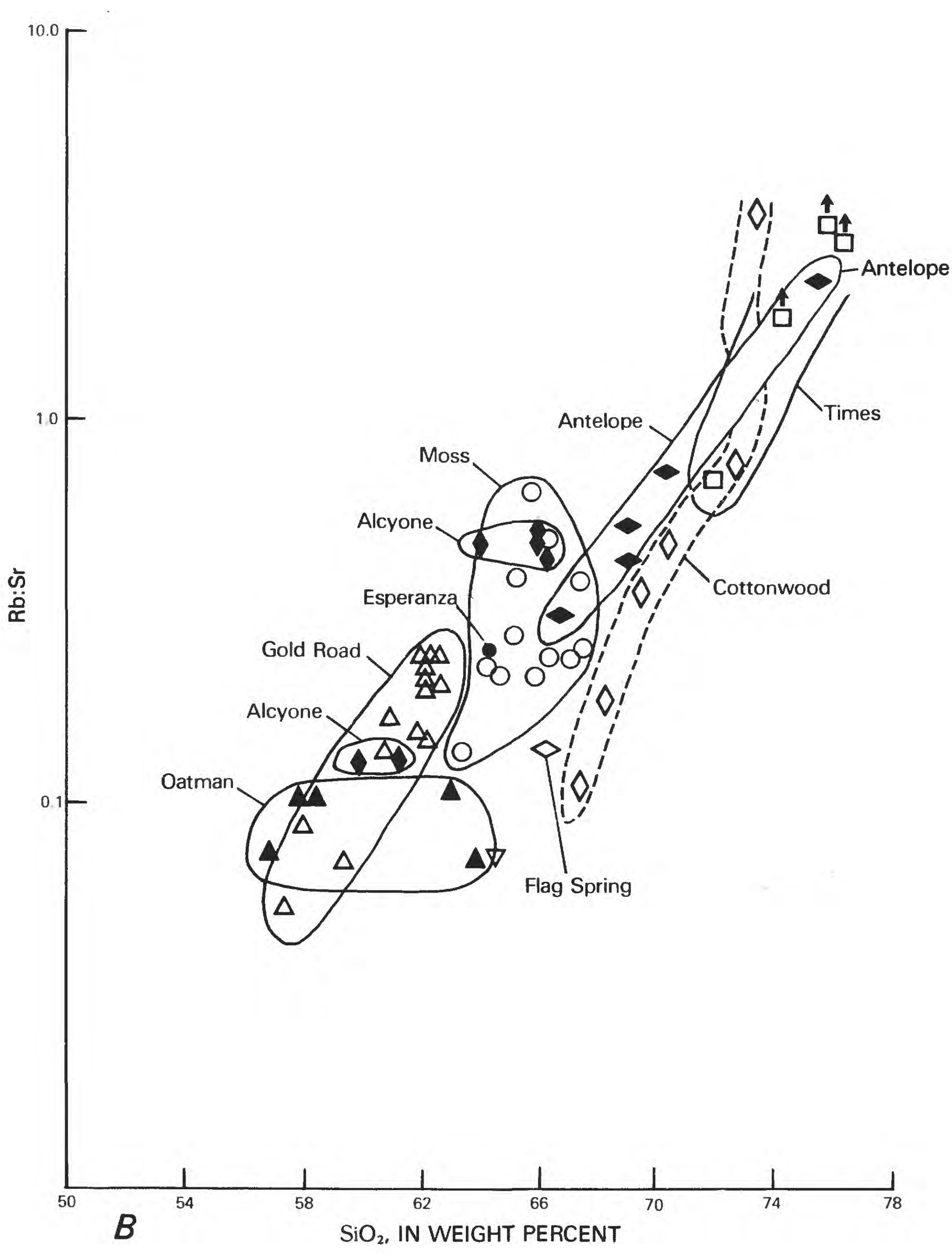
Figure 15 (above and facing page). Rubidium-strontium-SiO_2 plots of volcanic and plutonic rocks of the Oatman area. *A*, Rb vs. Sr; *B*, Rb:Sr vs. SiO_2.

dimension was 190 m. The average strike length of ore bodies in the Gold Road vein was 320 m, notably longer than those in the Tom Reed vein.

Clifton and others (1980) and Buchanan (1981) noted that gold mineralization was restricted to a vertical dimension which is everywhere less than 310 m, and commonly averages 180 m. On a district scale, both bottom and top of this mineralized zone are concave downward. The center of this inverted saucer-shaped zone is midway between the United Eastern and Gold Road mines (Clifton and others, 1980, figs. 17, 18, and 19), and the zone itself has a maximum relief of 240 m on the top of the zone and 180 m on the bottom. Therefore the maximum mineralized vertical dimension is greatest in the center of the zone (≈350 m) and decreases outward to 120 m or less.

Wallrock Alteration

Ransome (1923) noted the alteration of feldspar to aggregates of calcite, quartz, and sericite, of biotite to chlorite, and of augite to calcite, plus the introduction of pyrite in wallrocks near many of the gold-bearing veins, but he did not study the alteration in detail. Lausen (1931) noted kaolin as an alteration product of plagioclase, and calcite, quartz, and chlorite as products of the general breakdown of the groundmass of many flow units. He also remarked on the lack of secondary sericite next to many veins, suggesting that potassium enrichment did not occur in the adjacent wallrocks. Clifton and others (1980) studied alteration patterns in the Oatman district in detail and indicated that propylitic alteration near vein systems was nearly ubiquitous and consisted of the development of the assemblage chlorite-pyrite-carbonate minerals-montmorillonite-illite. Evidence of propylitic alteration, however, is not a useful guide to ore, as the alteration occurred over and adjacent to both barren and productive veins. Effects of silicification and minor introduction of adularia and albite along vein walls were noted by Clifton and others (1980) in ore-bearing veins. Presence of adularia was suggested by Smith (1984) to be one of the better guides



to ore. Another alteration guide to ore is the low-pH assemblage of illite-montmorillonite with or without sericite-kaolinite, which Buchanan (1981) and Clifton and others (1980) reported to overlie all productive vein systems in the Oatman area.

Alteration intensity and type of alteration varied along and between veins in the district. The Tom Reed–United Eastern vein system has a wide phyllic zone that is most extensively developed near ore bodies. Within the Gold Road vein system, alteration products are only poorly developed in the Gold Road Dacite, but are more abundant above and below the latite. Many post-mineral faults are characterized by argillic alteration minerals (Clifton and others, 1980).

Propylitically altered rocks from the Gold Road mine analyzed by Schrader (1909) and from Boundary Cone reported by Wells (1937) indicate that major and minor element exchange has taken place during alteration. SiO_2, Al_2O_3, FeO_{total}, MgO, MnO, and TiO_2 in altered rocks are unchanged from the averages reported by Thorson (1971)

Table 13. K-Ar data and age calculations and Rb-Sr data for Tertiary volcanic rocks and vein material of the Oatman area

[$^{40}Ar^*/^{40}Ar_t$, ratio of radiogenic argon to total argon. $^{87}Sr/^{86}Sr_m$, measured strontium isotopic ratio; $^{87}Sr/^{86}Sr_i$, initial strontium isotopic ratio if rocks are assumed to be 20 Ma]

Unit; mineral dated	%K	$^{40}Ar^*/^{40}Ar_t$	Date (Ma)	Reference
Moss Porphyry; biotite	6.230	0.588	10.7±0.5	Thorson (1971), recalculated with decay constants in Steiger and Jaeger (1977).
Antelope Rhyolite; biotite	6.430	0.175	19.2±0.9	Do.
Gold Road Dacite; biotite	6.53	0.615	18.6±0.9	Do.
Times Porphyry; hornblende	0.822	0.122	23.1±1.8	Do.
Kokomo vein material; adularia + quartz(?).	2.56	not reported	21.2±2.1	Conoco Minerals Company (unpub. data, 1982, 1983).

Unit	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr_m$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr_i$
Moss Porphyry	146±3	591±5	0.7109±0.0001	0.715	0.7107±0.0001
Oatman Andesite	91±1	1,052±8	0.7105±0.0001	0.250	0.7105±0.0001

Figure 16. Contact relationships of Moss Porphyry and Times Porphyry along Silver Creek. *A*, Dark dike of the border phase of the Moss cutting light Times Porphyry. Note chilled margin of dike of dark Moss to left of hammer handle. *B*, Another dark dike of the Moss cutting light Times Porphyry. Note fragments of Times in Moss and decrease in phenocryst percentage within the Moss toward right side of dike.

for fresh rocks, but CaO, Na_2O, K_2O, and Sr have changed notably. K_2O content has more than doubled, whereas CaO and Na_2O have been reduced to less than half, and Sr to one-third, of their average original values. Many of these changes probably have been accomplished by conversion of plagioclase to adularia by potassium metasomatism.

Mineralogy

The ore and gangue mineralogy of the vein deposits is remarkably simple. Virtually the only ore mineral is electrum that assays about 650 fineness. Schrader (1909) suggested that telluride minerals occur in minor quantities.

Table 14. U-Th-Pb analytical data and age calculations for zircon from the Moss and Times Porphyries, Oatman area

[Common lead correction used for zircon age calculations: $^{206}Pb/^{204}Pb=18.67$, $^{207}Pb/^{204}Pb=15.63$, $^{208}Pb/^{204}Pb=38.59$]

Rock unit (mesh size)	U (ppm)	Th (ppm)	Pb (ppm)	Atomic composition of lead[1] 204	206	207	208	$^{206}Pb/^{238}U$ age (Ma)	$^{207}Pb/^{235}U$ age (Ma)	$^{207}Pb/^{206}Pb$ age (Ma)	$^{208}Pb/^{232}Th$ age (Ma)
Moss Porphyry											
(–400)	381.98	785.78	4.24	1	93.75	21.06	69.79	34.0	52.3	99.6	20.9
(–325+400)	198.95	231.74	9.96	1	739.17	87.44	147.05	271.4	471.5	1617.9	108.4
(–250+325)	187.39	235.63	16.25	1	946.77	109.36	164.44	477.7	739.2	1642.4	161.6
Times Porphyry											
(–325+400)	236.96	426.90	6.44	1	415.14	53.62	120.60	136.7	253.2	1544.5	47.0

[1]Laboratory blank lead with isotopic composition $^{206}Pb/^{204}Pb=18.7$, $^{207}Pb/^{204}Pb=15.6$, $^{208}Pb/^{204}Pb=38.2$ removed. No common lead correction has been applied to these ratios.

Trace amounts of pyrite, chalcopyrite, sphalerite, galena, and marcasite(?) are present. Pyrite is fairly common in wallrocks adjacent to the veins, but is nearly absent in the veins. Hypogene gangue minerals are quartz, varicolored calcite, adularia, chlorite, and minor fluorite. Fluorite is noted only in small veins which cut the hypabyssal stocks and appears to be absent in the larger vein deposits in the volcanic rocks. The coarse-grained textures of calcite indicate open-space filling during vein formation. Adularia is normally microscopic and quartz is fine grained. Supergene gangue minerals include minor gypsum, pyrolusite, psilomelane, hematite, limonite, wulfenite, and possibly minium (Lausen, 1931). Silver is known only in electrum, and wire gold has been reported only from minor oxidized zones.

Electrum is seen only in high-grade veins where it normally occurs within quartz and less commonly in adularia or fluorite. Lausen (1931) found no electrum within calcite, and very little gold in pyrite concentrates from wallrocks adjacent to the veins. As much as 0.15 percent tellurium in electrum was noted from samples in the Gold Road vein (Smith, 1984). Gold-bearing quartz is characteristically a honey-yellow color and has an oily luster (Ransome, 1923; Lausen, 1931); the color is due to minute inclusions of chlorite (Lausen, 1931; Clifton and others, 1980), corrensite, and an unidentified magnesium-rich mineral (Smith, 1984).

Lausen (1931) distinguished five stages of vein filling that are determined by the color and texture of quartz and the ratio of gold to silver in associated deposits. He suggested that early, colorless to yellow quartz has Au:Ag ratios of 1:6 to 2:3, and that late, pale-green to honey-yellow quartz has Au:Ag ratios of 1:2 to 4:1 and contains more gold and silver than early quartz. Smith (1984) determined that most of the commercially valuable ore was deposited during the fourth of Lausen's five stages and was positively

Table 15. $^{40}Ar/^{39}Ar$ data and age calculations for hornblende from the Times Porphyry, Oatman area

[$^{40}Ar_R$, radiogenic ^{40}Ar; $^{39}Ar_K$, ^{39}Ar produced from ^{39}K by neutron interaction; 2σ uncertainty in age is analytical uncertainty calculated as in Haugerud and Kunk (1988)]

Temp, °C	$^{40}Ar/^{39}Ar$ measured	$^{37}Ar/^{39}Ar$ measured	$^{36}Ar/^{39}Ar$ measured	$^{40}Ar_R/^{39}Ar_K$	$^{39}Ar_K$ pct. of total	$^{40}Ar_K \times 100 / ^{40}Ar_{meas.}$	Date (Ma) ± 2σ
Ti-79							
(J = 0.005424)							
950	8.426	0.519	0.0211	2.218	10.7	26.3	21.57±0.36
1050	7.088	2.166	0.0171	2.188	8.8	30.9	21.28±0.38
1150	4.543	4.695	0.0096	2.068	17.3	45.6	20.12±0.22
1200	3.321	5.788	0.0062	1.926	28.4	58.1	18.75±0.24
1275	3.343	6.081	0.0063	1.947	20.6	58.4	18.95±0.22
1350	4.367	6.716	0.0094	2.111	8.0	48.5	20.54±0.26
FUSE	7.336	6.698	0.0156	3.227	6.2	44.1	31.30±0.38
Total gas							20.47
NO PLATEAU, but 49.1 percent of gas (1200–1275 °C) has weighted average age of							18.83±0.22

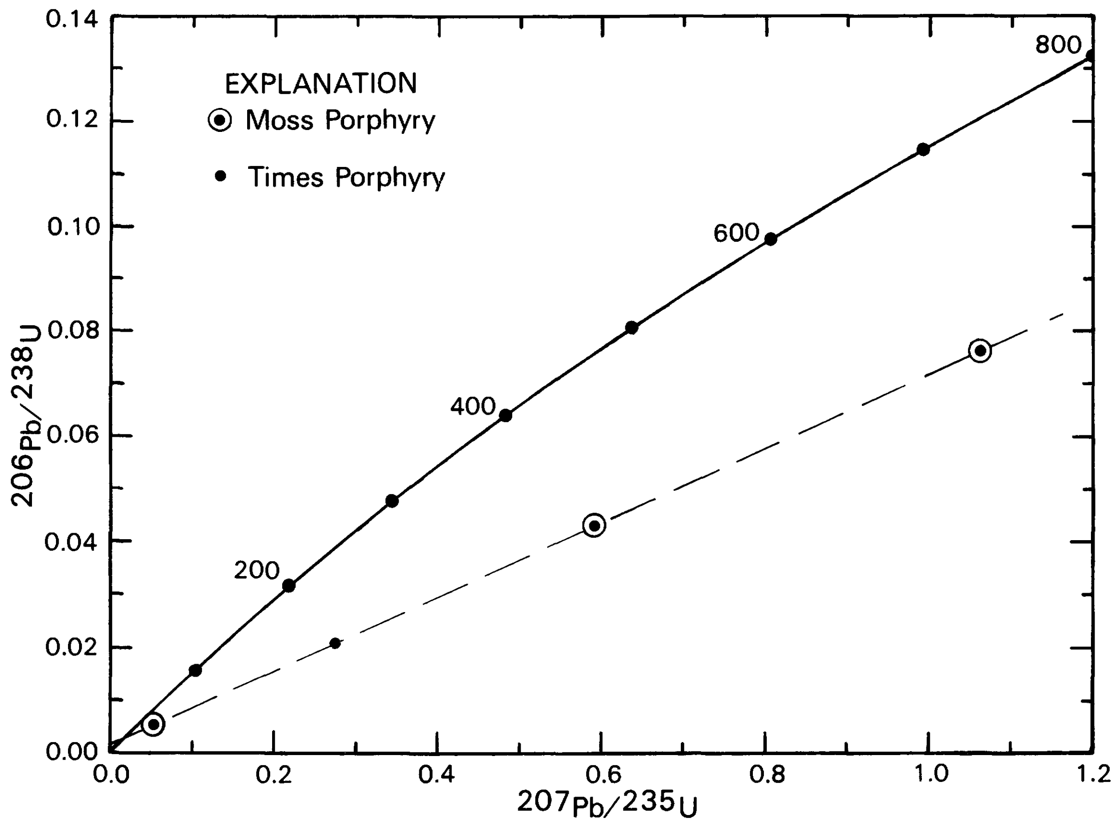


Figure 17. Concordia diagram for zircon from Moss and Times Porphyries, Oatman area. Intercept ages, at 95 percent confidence limits, calculated using 2σ uncertainties of 1.0 percent for U-Pb dates and error correlation of 0.95. Intercepts at 1,675±42 Ma and 18.5±2.5 Ma; mean square of the weighted deviates (MSWD)=2.14 (three zircon fractions of Moss Porphyry). Intercepts at 1,676±4 and 18.5±0.5 Ma; MSWD=1.58 (three zircon fractions of Moss Porphyry and one zircon fraction of Times Porphyry). Program of Ludwig (1988) used for age calculations.

correlated with the amount of adularia. Most of the samples from veins in the Oatman area analyzed by Smith had Au:Ag ratios of 1:2 to 1:6, but much lower ratios (from 1:10 to 1:100) were noted. In a sample from the Gold Road vein representing Lausen's fourth or fifth stage and containing 35 discrete mineralized "bands" (thin growth layers), Smith determined that gold and silver concentrations as well as Au:Ag ratios decreased from older to younger bands. These trends for one stage of mineralization are opposite to the overall trends noted previously for the district.

Age of Mineralization

A mixture of adularia and quartz(?) from the Kokomo vein has a K-Ar date of 21.2±2.1 Ma (table I3). Because the sample is impure (contained 2.56 percent potassium), the date is only an approximation of the time of mineralization, but it suggests that vein formation was partly coincident with the age of emplacement of the middle and upper volcanic sequences and the Times Porphyry. Also, because veins cut the Moss Porphyry, which has a U-Th-Pb zircon age of 18.5±2.5 Ma and a K-Ar cooling date of 10.7±0.5 Ma, mineralization was restricted to the time interval of about 22 to 11 Ma.

Trace Elements

Few trace element studies have been made in the Oatman area, but Durning (1980; written commun., 1982) stated that, although a few anomalies do exist, gold, silver, copper, lead, zinc, mercury, arsenic, antimony, and molybdenum show no consistent patterns over the tops of productive ore shoots.

Gold-Silver Zonation

Both gold grades of the district and Au:(Au+Ag) ratios have a crude zonal pattern characterized by a central high located over the Tom Reed vein system and lows on either side of the vein (fig. I10*A*, *B*). Gold grades (Arizona Bureau of Geology and Mineral Technology, unpub. data,

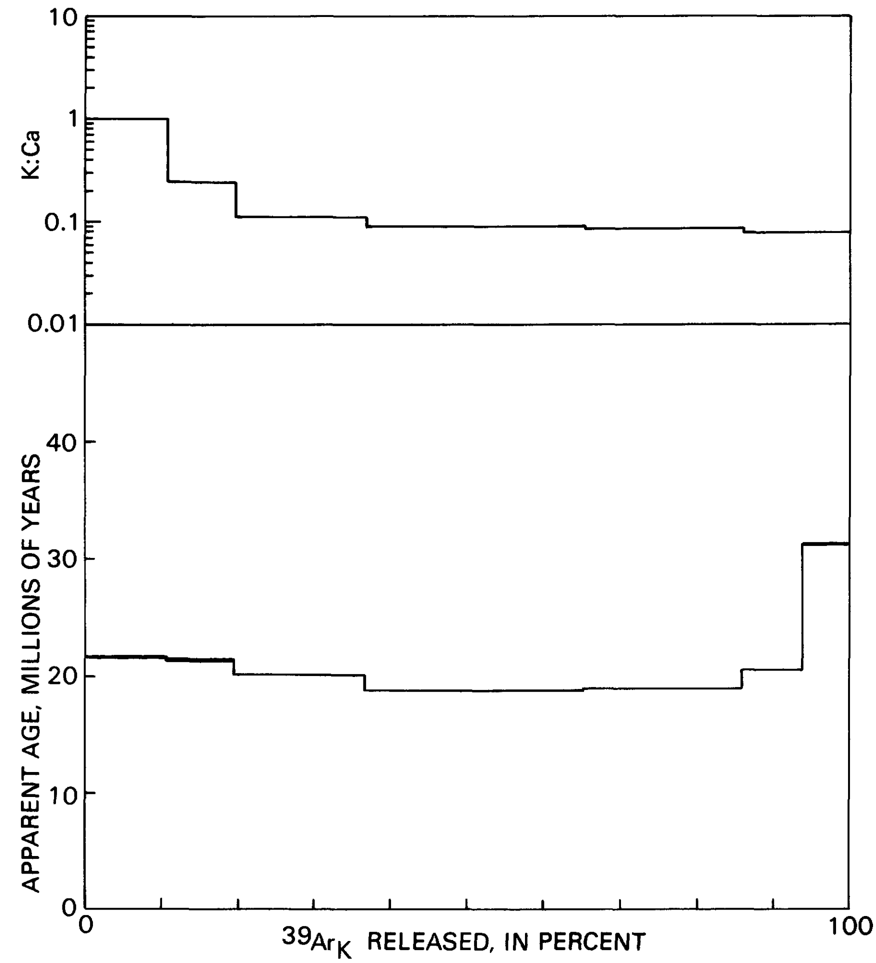
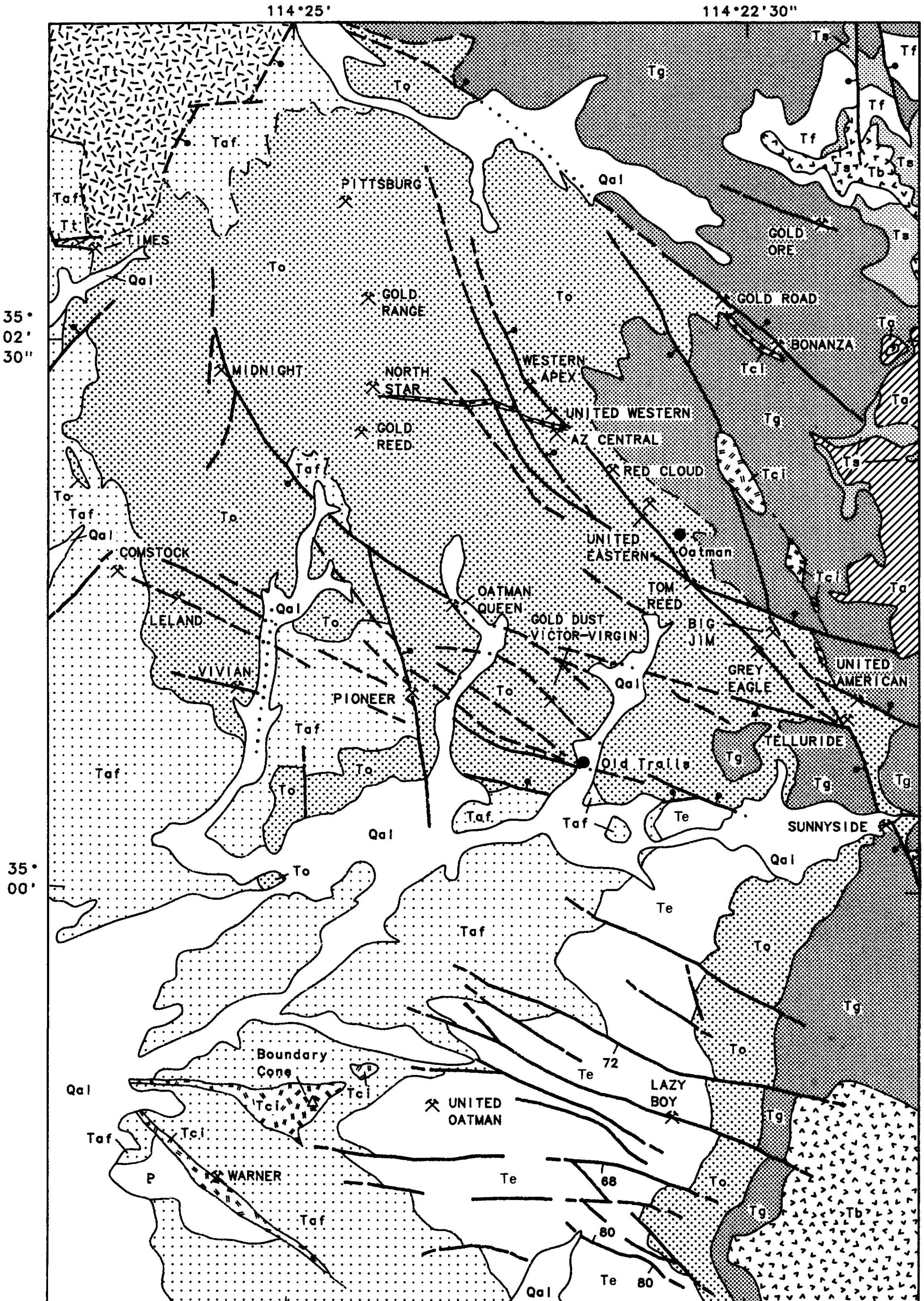


Figure I8. $^{40}Ar/^{39}Ar$ spectrum and K:Ca plot for actinolitic hornblende from Times Porphyry (sample Ti-79), Oatman area. Thicker horizontal bars on age spectrum represent 2σ uncertainty in age, calculated in manner suggested by Haugerud and Kunk (1988). Total gas data=20.47 Ma; 1,200°–1,275° weighted average date=18.83±0.22 Ma.

1982) along the Tom Reed system range from 0.19 to 0.97 oz Au/ton and have a weighted average of 0.699 oz Au/ton. By comparison, the weighted average for the Gold Road vein, northeast of the Tom Reed, is 0.307 oz Au/ton. The region of highest Au:(Au+Ag) trends northwesterly through the center of the district and roughly coincides with the high-grade zone. Near the center of the district, Au:(Au+Ag) ratios average more than 0.700, decreasing on either side to less than 0.400 (less than 0.300 on the southwest; fig. I10B). This regional pattern also was noted by Smith (1984) from samples collected along various vein systems.

The general coincidence of high gold grades and high Au:(Au+Ag) ratios at a regional scale is not true at the deposit level (fig. I11). The three largest mines in the district, the Gold Road, Tom Reed, and United Eastern, have Au:(Au+Ag) ratios of 0.628 to 0.658, but range in gold grade from 0.307 to 0.912 oz Au/ton. Individual mines in the Oatman district had very constant Au:(Au+Ag) ratios throughout their productive history, suggesting very little gold-silver zonation in the ore bodies, either vertically or laterally. The Gold Road mine during 22 years of annual production exceeding 1,000 tons of ore had Au:(Au+Ag) ratios of 0.524±0.062; at the Tom Reed, for 23 years of annual production exceeding 1,000 tons of ore, Au:(Au/Ag) ratios averaged 0.609±0.189; and at the United Eastern, during 8 years of annual production exceeding 1,000 tons of ore, Au:(Au+Ag) ratios averaged 0.584±0.108.

Because electrum is the only gold-bearing mineral in the district, the simple gold-silver zoning (fig. I10*B*) suggests a gold-rich central area flanked by silver-rich margins. For individual ore bodies, gold grade is



114°25'
114°22'30"
35° 02' 30"
35° 00'
PITTSBURG
TIMES
GOLD RANGE
MIDNIGHT
NORTH STAR
GOLD REED
WESTERN APEX
UNITED WESTERN
AZ CENTRAL
RED CLOUD
UNITED EASTERN
Oatman
GOLD ORE
GOLD ROAD
BONANZA
COMSTOCK
LELAND
VIVIAN
PIONEER
OATMAN QUEEN
GOLD DUST
VICTOR-VIRGIN
TOM REED
BIG JIM
GREY EAGLE
UNITED AMERICAN
TELLURIDE
Old Trails
SUNNYSIDE
Boundary Cone
UNITED OATMAN
LAZY BOY
WARNER
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Tt
Taf
To
Tg
Tf
Ts
Tb
Tci
Ta
Te
P
72
68
80
80

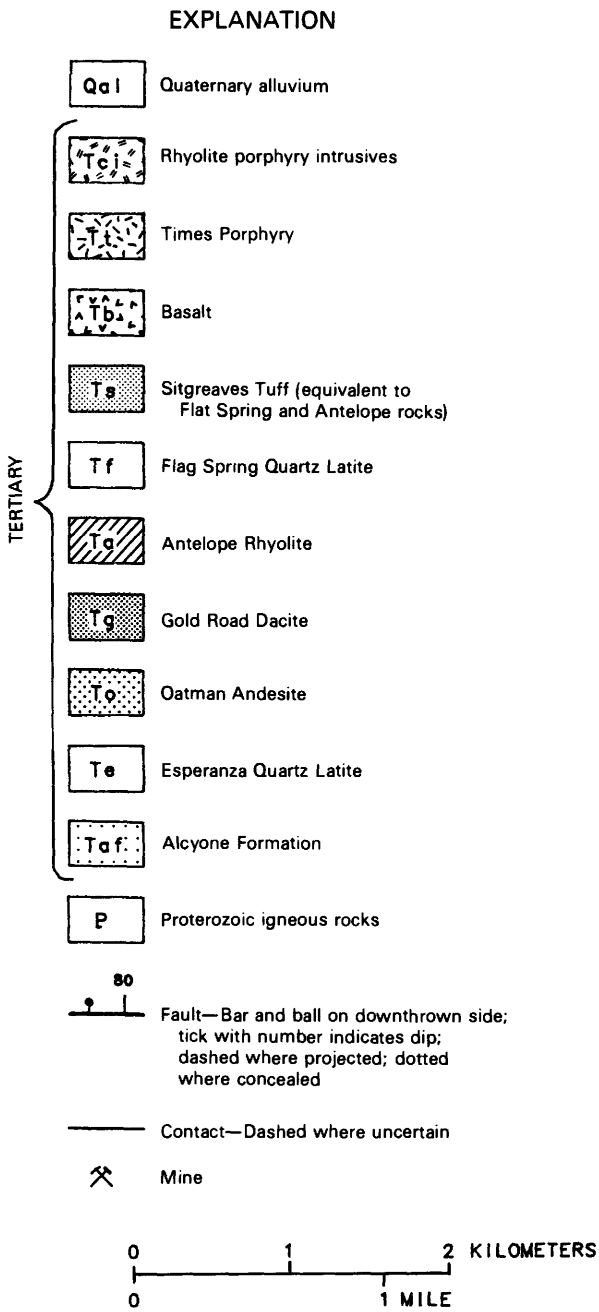


Figure I9 (above and facing page). Detailed geology and location of mines in the Oatman district. Compiled from Thorson (1971), Ransome (1923), and Clifton and others (1980).

independent of both Au:(Au+Ag) ratios and tonnage mined. Also, because most of the ore bodies in the district were not exposed at the surface, supergene enrichment is not believed to have greatly affected the pattern of gold grade and Au:(Au+Ag) ratios in figure I7.

Fluid-Inclusion Thermometry and Gas Analyses

Fluid inclusions in quartz, calcite, and fluorite from the Tom Reed, Gold Road, and Kokomo veins indicate temperatures of formation of ≈200–240 °C (Clifton and others, 1980; Buchanan, 1981). Smith (1984) noted that primary fluid inclusions in quartz and calcite have homogenization temperatures of 205–255 °C, and secondary inclusions have a wider range, 175–335 °C. Homogenization temperatures for both types of inclusions are slightly higher for samples from veins in the central part of the district than for samples from peripheral veins. Inclusions from the Gold Road, Midnight, Kokomo, and Ben Harrison vein systems exhibit a wide range of homogenization temperatures, suggestive of local boiling of the hydrothermal fluid. Salinities of the inclusions average 1.47±0.03 wt. percent NaCl equivalent. All inclusions noted by Smith (1984) contain liquid water and water vapor, with only minor amounts of CO_2 vapor. Expansion of the vapor bubble during crushing tests on a sample from the Midnight vein indicates a minimum fluid-inclusion trapping pressure of 65 bars.

Gases (primarily species of carbon and sulfur) within the fluid inclusions are more reduced and possess lower ratios of total carbon to total sulfur than gases in inclusions from other epithermal gold-quartz veins for which data exist (Smith, 1984). In fact, most of the gas data from Oatman samples more closely correspond to data from porphyry copper deposits and associated epithermal base-metal deposits in Arizona. In a sample containing 35 mineralized bands from the Gold Road vein, the ratio of the amount of oxidized gases to reduced gases decreased from older to younger bands, which was interpreted by Smith (1984) to indicate that boiling was strongest during deposition of the older mineralized bands. On a district scale the ratio of oxidized gases to reduced gases was highest in the center of the district, suggesting that boiling was more likely to have occurred in the center where hydrothermal fluids were hottest and gold mineralization was most concentrated.

CONCLUSIONS

Distinguishing Characteristics

The gold-bearing quartz veins of the Oatman district are, in many respects, typical epithermal deposits associated with mid-Tertiary volcanic rocks. However, they are unusual for such deposits in the Western United States because of their virtual lack of base metal minerals, extremely low pyrite content, and low silver content. The district has an unusually high Au:Ag ratio (≈1.7:1), comparable only to Goldfield and Round Mountain, Nev. (Buchanan, 1981).

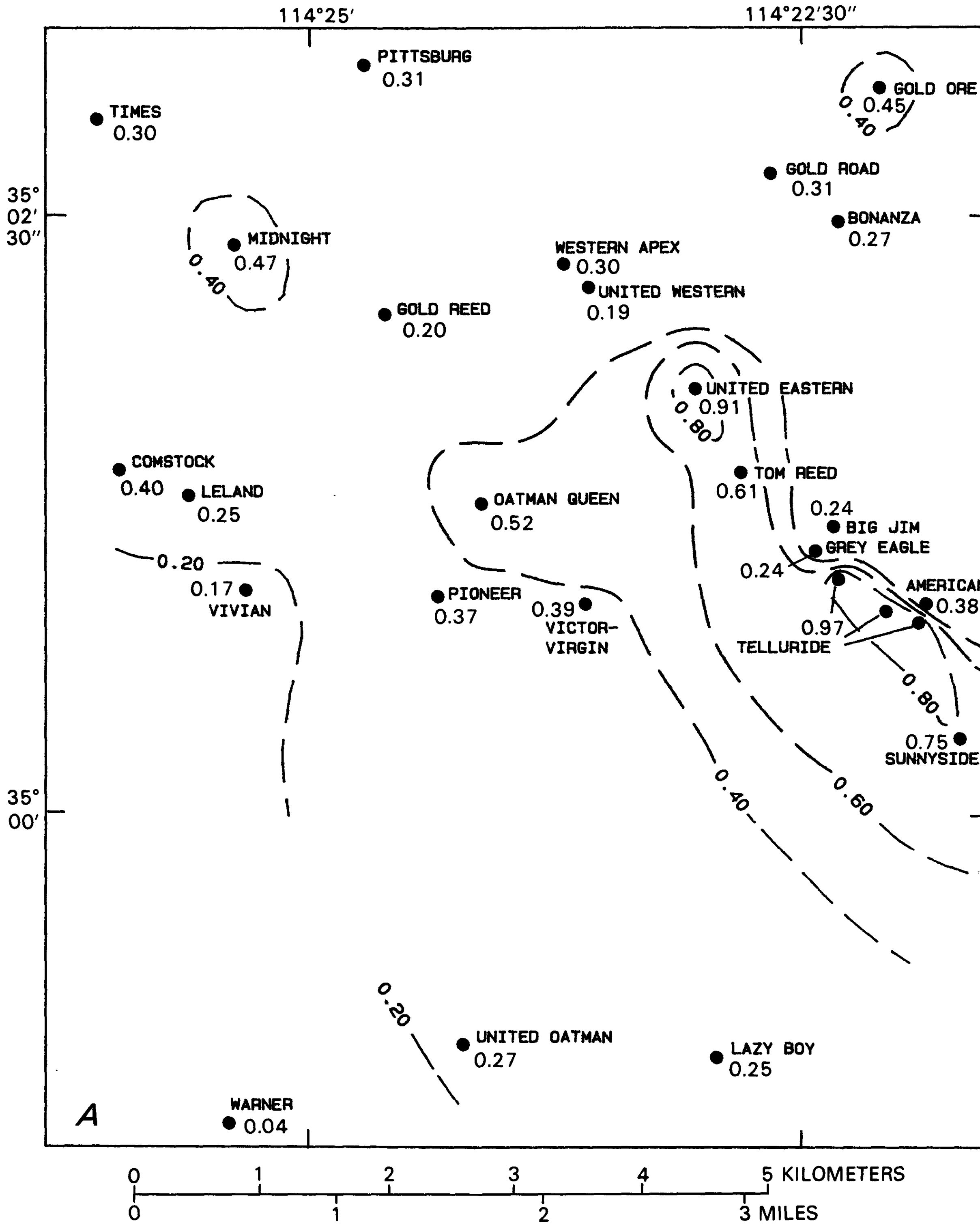
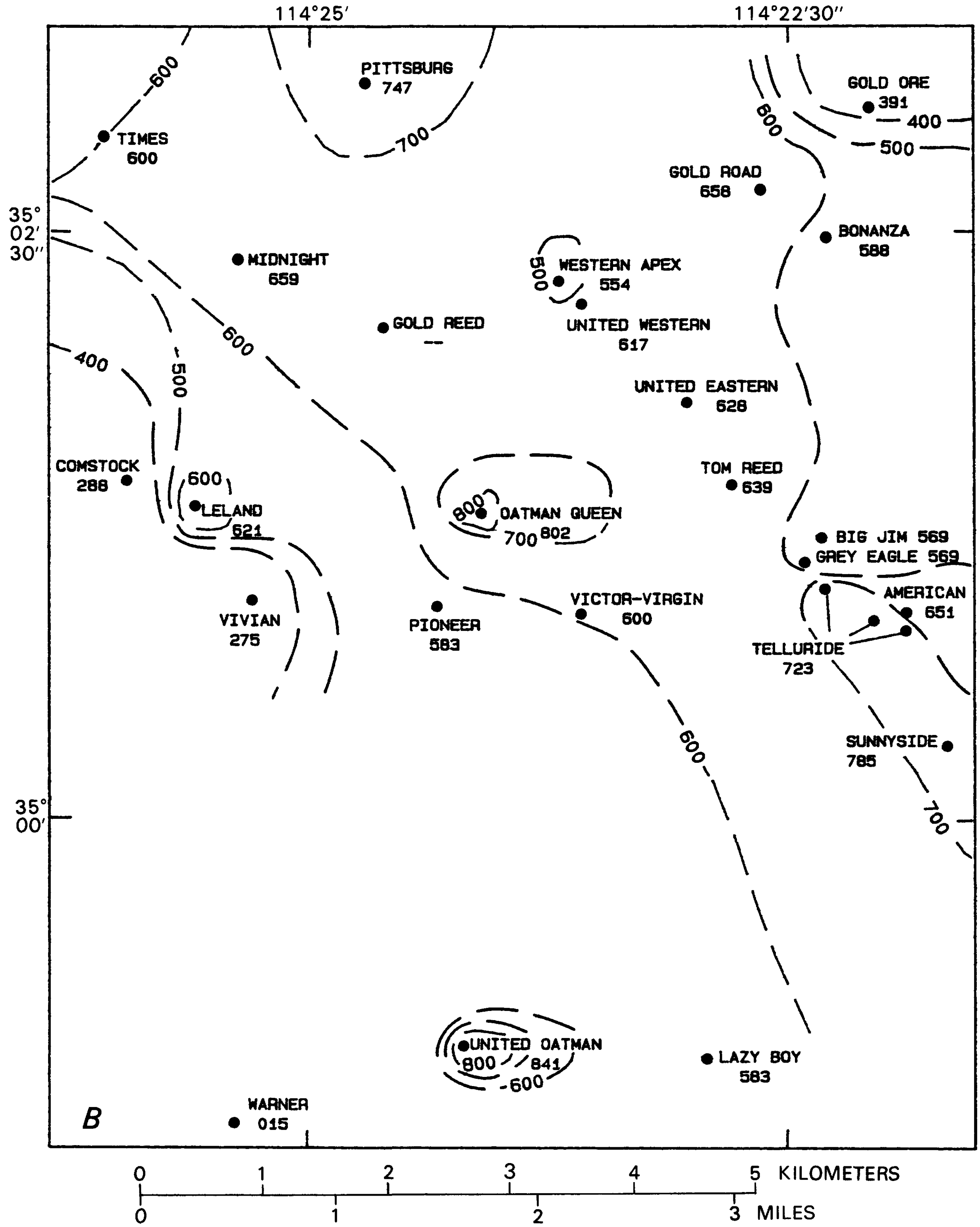


Figure 110 (above and facing page). Contoured gold relationships in the Oatman district. *A*, Gold grade, in oz Au/ton, of individual deposits. *B*, Au:(Au+Ag) ratios of individual deposits. Values in *B* are multiplied by 1,000 to eliminate decimal points. Gold Reed (---), Au: (Au+Ag) not calculated because of incomplete data.



114°25′
114°22′30″
35° 02′ 30″
35° 00′
PITTSBURG 747
GOLD ORE 391
TIMES 600
GOLD ROAD 658
BONANZA 588
MIDNIGHT 659
WESTERN APEX 554
GOLD REED —
UNITED WESTERN 617
UNITED EASTERN 628
COMSTOCK 288
LELAND 621
OATMAN QUEEN 802
TOM REED 639
BIG JIM 569
GREY EAGLE 569
AMERICAN 651
VIVIAN 275
PIONEER 583
VICTOR-VIRGIN 600
TELLURIDE 723
SUNNYSIDE 785
UNITED OATMAN 841
LAZY BOY 583
WARNER 015
400
500
600
700
800
B
0 1 2 3 4 5 KILOMETERS
0 1 2 3 MILES

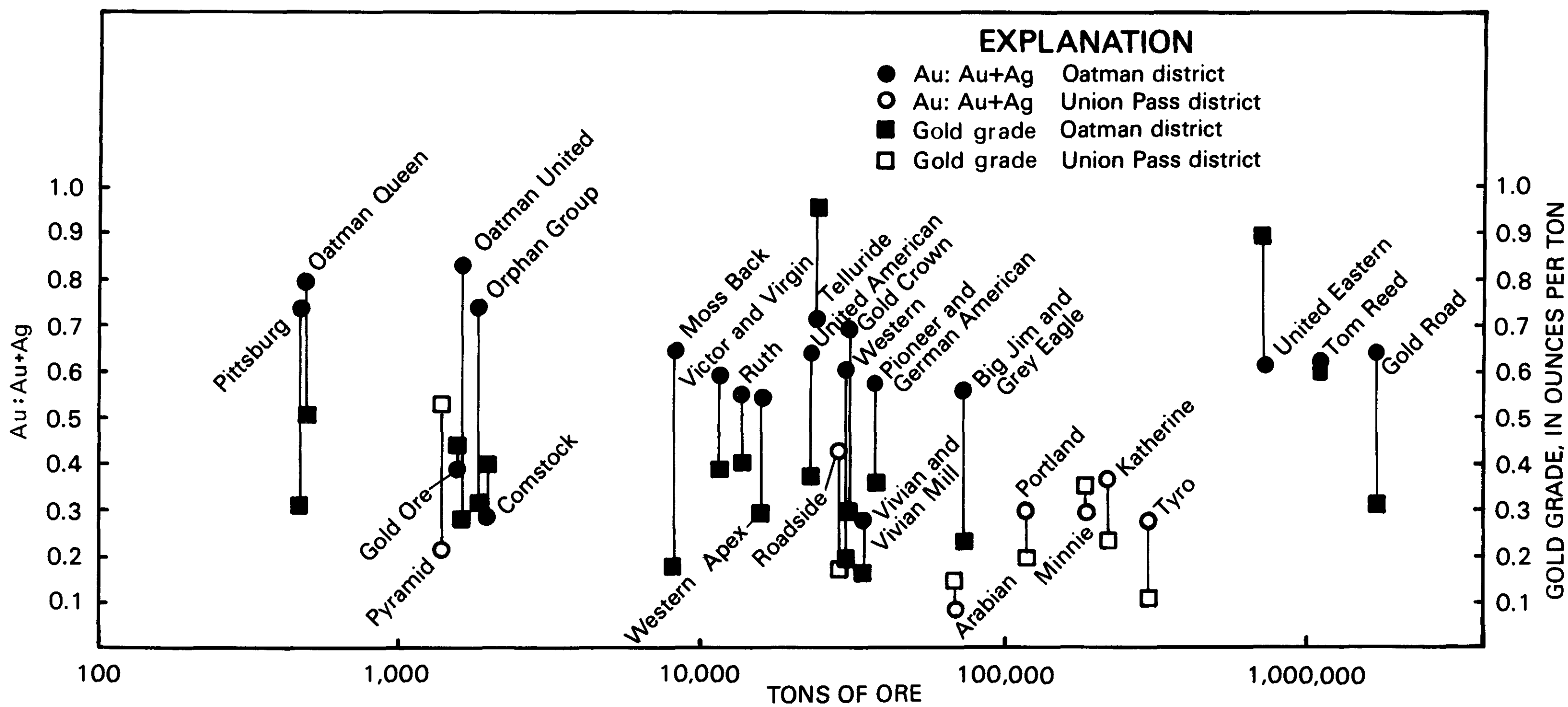


Figure I11. Plot of Au:(Au+Ag) ratios vs. tonnage, and grade in oz Au/ton vs. tonnage, for individual deposits in the Oatman district. Tons are short tons. Deposits in Union Pass district plotted for comparison. Tie lines connect Au:(Au+Ag) ratios and gold grades for individual deposits.

Ore Controls

Ore controls in the Oatman district appear to have been (1) curved fault planes and resultant dilatant zones; (2) distance below the paleosurface of the dilatant zones; and (3) fractured nature of wallrocks that controlled the associated hydrothermal alteration. Clifton and others (1980) stressed the importance of curved fault planes that formed during deformation and created dilatant zones that filled with vein material. Ransome (1923) and Lausen (1931) noted the restricted vertical dimension of ore bodies, and Clifton and others (1980) pointed out the inverted saucer-shape of the ore horizon in the veins as viewed on a district scale. All workers who have studied Oatman noted the difference between low fracture density in the Gold Road Dacite and high fracture density in the Oatman Andesite. This fracture density correlates positively with the low gold grade of ore in the Gold Road Dacite (Gold Road vein, average 0.307 oz Au/ton), and high gold grade of ore in the Oatman Andesite (Tom Reed vein, average 0.699 oz Au/ton). A characteristic low-pH alteration assemblage structurally overlies most ore bodies (Buchanan, 1981). Most gold-bearing veins contain trace to major amounts of adularia (Smith, 1984), implying that hydrothermal fluids moderately enriched in potassium caused the wallrock alteration as well as deposition of precious metals.

The most important ore control may have been the chemistry of the associated volcanic rocks rather than the factors just cited. As noted in the section on stratigraphy, the volcanic rocks at Oatman are products of an alkalic to subalkalic, high-potassium magma series and are similar in many respects to shoshonitic rocks of continental margins (Morrison, 1980). Characteristically, such volcanic rocks contain abnormally high amounts of potassium, rubidium, strontium, and barium. Potassium metasomatism, in the form of disseminated sericite and fine-grained adularia, noted in the veins of the district, may have been facilitated by the high potassium content of the magma series. Similar Tertiary epithermal gold-silver vein deposits at Eldorado Canyon, Nev. (Hansen, 1962; Longwell and others, 1965), are associated with subalkalic to alkalic, high-potassium volcanic rocks (Anderson, 1978). Gold-silver deposits at Round Mountain, Nev., are spatially associated with subalkalic rhyolite that has anomalously high strontium and barium contents and moderately elevated K_2O contents (D.R. Shawe, written commun., 1982). The gold veins at Goldfield, Nev., are likewise localized in Tertiary volcanic rocks with elevated K_2O contents and anomalously high strontium and barium contents (Ashley, 1979; written commun., 1982).

Origin

The vein deposits of the Oatman district are a late-stage product of early Miocene shoshonitic volcanism, and were formed during extensional tectonism about 22–15 Ma. The veins are localized along northwest-trending faults, many of which are subparallel to, or are occupied by, late-stage rhyolite dikes. The veins cut most of the dikes, but the heat and fluid source for the veins is believed to have been genetically related to emplacement of the rhyolite. The veins were filled by gold-bearing quartz, calcite, and adularia at temperatures of 200–240 °C as a response to local fluid boiling and change in pH (Buchanan, 1981; Smith, 1984). The ore bodies occupy restricted vertical intervals in the vein that were limited on the bottom by the boiling interface and on the top by their depth below the paleowater table (Clifton and others, 1980). Gold and silver are believed to have been derived from the shoshonitic magma and concentrated in hydrothermal fluids related to emplacement of late-stage rhyolite bodies. Many structural features have controlled the localization of ore bodies within the vein system, but the ultimate control and source of the gold and silver may have been the shoshonitic magma and derivative volcanic rocks.

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Geology and Gold Deposits of the Marysville Mining District, Montana

By James W. Whipple

Abstract

The Marysville mining district is a few kilometers northwest of Helena, Montana. Gold was discovered within the district as early as 1862 when placer deposits were worked along Silver Creek. In the late 1800's, lode mines developed gold deposits throughout the district, and the town of Marysville boomed. Only limited production of gold in the last 40 years has been reported, and exploration for molybdenum has created the only recent interest in the district's mineral deposits. Total lode-gold production through 1973 is estimated to be about 1,148,000 ounces; no production has been reported since 1973.

The district is underlain by Middle Proterozoic strata of the Belt Supergroup that are locally intruded and metamorphosed by Late Cretaceous and Tertiary granitic rocks. A geothermal anomaly in the Empire Creek area was explored by deep drilling in 1974; the drilling discovered a shallow-buried intrusive emplaced between about 40 and 37 Ma.

Gold in the Marysville district occurs primarily as native gold in manganiferous, quartz-calcite fissure veins associated with the Late Cretaceous and Tertiary intrusive events. Three types of veins characterize the gold-bearing veins. Type one veins contain molybdenite, pyrite, and fluorite with no appreciable amounts of gold; type two veins contain gold, pyrite, chalcopyrite, sphalerite, and galena; and type three veins contain gold, tetrahedrite, and chalcopyrite. Most gold production from these veins has been from near-surface ore bodies rarely deeper than 150 meters. An exception was the North Star vein at the Drumlummon mine, which produced gold to a depth of 370 meters. The Drumlummon mine, just south of the town of Marysville, accounted for more than half the gold production of the district and was the most extensively developed mine; it is presently inactive and its workings inaccessible.

Because of the presence of young intrusives, active hydrothermal systems, carbonate host strata, and penecontemporaneous faulting, exploration for Carlin, Nevada-type disseminate gold deposits in the Marysville mining district seems warranted.

INTRODUCTION

The Marysville mining district is about 27 km northwest of Helena, Mont., near the Continental Divide, where much of the terrain is mountainous and sparsely forested (fig. I12). Mount Belmont, near the center of the district, has an elevation of 7,330 ft (2,234 m) and is the highest mountain in the area. The settlement of Marysville, once a prosperous boom town, now contains only a fraction of the population it had during the late 1800's.

In 1862, placer deposits of gold were discovered along Silver Creek, which flows eastward from Marysville (fig. I13). Koschmann and Bergendahl (1968, p. 156) estimated that the placer mines have yielded about 64,500 oz of gold. In 1876, near the headwaters of Silver Creek, Thomas Cruse discovered the Drumlummon lode, and it became the most productive mine in the Marysville district. The estimated production between 1878 and 1910 from all lode mines in the district was $30,000,000 in gold and silver at prevailing prices (Pardee and Schrader, 1933, p. 63). More than half that amount came from the Drumlummon mine, which produced 568,898 oz of gold and 4,982,942 oz of silver from 1883 to 1910 (Goodale, 1915, p. 276). The remaining production came principally from the Penobscot, Bald Butte, Belmont, Empire, and Piegan-Gloster mines (fig. I13). Total lode-gold production through 1973 has been about 1,148,000 oz. No gold production has been reported from the lode mines since 1973 and reserves are unknown.

Only desultory work has been performed in the district over the past two decades. The possibility of production of molybdenum associated with intrusives in the district has created some recent interest and has resulted in some diamond drilling. In 1973, the National Science Foundation sponsored research to evaluate the geothermal resources of the Marysville area; this research (Blackwell and others, 1974; Blackwell and others, 1975) resulted in the most complete geologic study of the area to date.

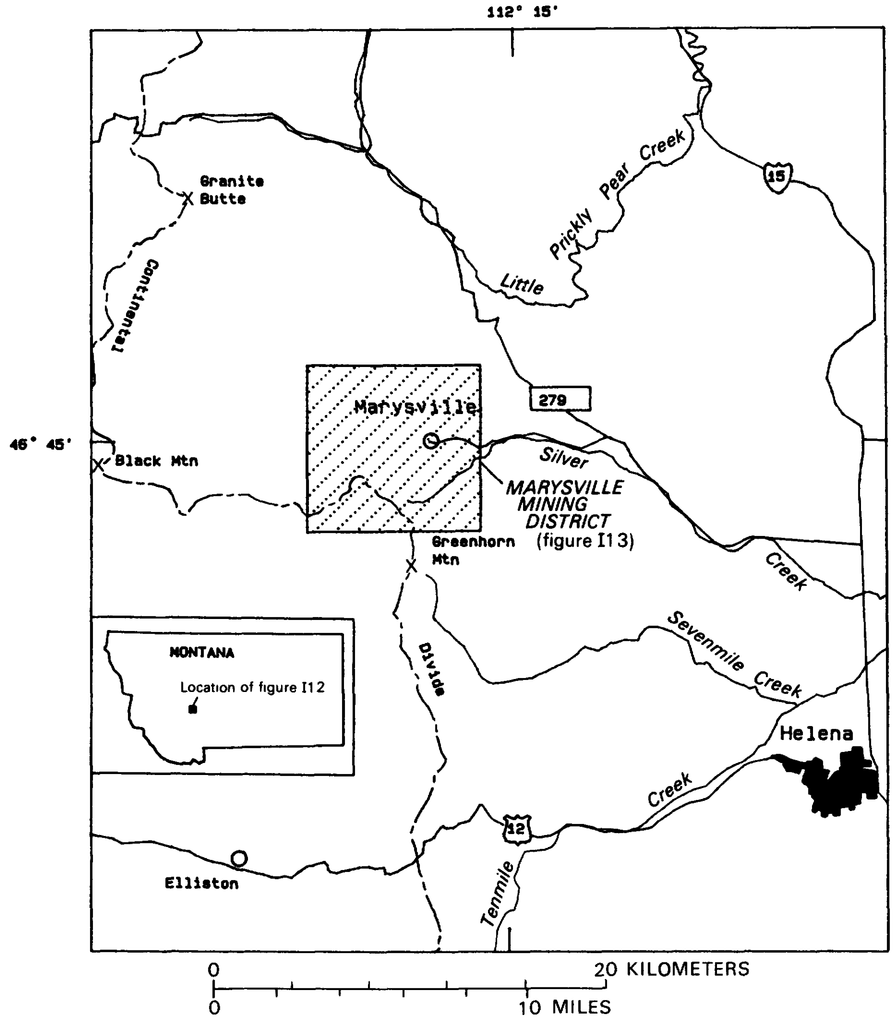

Figure I12. Index map of the Marysville mining district, Montana.

GEOLOGIC SETTING

Precambrian (Middle Proterozoic) sedimentary and metasedimentary rocks of the Belt Supergroup underlie most of the Marysville mining district (fig. I13). The dominant feature of the area is the Marysville stock that intruded the sedimentary rocks in Late Cretaceous time. Studies by Rostad (1969) and Blackwell and others (1975) revealed at least two younger unexposed stocks.

Sedimentary Rocks

Empire Formation (Middle Proterozoic).—The Empire Formation, the oldest rock unit exposed in the district, crops out mainly along the axis of an anticline west of Marysville and along the southwest flank of the Marysville stock. North of Trinity Hill, the Empire is composed of pale-green arenite, siltite, and argillite that occur as wavy, nonparallel-laminated, fining-upward couplets. Interbedded sequences of rose or lavender argillite, as noted by Knopf (1950, p. 836), probably represent the transition zone between the Empire Formation and underlying Spokane Formation (not exposed in the district). Carbonate content increases upward, and a transition zone about 40 m thick separates the Empire Formation from the overlying Helena Formation. The contact is placed where the overlying rocks become dominantly carbonate (Blackwell and others, 1975, p. E10). Where the Empire Formation is adjacent to intrusive rocks, it is characterized by light- and dark-green to blackish-green banded calc-hornfels. Although the base of the Empire Formation is not exposed in the Marysville district, regional studies have shown the thickness of the formation to be about 300 m.

Helena Formation (Middle Proterozoic).—Carbonate rocks of the Helena Formation nearly enclose the Marysville stock and form the most abundant rock unit in the district. Two lithologies typify the formation: tan-weathering gray limestone, and brown siliceous dolomite (Blackwell and others, 1975, p. E10). Limestone beds

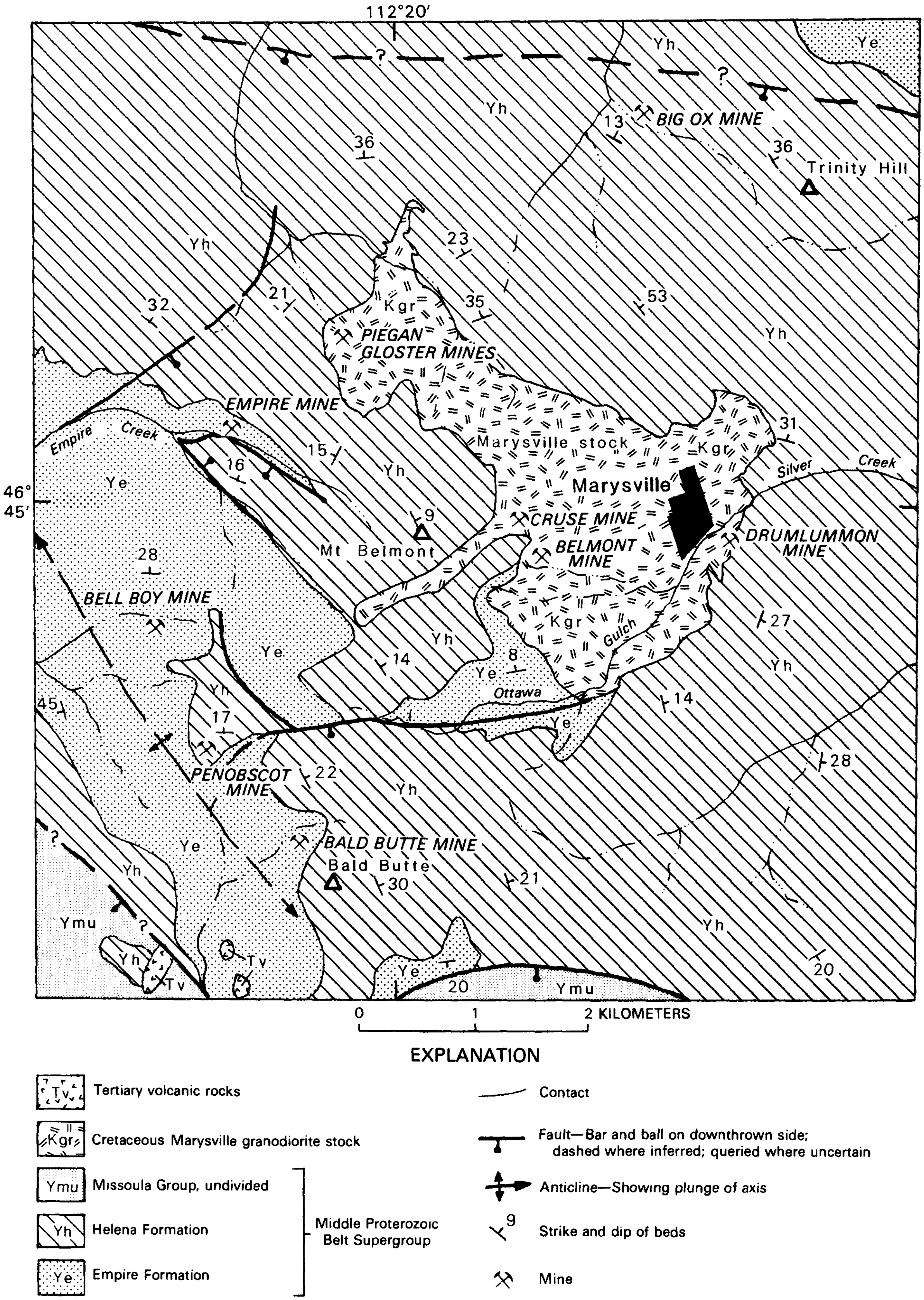

Figure I13. Generalized geology of the Marysville mining district, Montana (modified from Barrell, 1907, and Blackwell and others, 1975).

commonly contain a clastic component that includes oolites and edgewise conglomerate. Stromatolite biostromes, as much as 3 m thick, occur throughout the formation (Knopf, 1950, p. 838), and molar-tooth structures are common. Near the contact of the Marysville stock, the Helena Formation is metamorphosed to white and tan banded calc-hornfels. In the mining district, the Helena is estimated to be as much as 1,200 m thick (Barrell, 1907, p. 9).

Missoula Group (Middle Proterozoic).—The lower part of the Missoula Group is exposed along the southern boundary of the district where it is in fault contact with the Empire and Helena Formations. Interpretation of geologic mapping by Bierwagen (1964) suggests that here the Missoula Group consists of the upper part of the Snowslip Formation and the lower part of the Shepard Formation. The Snowslip is typically reddish brown interlaminated siltite, arenite, and argillite. Greenish-gray, yellowish-gray, and light-brown dolomite, and calcareous arenite and siltite characterize the Shepard Formation.

Igneous Rocks

Pre-Late Cretaceous Intrusive Rocks.—Widespread metamorphosed dikes and sills mapped by Barrell (1907, pl. 1) (not shown on fig. I13 of this report) are interpreted to have been intruded before the Late Cretaceous emplacement of the Marysville stock. Rocks included in this group are microcrystalline diorite and coarse-grained diorite and gabbro (Barrell, 1907; Blackwell and others, 1975). Generally, the feldspars are sericitized, and ferromagnesian minerals are chloritized. Coarse-grained metadiorite and metagabbro sills in the Empire Formation may correlate with Precambrian (Late Proterozoic) sills in the Empire and Spokane Formations to the north and east (Whipple and others, 1987).

Marysville Stock (Late Cretaceous).—The Marysville stock forms an irregularly shaped exposure of granodiorite in the center of the district (fig. I13). The granodiorite is composed mostly of zoned plagioclase (An_{15} to An_{40}), quartz, orthoclase, and about equal amounts of hornblende and biotite (Barrell, 1907, p. 15–16; Knopf, 1950, p. 840). Much of the granodiorite has medium- to coarse-grained equigranular texture; the textures are finer grained toward the center and near the chilled margins of the stock (Mantei and Brownlow, 1967, p. 226). Barrell (1907), in his classic paper on the Marysville district, ascribed the emplacement of the stock to magmatic stoping. Studies of contact metamorphism and field magnetic intensity show that the contacts between the stock and host strata dip gently to the southwest and northwest but dip steeply to the southeast and northeast (Blackwell and others, 1974, p. 47). A potassium-argon age of 78±4 Ma indicates a Late Cretaceous age, similar to the age of the Boulder batholith to the south (Baadsgaard and others, 1961).

Early to Middle Tertiary Intrusive Rocks.—An intrusive event at about 48 Ma resulted in the emplacement of porphyritic dikes and small stocks in the district. Large diorite porphyry dikes were emplaced in the areas of the Bald Butte, Belmont, Drumlummon, and Big Ox mines. The diorite porphyry consists of plagioclase phenocrysts in a gray fine-grained groundmass of quartz, feldspar, and biotite (Barrell, 1907). At many locations, the feldspars are altered to sericite. Dikes of fine-grained hornblende diorite near Bald Butte were dated at about 48 Ma (Blackwell and others, 1975).

Recent drilling southwest of Bald Butte revealed a quartz porphyry stock at a depth of less than 100 m (Rostad, 1969, p. 447). The age of the stock is 47.8±2 Ma (Blackwell and others, 1974, p. 11). The extent of metamorphism at the Big Ox mine suggests another intrusive at shallow depth near the north boundary of the district (Barrell, 1907, p. 111).

Extensive studies of the geothermal anomaly and possible geothermal resource in the area of Empire Creek by Blackwell and Baag (1973), Blackwell, Brott, and others (1974), and Blackwell, Holdaway, and others (1975) have indicated an intrusive at shallow depth that was emplaced sometime between ≈40 and 37 Ma. An exploratory borehole encountered the stock at 294 m below the surface and penetrated it to a depth of 2,070 m. Rock in the upper part of the stock consists of orthoclase, plagioclase, quartz, and biotite phenocrysts in a fine-grained greenish- to light-gray groundmass of orthoclase and quartz. Deeper in the bore, the mineralogy is about the same, but the texture is more equigranular so that the intrusive resembles pink granite. Alteration of feldspars was more intense and pervasive in the upper part of the stock. Blackwell and others (1975) suggested that the Empire Creek and the Bald Butte stocks were emplaced at a depth of about 2 km.

Middle Tertiary Extrusive Rocks.—Rhyolite, dacite, and rhyodacite tuffs occur in isolated outcrops in the Marysville district, and probably are related to the volcanic rocks 24 km northwest of Marysville in the Crater Mountain area, which are of late Eocene or early Oligocene age (Melson, 1971). Some of the gold mineralization in the district may have been related to this volcanic event.

Metamorphism and Alteration

Pronounced contact metamorphism and hydrothermal alteration accompanied the intrusion of the Marysville stock and other buried intrusive bodies. Several zones of progressive metamorphism in the enclosing carbonate rocks have been recognized by Rice (1975) and Blackwell and others (1975) (fig. I14). Studies of contact metamorphism were very effective in outlining the buried Empire Creek and Bald Butte stocks.

Hydrothermal alteration accompanied the intrusion of the Tertiary Bald Butte and Empire Creek stocks. At Bald

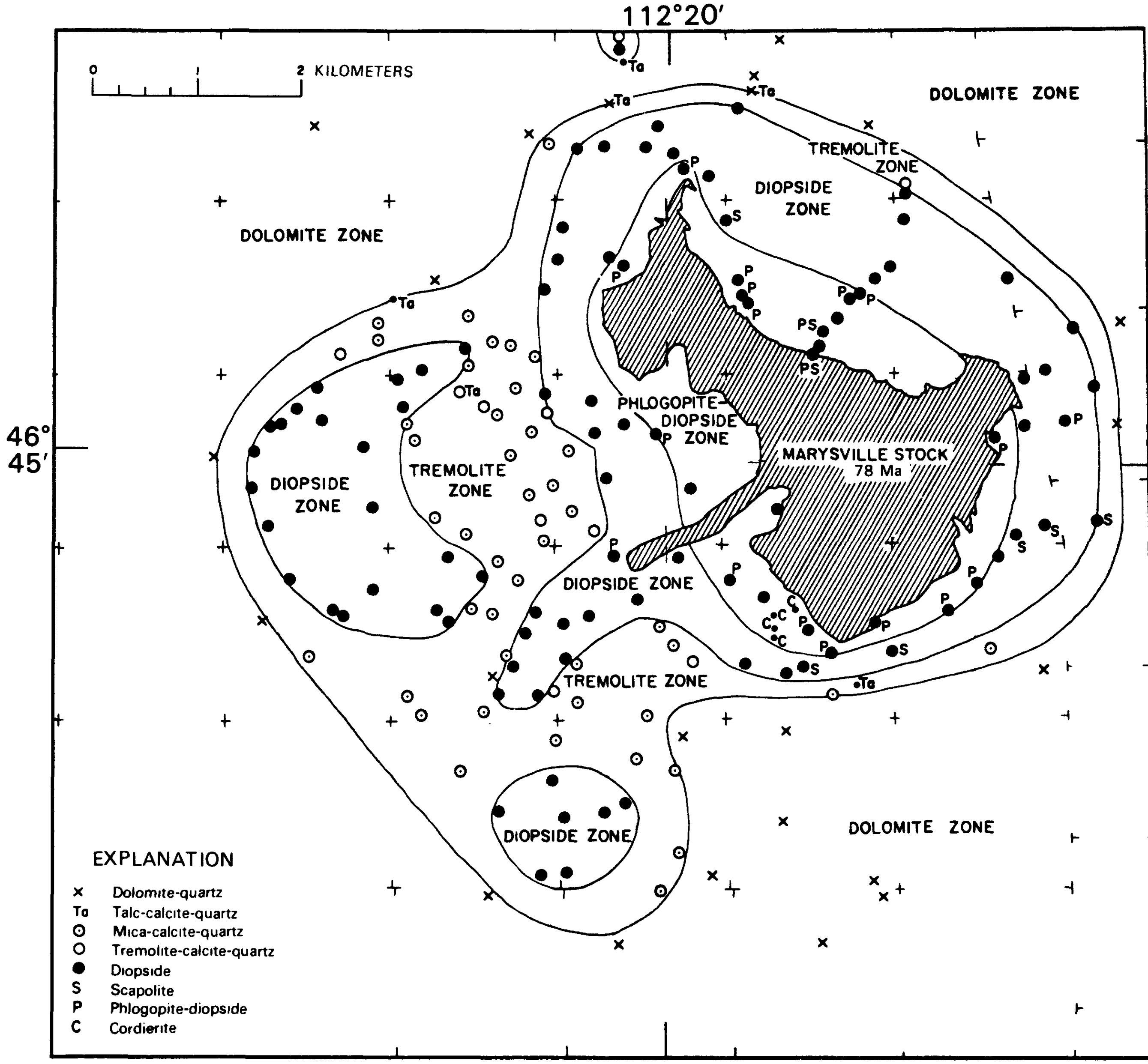

Figure I14. Map showing zones of contact metamorphism, and the Marysville stock (from Blackwell and others, 1975). Cross ticks show section corners.

Butte, the diopside hornfels has been altered to very fine grained rock composed of hornblende, quartz, reddish-brown biotite, and potassium feldspar (Rostad, 1969, p. 440). Sedimentary features in host rocks preserved during contact metamorphism were destroyed by hydrothermal alteration. In the upper parts of the Empire Creek stock, most feldspars were altered to clay minerals or sericite, biotite has been partly altered to chlorite, and numerous small veinlets as much as 1 cm wide display alteration envelopes the same width as the veinlets (Blackwell and others, 1975).

Structure

Prominent structural features in the district are east-trending south-dipping normal faults and a dome produced by intrusion of the Marysville and Empire Creek stocks (fig. I13). Most normal faults have had relatively small vertical movements; the largest and southernmost fault placed lower Missoula Group strata against the Empire Formation, a displacement of at least 1,200 m. In some places, intrusive bodies appear to be bounded by normal faults. A fault along Ottawa Gulch has minor displacement (60–100 m), but it may have played an important role in localization of the Marysville stock (Blackwell and others, 1975). Many of the small faults in the district, which are not shown on the generalized geologic map (fig. I13), contain fissure veins, and some are younger than the intrusive rocks. Thrust faults that are exposed north and east of the Marysville area probably underlie most of the mining district.

ORE DEPOSITS

Gold in the Marysville district occurs primarily as native gold in manganiferous quartz-calcite veins characterized by quartz pseudomorphs after lamellar calcite. The veins are steeply dipping and have an average length of about 300 m and a maximum width of 12 m (Knopf, 1913, p. 64). Many veins are brecciated and contain angular fragments of wallrock in a matrix of quartz and calcite; the fissure veins indicate movement along faults in the district before and after mineralization. Major gold-producing veins such as the Empire vein (Empire mine), Bald Mountain vein (Cruse mine), Nile vein (Bell Boy mine), and North Star vein (Drumlummon mine) trend approximately east and are vertical to south dipping, the same orientation as the major structural trend. Exceptions are veins at the Bald Butte, Bell Boy (Bell Boy vein), and the Penobscot mine that trend N. 50°–60° W., and the main vein at the Drumlummon mine that trends N. 15° E. Veins are near the margin of the Marysville stock and are commonly hosted by hornfelsed Proterozoic strata. Crosscutting relations of the veins to igneous rocks suggest that the gold-bearing veins are younger than the Marysville stock and probably also the Bald Butte stock.

The episode of mineralization formed three types of veins. Type one veins contain molybdenite, pyrite, and fluorite with no appreciable amounts of gold; these veins are related to the intrusion of the Empire Creek and Bald Butte stocks, and are most abundant in the upper parts of the stocks. Type two veins contain gold and associated pyrite, chalcopyrite, sphalerite, and galena. At Bald Butte, type two veins contain minor amounts of molybdenite and fluorite, and they crosscut type one veins, clearly demonstrating a younger age (Rostad, 1969, p. 440). The third type of vein, typical of the Drumlummon mine, is characterized by gold, tetrahedrite, and chalcopyrite.

Most of the gold production from veins in the district has been from near-surface ore bodies, rarely deeper than 150 m. Apparently, the gold in the deeper parts of veins was insufficient to warrant mining, except at the Drumlummon mine where gold was mined to depths of 370 m on the North Star vein (Goodale, 1915). The impoverishment of ore at depth has been the subject of much speculation. The fact that most of the mined ore bodies were discontinuous shoots led some to believe in the late 1800's that the mines did not go deep enough to discover other lodes.

Drumlummon Mine

The Drumlummon mine, just south of the town of Marysville, accounted for more than half the gold production of the district and was the most extensively developed mine; it is presently inactive and its workings inaccessible. Most of the gold ore was mined from the Drumlummon, North Star, Empire, and the Old and New Castletown veins (fig. I15). The Drumlummon vein was developed 915 m along its length and to a depth of about 500 m; however, the grade of the ore decreased rapidly below the 120-m level (Goodale, 1915). The North Star vein, at nearly right angles to the Drumlummon vein, trends N. 80° E., crosscuts the granodiorite-hornfels contact, and yielded ore to a depth of 370 m. Most of the veins are enclosed by hornfels and contain angular fragments of wallrock in a matrix of quartz or calcite, or both.

Gold is associated with primarily tetrahedrite and chalcopyrite, and occurs in discontinuous ore shoots. The gold:silver ratio of the Drumlummon, Castletown, and Empire veins is 1:3, and of the North Star vein is 1:15 (Goodale, 1915, p. 267). Goodale (1915, p. 276) estimated that between 1883 and 1910 the Drumlummon mine produced about 568,898 oz of gold. Actual production figures from the mine between 1901 and 1948 show that 115,694.49 oz of gold was produced (McClernan, 1983, p. 46). Low-grade ore (less than 0.5 oz Au/ton), water problems, and financial difficulties led to the closure of the mine; in 1971 the mill burned.

CONCLUSIONS

The Marysville mining district has yielded more than 1 million oz gold from fissure veins. Most veins are characterized by manganiferous calcite, quartz pseudomorphic after lamellar calcite, and angular fragments of hornfelsed wallrock. Mineralization formed three types of veins; gold appears to be most abundant in the youngest of the three types of veins. A common feature of the highest grade ore is that it occurs in discontinuous shoots less than 150 m from the ground surface.

Gold mineralization does not appear to have been related to the Late Cretaceous intrusion of the Marysville stock. Concentration of lodes along east-trending structures indicates that regional faulting played a major role in controlling mineralization. Faults and fissures active before and during mineralization provided pathways for ore-forming fluids and sites for metal precipitation. Gold mineralization appears to have been the youngest event in the Marysville district and could have been related to the emplacement of the early to middle Tertiary Empire Creek stock, the volcanic event in late Eocene or early Oligocene time, or even to the presently recognized geothermal anomaly. The physical character and mineralogy of the veins strongly suggest that they are epithermal.

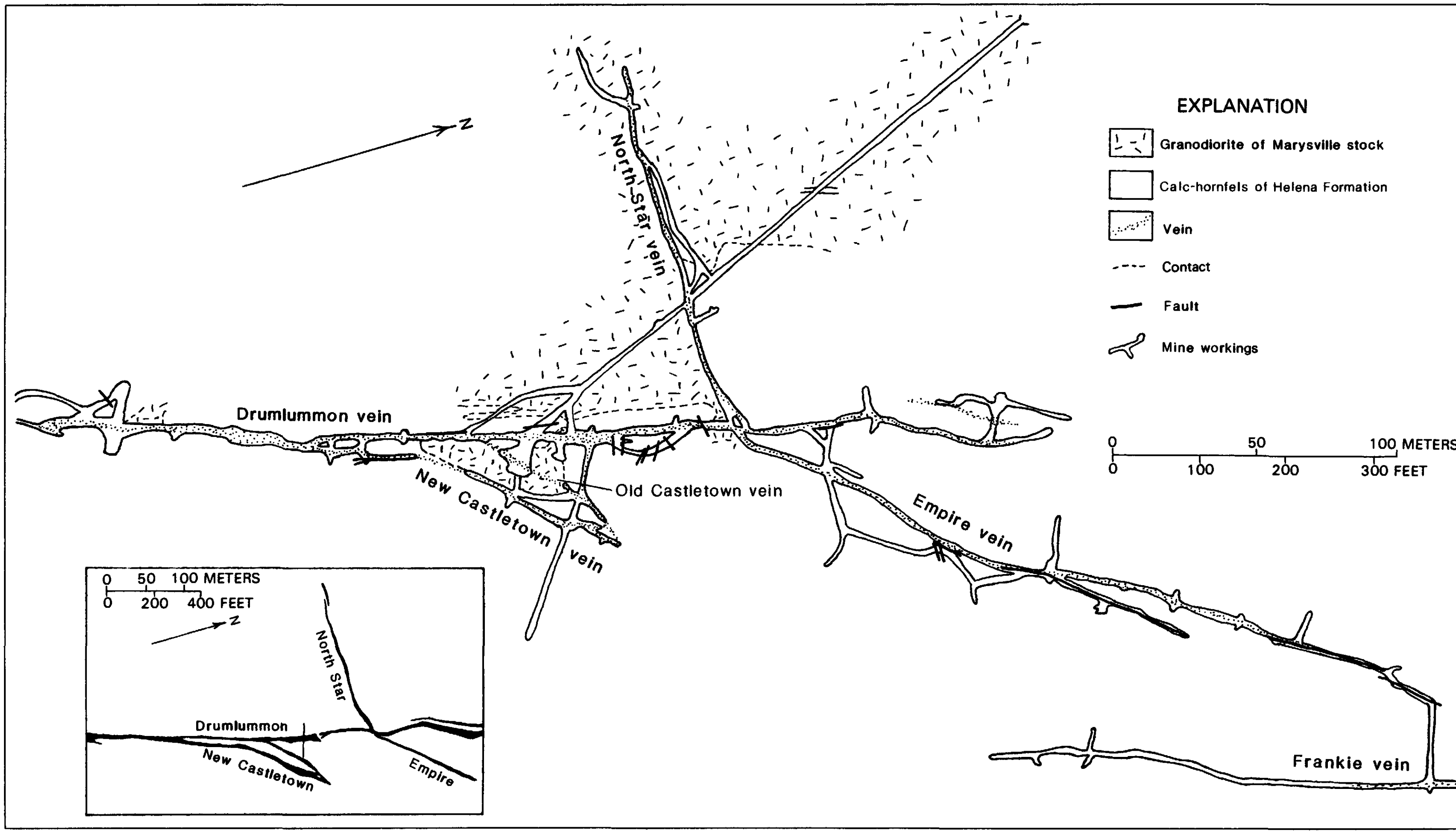

Figure I15. Geology of the fourth level, Drumlummon mine; inset shows relations of major veins (modified from Barrell, 1907).

Although no disseminated gold has been reported in the carbonate host rocks of the Empire and Helena Formations, the fact that most of the ore occurs in discontinuous shoots near the surface suggests enrichment other than in the oxidized zone; it could indicate primary control by the host strata or near-surface deposition in an epithermal hydrothermal system. For the most part, the Helena Formation is a dolomitic limestone that commonly contains sedimentary pyrite. The abundant stromatolites and cryptalgal laminae suggest that organic material was present during sedimentation; whether or not carbonaceous material is present in the rocks now is unknown. These characteristics of the Helena Formation are similar to host rocks of precious metal deposits of the Carlin, Nevada, type. Because of the presence of young intrusives, active hydrothermal systems, carbonate host strata, and penecontemporaneous faulting, exploration for disseminated gold in the Marysville mining district seems warranted.

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Gold Deposits of the Boulder County Gold District, Colorado

By James A. Saunders[1]

Abstract

Gold deposits of the Boulder County district, Colorado, occur in a Precambrian igneous and metamorphic terrane and are spatially and temporally associated with Tertiary alkalic hypabyssal stocks and dikes. The district, located at the northeast end of the Colorado mineral belt, contains some of the youngest intrusions emplaced during the Laramide orogeny. Gold production in the district has come primarily from gold-telluride and pyritic-gold veins. Both deposit types are typically located within a few kilometers of major northwest-trending faults, but the deposits commonly are hosted by smaller scale northeast-trending faults. Pyritic-gold veins, whose silver:gold ratios typically exceed 10:1, are composed predominantly of quartz, pyrite, chalcopyrite, and native gold, with minor amounts of tetrahedrite, sphalerite, and galena. Gold-telluride veins crosscut earlier pyritic-gold veins, and typically have silver:gold ratios less than 2:1. The most important ore minerals are sylvanite ($AuAgTe_4$), petzite ($AuAg_3Te_2$), calaverite ($AuTe_2$), hessite (Ag_2Te), and native gold. Fluid-inclusion studies indicate that gold-telluride deposition took place at temperatures lower than those at which the pyritic-gold veins in the district formed and lower than those at which "typical" epithermal precious metal veins formed. Field relationships, fluid-inclusion data, and reconnaissance geochemical data suggest that the fluids responsible for gold deposition in the northeastern part of the district may have evolved from the apparent magmatic solutions that formed a stockwork molybdenum-gold-tellurium zone within the Tertiary Porphyry Mountain stock and associated mineralized fluorite breccia pipes. A process of mixing of magmatic solutions with a peripheral convective meteoric water system in the vicinity of a differentiating pluton is consistent with the timing, zoning, and characteristics of the numerous deposit types near the Porphyry Mountain stock. Gold deposits elsewhere in the district may have had a similar origin, although a relationship between intrusive events and vein deposition elsewhere is less clear.

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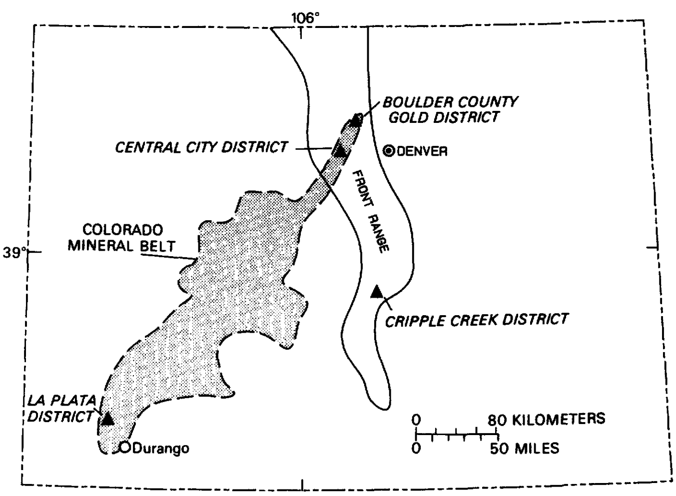

Figure I16. Map of Colorado showing location of the Boulder County gold district and other gold camps referred to in text.

INTRODUCTION

The Boulder County gold district lies in the Front Range, northwest of Denver, Colo. (fig. I16). The district is made up of numerous smaller mining camps, referred to here as subdistricts, the most important of which are Gold Hill, Jamestown, Magnolia, and Ward. Gold production came predominantly from gold-telluride veins at the first three camps, whereas pyritic-gold veins were most important at Ward. The bulk of gold production occurred prior to 1900, and records for this period are incomplete. Koschmann and Bergendahl (1968) have estimated that 1,048,000 troy oz (32.6 t (metric tons)) of gold was produced, 60–70 percent of which came from telluride ores (Kelly and Goddard, 1969).

Placer gold was first discovered in the district in 1859 near Gold Hill. Oxidized vein deposits were discovered at Gold Hill the following year, at Ward in 1862, and at Jamestown in 1865 (Lovering and Goddard, 1950). The discovery of primary gold-telluride minerals at the Red Cloud mine in the Gold Hill area led to a rapid increase in production from high-grade ores. Similar deposits were discovered in Jamestown and Magnolia in 1875. Production from Boulder County peaked in the early 1900's, and declined until 1934, at which time the price of gold increased. The price increase stimulated renewed activity in the district until World War II, when most mines closed permanently. Production from the district since 1960 has been sporadic and minor.

Both the district geology and aspects of lithologic relationships, structural control, and mineralogy of deposits of the Boulder County gold district have been well documented (Goddard, 1935; Wilkerson, 1939; Lovering and Goddard, 1950; Kelly and Goddard, 1969; Gable, 1985). The present study summarizes these results and includes additional data from more recent studies in the district. General characteristics of the deposits are considered in the context of (1) new studies in the Central City (Rice and others, 1985; Dickin and others, 1986; Spry, 1987) and Cripple Creek (Thompson and others, 1985) gold districts of the Front Range; and (2) these districts' general tectonic-metallogenic setting during the Tertiary in Colorado.

ACKNOWLEDGMENTS

Access to surface and underground workings in the Jamestown subdistrict was provided by Moritz Mining Company. Discussions about the gold deposits of Boulder County with Don Baker, Sam Romberger, Bill Threlkeld, Tom Nash, Steve Olmore, and Dave Rife were very helpful. Earlier versions of this manuscript were improved by reviews by Alan Wallace and Dan Shawe.

GEOLOGIC SETTING

The Boulder County gold district lies at the northeast end of the Colorado mineral belt (fig. I16), which was the site of abundant igneous activity and hydrothermal mineralization throughout the Tertiary. The mineral belt is interpreted to be a reactivated Precambrian shear zone, and it trends obliquely to the general north-south structural trend of the mountain ranges in Colorado (Tweto and Sims, 1963; Warner, 1978).

The Boulder County gold district occupies an area of approximately 225 km^2 within the Front Range. The district is underlain by a predominantly Precambrian intrusive and metamorphic terrane. Major lithologies include ≈1.8 Ga schist and gneiss; granitic rocks related to the 1.7 Ga Boulder Creek intrusive event; and granitic rocks of the 1.4 Ga Silver Plume intrusive event (Gable, 1980). Numerous small generally porphyritic Late Cretaceous and Tertiary stocks and dikes are exposed throughout the district (fig. I17).

Gold deposits in the district generally have a spatial association with the porphyritic intrusions, except in the Magnolia area where no stock is exposed (fig. I17). In addition, Lovering and Goddard (1950) and Jenkins (1979) cited field evidence, based on crosscutting relationships, that the deposits are similar in age to some of the porphyritic intrusions. Geochronologic data on the Tertiary intrusions in Boulder County (compiled by Gable, 1985) are sparse. Ages of the intrusions fall into two groups. The older suite, at 72–62 Ma, consists of monzonite, granodiorite, and quartz monzonite (Gable, 1985). The younger suite, which ranges in age from 59 to 44 Ma, consists of alkalic syenite, bostonite, and monzonite. Included in this latter group are the Sunset stock near Gold Hill, dated at 54–44 Ma, and the Porphyry Mountain stock near Jamestown, dated at 45 Ma (fig. I17). Also included in this group (although possibly younger) is the Bald Mountain stock near Gold Hill, which crosscuts the Sunset stock (Lovering and Goddard, 1950).

Gold mineralization in Boulder County was related to the younger alkalic suite, which is part of the monzonite suite as defined by Simmons and Hedge (1978) for the Colorado Front Range. The principal alkalic stocks in the district include the Porphyry Mountain stock at Jamestown, and the Tuscarora, Burnt Mountain, Bald Mountain, Sunset, and Sugarloaf stocks in the Gold Hill-Ward area (fig. I17). In addition, dikes of alkali syenite, bostonite, and biotite–quartz latite are common in the district.

The Porphyry Mountain stock, which Gable (1985) referred to as the northern part of the Jamestown stock, is a composite of three intrusive phases, one of which probably vented (Threlkeld, 1982). All the intrusive phases are generally porphyritic, leucocratic, and quartz bearing, and they have been classified as syenite by Gable (1985) and alkalic granite by Threlkeld (1982). Coarse phenocrysts of plagioclase, orthoclase, and antiperthite occur in a sheared, aphanitic groundmass. Fluorite is a common accessory mineral, and it is also present in breccia pipes along the margins of the stock. The Porphyry Mountain stock has undergone varied degrees of hydrothermal alteration, and whole-rock chemical analyses may not completely reflect the original rock chemistry. Representative chemical analyses of this stock are shown in table I6.

The Sunset, Burnt Mountain, Tuscarora, and Sugarloaf stocks are classified as alkali syenite by Gable (1985), who suggested that they all had a common parental magma. All the stocks are strongly porphyritic, generally with a trachytic groundmass. Plagioclase and hornblende are the predominant phenocrysts. A chemical analysis from the Sunset stock, which is representative of the suite of intrusions, is presented in table I6.

The Bald Mountain stock is a quartz bostonite porphyry, and the largest exposed mass of this rock type in the district. Bostonite is essentially a textural variety of trachyte, and the term was originated by Rosenbusch (1882) for the dike rocks near Boston, Mass. In bostonites, the

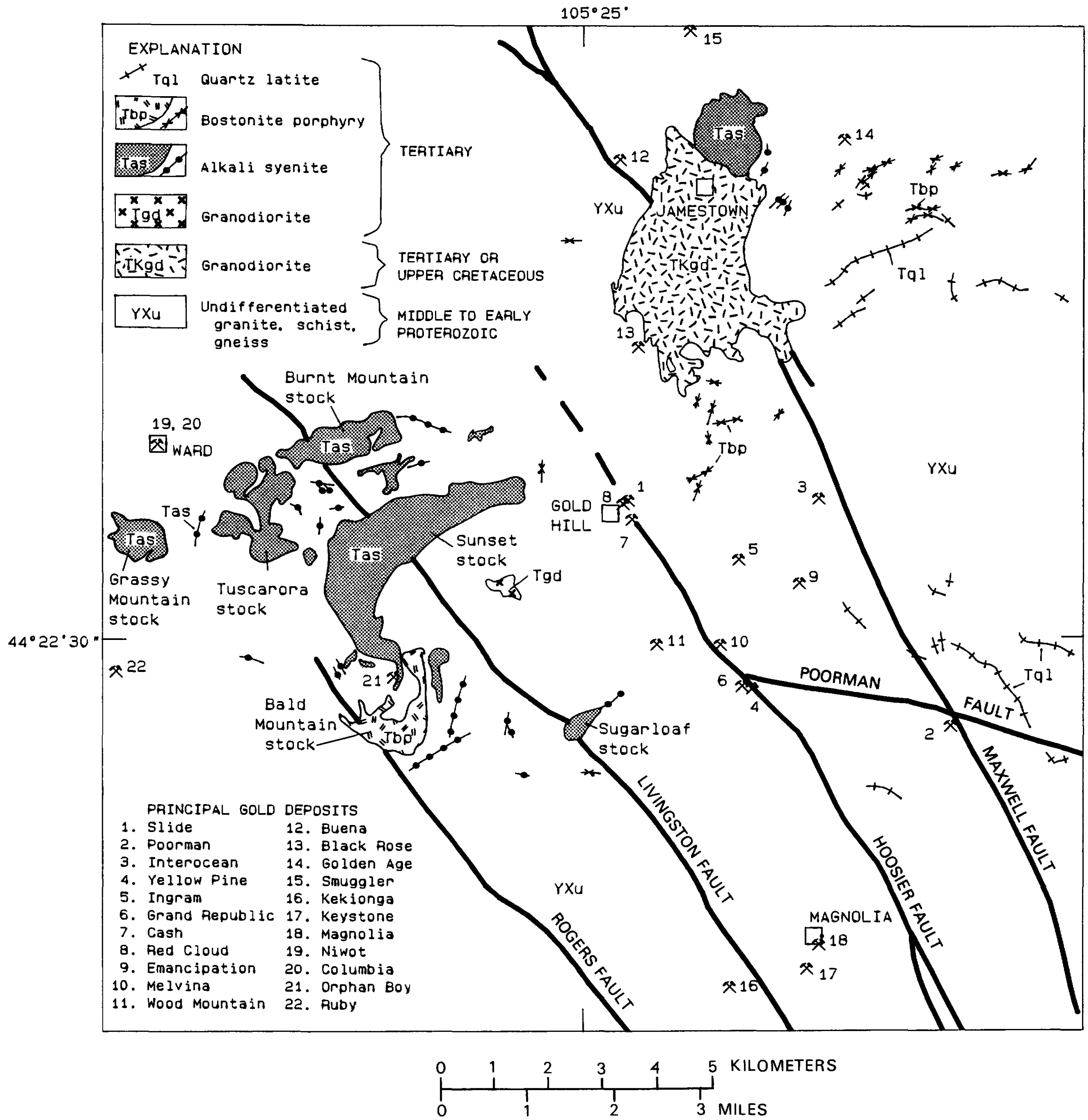

Figure I17. Schematic geology of the Boulder County gold district showing location of the most productive gold deposits. Compiled from Lovering and Goddard (1950) and Gable (1985).

alkali feldspars are arranged in a random pattern in the groundmass. Quartz bostonite from the Bald Mountain stock is pink colored in outcrop, and it contains large white alkali feldspar phenocrysts. Partially replaced quartz and pyroxene are present in the groundmass, as are opaque minerals and apatite (Gable, 1985). A chemical analysis of a sample of the Bald Mountain stock is presented in table I6, along with an analysis of a quartz bostonite dike from the Jamestown area. An analysis of a quartz bostonite stock spatially associated with the gold deposits in the Central City district is included for comparison.

The most prominent structural feature in the district is a set of northwest-trending normal and strike-slip faults (fig. I17) called "breccia reefs" by Lovering and Goddard (1950). These faults range in width from approximately 1 m to 100 m, and they consist of brecciated and sheared zones which are locally gougy (Lovering and Goddard, 1950). The faults are commonly silicified, and contain disseminated

Table 16. Whole-rock chemical analyses, in percent, of samples from alkalic stocks in the Boulder County district

[NA, not analyzed for]

Sample No.--	1 221	2 222	3 SD-5	4 208	5 206	6 290
SiO_2	66.4	68.2	72.4	65.4	63.8	69.3
TiO_2	0.17	0.20	0.02	0.09	0.41	0.02
Al_2O_3	17.4	16.4	15.6	16.9	16.5	15.6
Fe_2O_3	1.8	1.1	0.80	1.5	2.9	1.81
FeO	0.20	0.32	1.60	0.32	1.3	0.19
MgO	0.15	0.18	0.14	0.06	0.86	0.12
CaO	0.83	0.90	0.07	1.1	2.9	0.3
Na_2O	5.6	5.2	3.60	5.4	5.6	5.2
K_2O	5.3	5.9	5.30	5.9	4.0	6.9
H_2O	1.45	0.62	0.40	1.34	0.47	0.7
P_2O_5	0.06	0.07	0.01	0.07	0.36	0.02
MnO	0.01	0.04	0.05	0.08	NA	0.0
CO_2	0.01	0.01	NA	0.42	0.05	NA
F	0.32	0.50	NA	NA	0.05	NA

SAMPLE DESCRIPTIONS

1. Porphyry Mountain stock (Gable, 1985).
2. Porphyry Mountain stock (Gable, 1985).
3. Quartz bostonite dike, Jamestown area (Jenkins, 1979).
4. Bald Mountain stock, Gold Hill area (Gable, 1985).
5. Sunset stock, Gold Hill area (Gable, 1985).
6. Banta Hill stock, Central City, Colorado (Rice and others, 1985).

hematite, a combination which produces dikelike, red-tinged outcrops. The breccia reef faults are the oldest Tertiary structures in the district (Lovering and Goddard, 1950), and they may have controlled emplacement of the alkalic stocks. Jenkins (1979) proposed that the Porphyry Mountain stock was emplaced in one of the northwest-trending breccia faults at its intersection with less well defined northeasterly structures. The northeasterly fault orientation may have been important elsewhere in the district, based on the northeasterly trend of the Tuscarora, Burnt Mountain, and Sunset stocks (fig. I17).

GOLD DEPOSITS

The majority of the more productive gold-telluride and pyritic-gold deposits in the Boulder County district are located within a few kilometers of major northwest-trending breccia reef faults (fig. I17). However, gold deposits are generally hosted by younger, smaller scale, steeply dipping faults that have a northeasterly trend (Lovering and Goddard, 1950). The northeast-trending faults have strike lengths generally less than 3 km, and displacement on the order of 1–6 m (Lovering and Goddard, 1950). Multiple episodes of movement locally along these faults are evidenced by brecciated and recemented clasts of country rock and vein minerals hosted by these structures. Lovering and Goddard (1950) proposed that the breccia reef faults served as conduits for ascending ore solutions, but ore deposition occurred in the more open but less persistent northeast-trending faults.

The size of the productive deposits was generally small, with strike lengths commonly less than 100 m. The veins range in width from a few centimeters to more than 1 m, with a few as much as 6 m (Kelly and Goddard, 1969). Production along the larger vein systems extended to depths greater than 300 m. Gold ore generally was discontinuous within a given deposit, although relatively large continuous ore bodies were mined at the Slide and Buena mines (Kelly and Goddard, 1969). In the Slide mine, a single ore body 20–50 m in breadth was mined from the surface to a depth of 320 m. In the Buena mine (fig. I18), the intersection of three divergent veins formed a stockwork ore body called the "Big Stope," which was 50 m long, 20 m wide, and 10 m thick (Lovering and Goddard, 1950). The characteristically small and discontinuous nature of gold deposits in the Boulder County district has made exploration for them difficult, but their high-grade nature (commonly more than 1 oz Au/ton) accounted for significant amounts of contained gold.

The gold-telluride veins typically consist of fine-grained, dark-gray to white quartz enclosing breccia fragments and lenticular fragments of sheared wallrock (Kelly and Goddard, 1969). Telluride-bearing veins range

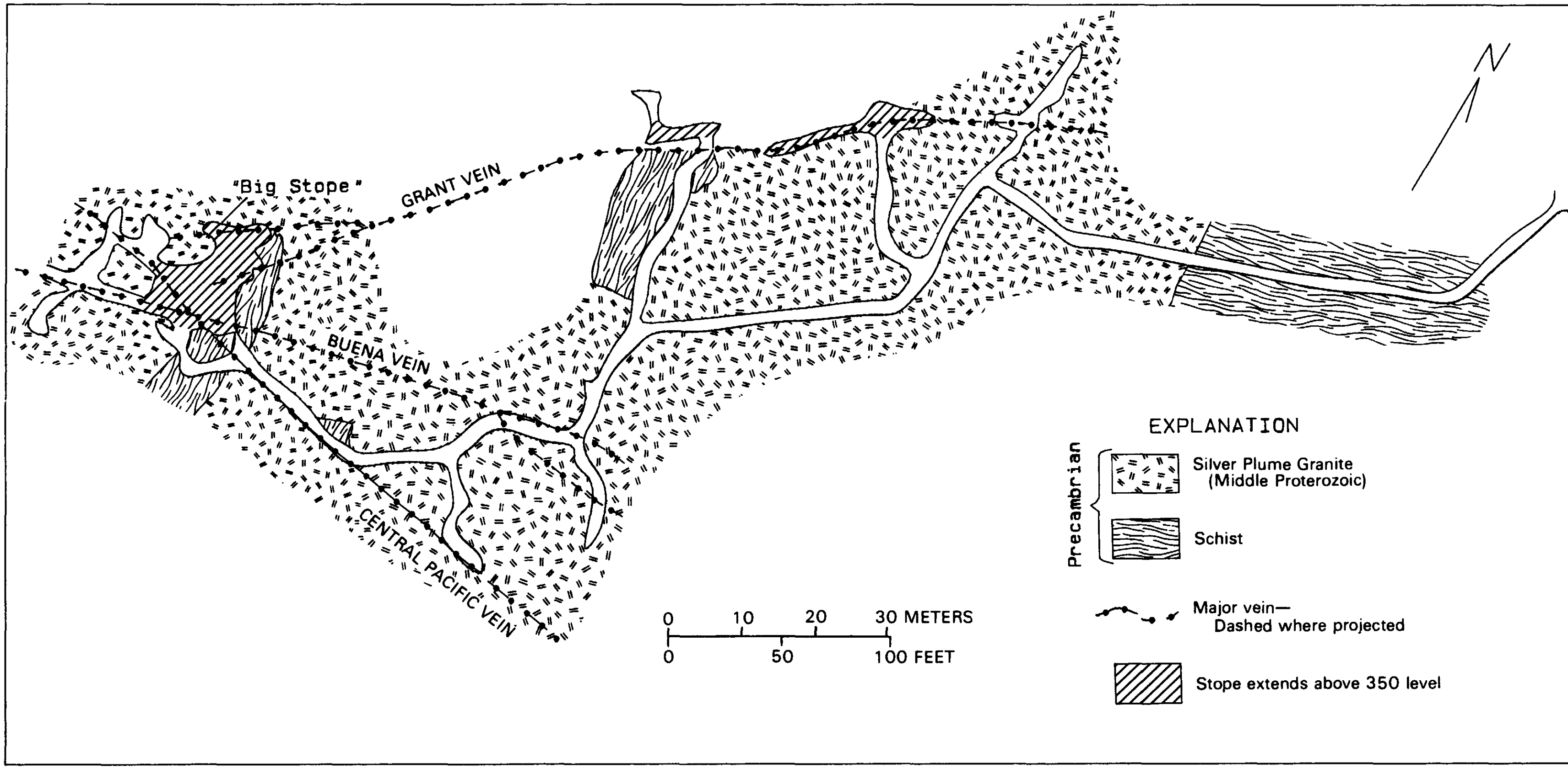

Figure I18. Simplified geology of the 350 level of Buena mine, Jamestown subdistrict. Modified from Lovering and Goddard (1950).

from a few millimeters to 0.5 m in width. Telluride minerals either are intergrown with the fine-grained quartz or project into voids. In some deposits, thin veinlets of quartz and tellurides extend into the predominantly gneiss and schist wallrocks as far as 1–2 m (Kelly and Goddard, 1969; Saunders, 1986).

The telluride minerals occur in groups of blades or irregular small masses in quartz seams. Complex intergrowths of several tellurides are common in these aggregates. Sylvanite ($AuAgTe_4$), petzite ($AuAg_3Te_2$), hessite (Ag_2Te), and native gold are the most important ore minerals. Locally, calaverite ($AuTe_2$) and krennerite ($(AuAg)Te_2$) are important. In addition, Kelly and Goddard (1969) have identified 10 other telluride minerals as well as native tellurium in the ores. Copper, lead, zinc, and iron sulfides are common, and sulfosalts are present in minor amounts. Quartz is the chief gangue mineral; roscoelite, the vanadium-rich mica, is extremely common and is intergrown with the tellurides. Locally, ankerite-dolomite, calcite, barite, and fluorite are also present.

Lovering and Goddard (1950) suggested that the drusy nature of the telluride and associated gangue minerals indicates that they were deposited late in the sequence of vein-forming events. Kelly and Goddard (1969) established the following generalized paragenetic sequence for ore minerals in the district from detailed petrographic studies: (1) early iron and base metal sulfides, (2) sulfosalts, (3) tellurides, (4) native gold. In addition, Saunders and Romberger (1985) observed that the tellurides with the highest tellurium content formed earlier than the low-tellurium tellurides.

Based on the mineralogy and limited geochemical data (table I7), the telluride ores are enriched in mercury, arsenic, antimony, molybdenum, copper, lead, zinc, fluorine, and vanadium, and possibly nickel in addition to gold, silver, and tellurium. This suite is typical of many epithermal precious metal deposits (Berger and Eimon, 1983), with the exception of nickel and vanadium. However, the extreme enrichment of these ores in tellurium resulted in a unique mineralogy not common to "typical" epithermal deposits (Saunders, 1986).

The vuggy, open-space-filling nature of the telluride ores has led many previous investigators to conclude that the ores were deposited from relatively low temperature hydrothermal solutions (for example, Lovering and Goddard, 1950). Reconnaissance fluid-inclusion data from gold deposits in the Jamestown area (Kelly and Goddard, 1969; Nash and Cunningham, 1973) have supported this conclusion. Their data indicate that deposition of gold tellurides from relatively dilute solutions occurred at temperatures less than 280 °C. In addition, Kelly and Goddard (1969) estimated that the deposits formed at depths between 650 and 1,300 m, based on geomorphic reconstructions.

More recent fluid-inclusion data from the Buena and Black Rose mines in the Jamestown area are consistent with the earlier data (Saunders, 1986). Homogenization temperatures from primary fluid inclusions from telluride-stage quartz in the Black Rose mine (fig. I19*A*) indicate ore deposition at temperatures of less than 215 °C (uncorrected for pressure). The salinity of the gold-stage solutions is approximately 6 weight percent NaCl equivalent. Homogenization temperatures from earlier quartz and pyrite in the veins range from 200 to 300 °C.

Three different types of veins are present in the Buena mine: (1) early stage fluorite-quartz veins with iron, copper, lead, zinc, and bismuth and minor gold (analysis 1, table I7); (2) quartz-pyrite-fluorite veins; and (3) quartz-tellurides-fluorite veins (Saunders, 1986). Fluid-inclusion data from each of these stages (fig. I19*B* and I19*C*) indicate a decrease

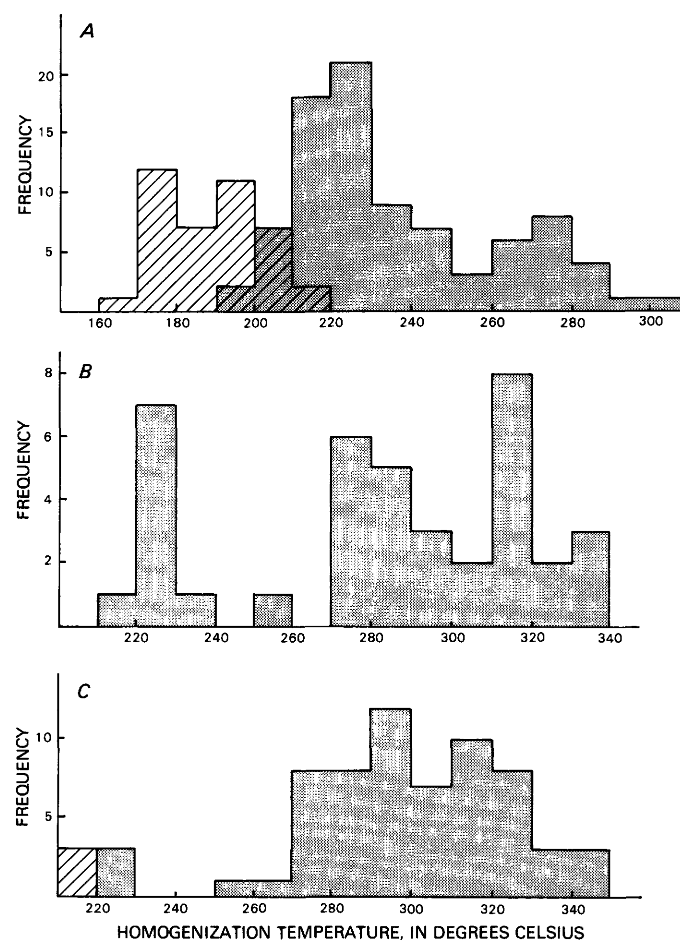

Figure I19. Fluid-inclusion data from gold deposits in the Jamestown subdistrict (Saunders, 1986). *A*, Homogenization temperatures from telluride-stage (cross-lined) and earlier quartz, pyrite, base metal sulfide deposits (shaded), Black Rose mine. *B*, Homogenization temperatures from Stage I fluorite-quartz-sulfides-gold veins, Buena mine. *C*, Homogenization temperatures from Stage II quartz-fluorite-pyrite veins (shaded) and Stage III gold-telluride veins (cross-lined), Buena mine. All temperatures uncorrected for pressure.

Table 17. Geochemical analyses of ore samples, Jamestown subdistrict, Colorado

[Samples 1-5 analyzed by T. Hopkins, U.S. Geological Survey, by semiquantitative emission spectroscopy. Sample 6 analyzed commercially by IGC/MS and atomic absorption (aa) where noted. Fe, Mg, Ca, and Ti in percent; all other values in ppm. ND, not detected]

Sample No.--	1 JB84–1	2 BR–300	3 BR–84–16	4 BR84–5	5 BR84–9	6 2701AJ	
Fe	0.07	1.5	2	2	1.5	5.5	
Mg	0.1	0.15	0.15	0.15	0.1	0.57	
Ca	10	0.3	<0.05	<0.05	<0.05	>40	
Ti	0.03	0.2	0.15	0.15	0.1	0.09	
Mn	70	50	30	30	30	10,000	
Ag	70	2,000	>5,000	>5,000	>5,000	9	aa
As	ND	1,500	700	700	500	179	aa
Au	10	500	>500	>500	>500	>0.045	aa
Ba	30	500	200	300	100	3,700	
Bi	1,000	ND	ND	15	ND	123	aa
Co	ND	7	10	10	10	ND	
Cr	100	150	200	300	200	40	
Cu	100	100	500	200	700	460	aa
La	1,000	<20	<20	30	20	ND	
Mo	70	ND	70	10	50	6.6	aa
Ni	7	20	70	100	150	<2	aa
Pb	15,000	150	10,000	5,000	20,000	2,900	
Sb	ND	ND	<100	ND	ND	2.3	aa
Sr	300	ND	ND	ND	ND	950	
V	20	150	200	200	700	120	
Y	200	30	ND	15	10	240	
Za	1,500	ND	200	200	200	288	aa
Zr	30	100	100	50	ND	ND	

SAMPLE DESCRIPTIONS

1. Early fluorite-quartz-sulfide-gold vein, Buena mine.

2-5. High grade gold-telluride ore, Black Rose mine.

6. Composite of sulfide-rich fluorite samples, Emmett glory hole. Additional analyses (all in ppm): Ga, 4.3 aa; Se, 5.52 aa; Te, 0.69 aa; U, 27 (IGC/MS).

in temperature with each successive stage. Similar decreasing trends were observed in CO_2 content and salinity (Saunders, 1986). The Buena mine is located less than 1 km from large fluorite breccia pipes which were deposited from high-temperature, supersaline, and CO_2-rich solutions (Nash and Cunningham, 1973). The spatial association of the two types of deposits, coupled with the fluid-inclusion data presented herein, led Saunders (1986) to conclude that the gold-bearing solutions evolved from the higher temperature fluids that produced the fluorite deposits, a possibility suggested by Nash and Cunningham (1973).

Although the gold deposits in the Boulder County district resemble epithermal veins elsewhere, fluid-inclusion evidence suggests that the gold-telluride veins formed at lower temperatures from solutions of higher salinity and CO_2 content than the "typical" epithermal deposits reviewed by Hedenquist and Henley (1985). There is no evidence of boiling during the deposition of the telluride stage minerals (Saunders, 1986).

Wallrock alteration effects associated with the gold-telluride-stage mineralization and those resulting from earlier, higher temperature vein mineralization are difficult to distinguish. The wallrocks closest to the veins have a quartz-sericite-pyrite alteration assemblage that grades outward either into a zone of argillically altered wallrock or into fresh wallrock (Kelly and Goddard, 1969). Sericite is present from a few centimeters to a meter outward from the veins, and silicified rocks extend as far as 10 cm away from the veins. Fragments of country rock enveloped by vein minerals have been intensely silicified. Locally, as at the Black Rose mine, roscoelite is an alteration mineral adjacent to telluride-bearing veinlets in schist (Saunders, 1986).

Pyritic-gold deposits accounted for the bulk of gold production in the Ward subdistrict, and significant amounts in the Gold Hill and Jamestown subdistricts. Oxidized parts of these deposits locally contained rich pockets of free gold that were encountered in the early mining. In the Ward subdistrict, nearly all the ore occurs as tabular shoots or in chimneys of roughly elliptical cross section that are hosted by Precambrian granite and gneiss (Lovering and Goddard, 1950). Byproduct silver, lead, copper, and zinc were recovered from ores consisting predominantly of pyrite and chalcopyrite with lesser amounts of galena, sphalerite, fluorite, molybdenite, and wolframite. In addition, ore samples from recent (early 1980's) underground workings in the Sunset area along the east edge of the Ward subdistrict contain gold in close association with abundant tetrahedrite (J.A. Saunders, unpub. data). Silver:gold ratios for ore shipped from the Ward subdistrict were approximately 10:1. In comparison, silver:gold ratios from gold-telluride ores typically were less than 2:1 (Lovering and Goddard, 1950).

Pyritic-gold veins generally formed earlier than the telluride veins, but locally the reverse was true. Lovering and Goddard (1950) described the typical age relationship between the two vein types in the Golden Age mine in the Jamestown subdistrict. Principal production from the mine came from the Golden Age pyritic-gold vein, which was crosscut and offset by the smaller Sentinel gold-telluride vein (Lovering and Goddard, 1950). Recent (early 1980's) underground workings beneath the original Gold Age mine exhibit similar relationships. These low-grade (less than 0.1 oz Au/ton) quartz-pyrite veins are crosscut locally by telluride-bearing veinlets (J.A. Saunders, unpub. data). In the Buena and Black Rose mines of the Jamestown subdistrict, quartz-pyrite veins were deposited earlier than the gold-telluride ores, the telluride ores typically having precipitated in open spaces along the existing veins (Saunders, 1986). The quartz-pyrite stage in these deposits reportedly contains minor gold, and this stage may have been synchronous with the deposition of more productive, pyritic-gold veins elsewhere in the district.

Fluid-inclusion data from pyritic-gold veins indicate that they formed at approximately 240–280 °C from relatively dilute solutions (Kelly and Goddard, 1969; Nash and Cunningham, 1973). This temperature range is similar to that of the quartz-pyrite vein mineralization that preceded telluride deposition in the Black Rose and Buena mines (fig. I19). Wallrock alteration associated with pyritic-gold veins has not been studied in detail, and is interpreted to have been similar to the alteration around the telluride veins (Kelly and Goddard, 1969). However, Saunders (1986) suggested that the quartz-sericite-pyrite alteration assemblage typical of the wallrocks adjacent to gold-telluride-bearing veins at the Buena and Black Rose mines was a result of the earlier stage, higher temperature quartz-pyrite vein mineralization. If so, this assemblage may be more typical of the pyritic-gold veins than it is of the gold-telluride stage.

DISCUSSION AND CONCLUSIONS

Gold deposits in the Boulder County district are spatially and apparently temporally associated with 55–44 Ma hypabyssal stocks of alkalic affinity that were intruded into a Precambrian igneous and metamorphic terrane. These deposits represent the youngest gold deposits associated with the Laramide orogeny. (See also Bookstrom, 1981.) The youngest stock in the Jamestown subdistrict, the Porphyry Mountain stock, is interpreted to have formed during a time of decelerated plate convergence (Threlkeld and Gonzales-Urien, 1985) prior to the general extensional tectonic environment typical of the central Rocky Mountains beginning about 35 Ma. Gold telluride deposits in Colorado formed during both the Laramide orogeny and the later extensional tectonic environment manifested by the Rio Grande rift (fig. I20). Included in the latter group are the Cripple Creek district, the most productive gold-telluride camp in the world, and minor but significant precious metal telluride deposits in the San Juan Mountains. Climax-type molybdenum deposits were emplaced during the extensional tectonic regime (fig. I20), along the intersection of north-south-trending faults with earlier northeast-trending Laramide (Colorado mineral belt) structures (Bookstrom, 1981). Bookstrom (1981) proposed a southwest retreat of the magmatism associated with Climax-type deposits during the mid to late Tertiary. Tertiary paleotectonic reconstructions for Colorado are mostly speculative for this time interval, but some correlation between the changing tectonic environment, deep crustal structures, compositions of magmas, and types of associated hydrothermal ore deposits seems evident.

The origin of the Boulder County gold deposits is not well understood. Lovering and Goddard (1950) suggested that the pyritic-gold deposits in the district are genetically related to the intrusion of monzonite, bostonite, and quartz bostonite. In addition, field relationships indicate that the gold-telluride veins are younger than the emplacement of the biotite latite dikes, which are the youngest intrusions in the district (Lovering and Goddard, 1950; Kelly and Goddard, 1969; Jenkins, 1979). Gable (1985) concluded that these deposits could not have been derived from the intrusions based on limited semiquantitative trace-element geochemical data. The Jamestown subdistrict has received the most study in the district, and it is exposed at a probable lower structural level than the rest of the district. Consequently, details of the complex mineralization and intrusive history there are considered in some detail here in order to provide constraints for a model for the origin of these deposits.

The Jamestown subdistrict includes several varieties of gold-bearing deposits: (1) commercial fluorite in breccia pipes with minor byproduct gold from sulfide-rich zones (table I7, analysis 6); (2) stockwork molybdenum-gold ore including parts per million-level tellurium within the

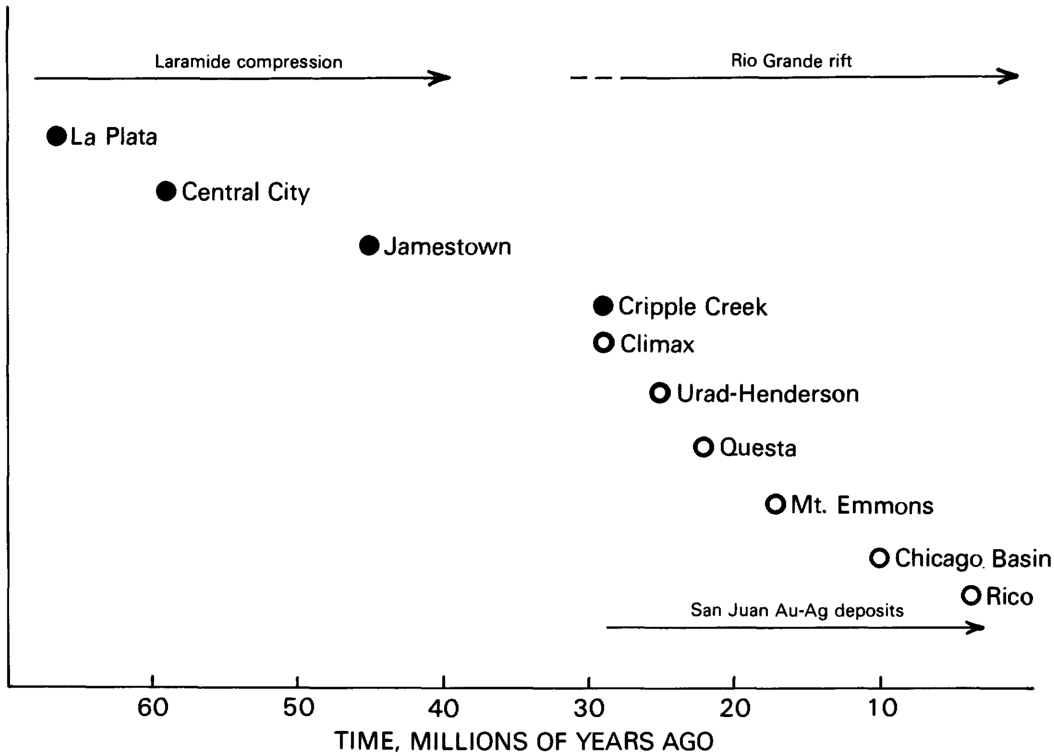

Figure I20. Timing of gold-telluride deposits in some representative districts in relation to Tertiary tectonic style and other mineral deposits in Colorado. Solid dot, Au-telluride deposit; open circle, Climax Mo deposit. Data from White and others (1981), Bookstrom (1981), Werle and others (1984), and unpublished data. Note that gold from Central City came primarily from base-metal-rich ores.

Porphyry Mountain stock (Threlkeld, 1982); (3) bismuth- and germanium-rich gold-bearing vein deposits marginal to the Porphyry Mountain stock (Jenkins, 1979); (4) pyritic-gold veins; and (5) gold-telluride veins. The relationships between the mineralizing and intrusive events are illustrated diagrammatically in figure I21. The limited fluid-inclusion data suggest that the temperature, salinity, and CO_2 content of the various episodes of mineralization decreased with time. If this assertion is correct, then it is possible that the fluids responsible for the bulk of the economic gold deposits evolved from early higher temperature, apparently magmatic-hydrothermal solutions.

The accumulated geochemical and geologic data from the Jamestown subdistrict indicate that the source of the suite of metals present in the deposits was the alkalic magmas. The Porphyry Mountain stock contains anomalous gold in many places at the surface (Jenkins, 1979), and parts-per-million levels of gold and tellurium in a stockwork molybdenite deposit at depth (Threlkeld, 1982). Data are lacking on gold and tellurium contents in bostonite or biotite latite dikes in the Jamestown subdistrict, but relatively fresh bostonite associated with some of the gold deposits in the Central City district (fig. I16) contain 0.09–0.22 ppm Te (Rice and others, 1985), and O.X ppm Au, Ag, and Te in the Idaho Springs district (Budge, 1983). In addition, bostonite reportedly hosts gold in the Jamestown subdistrict (Mike Wendell, Moritz Mining Co., oral commun., 1986).

The various intrusive phases and hydrothermal fluids in the Jamestown subdistrict are interpreted to have been derived from a differentiating monzonitic or syenitic body at depth. Volatile-rich fluids containing incompatible metals were concentrated in cupolas at the top of this body, probably represented by the Porphyry Mountain stock. These fluids were released explosively to form the fluorite breccia pipes and stockwork molybdenum-gold deposits. Mixing of these fluids with meteoric water in a peripheral convective hydrothermal system is consistent with the progressively lower temperatures of formation for each stage of gold deposition in the Jamestown subdistrict. The general aspects of the interpreted origin of deposits in the Jamestown subdistrict are shown in figure I22. In this interpretation, the discrete ore-forming events are not specifically related to individual intrusive events, but all are considered to have been derived to some extent from a differentiating magma chamber at depth.

The extent to which the Jamestown subdistrict is representative of the larger Boulder County district as a whole is not clear. However, the low-temperature nature of the telluride veins suggests that they formed either in a position distal to the magma chamber or very late in the

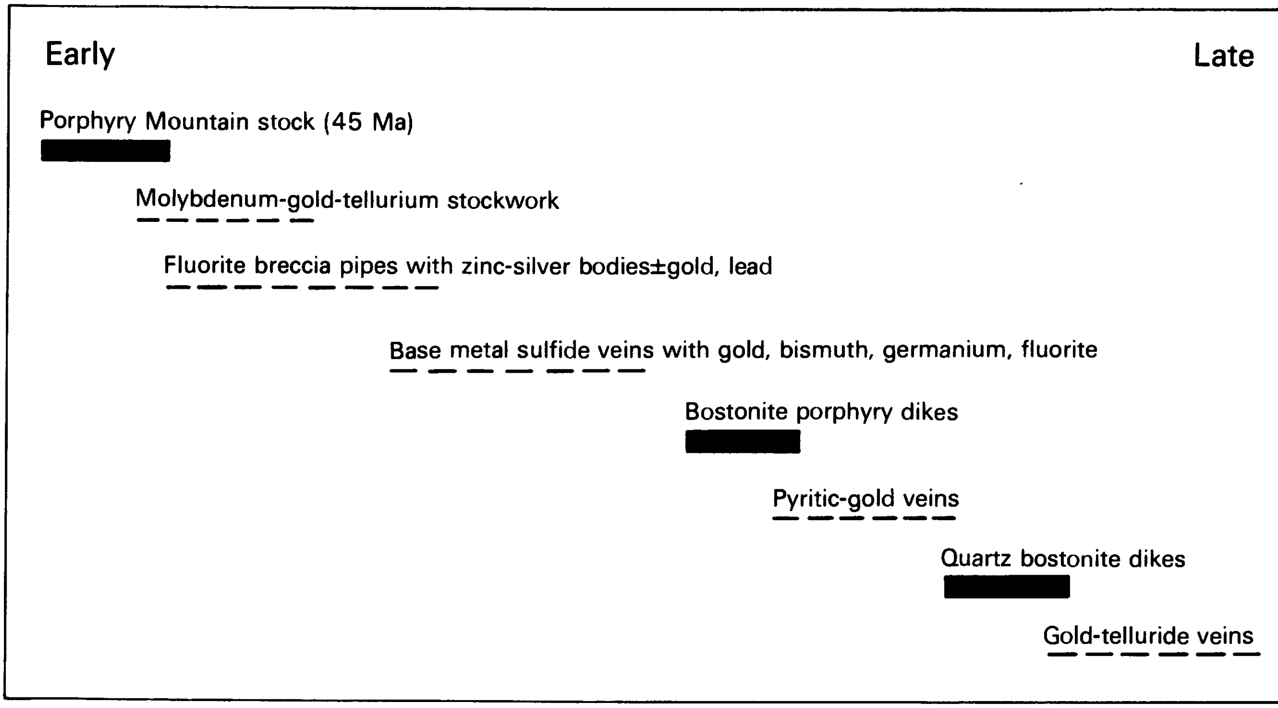

Figure 121. Relationships between intrusive events (solid bars) and mineralization (dashed lines) in the Jamestown subdistrict. Compiled from Lovering and Goddard (1950), Nash and Cunningham (1973), Jenkins (1979), and Saunders (1986).

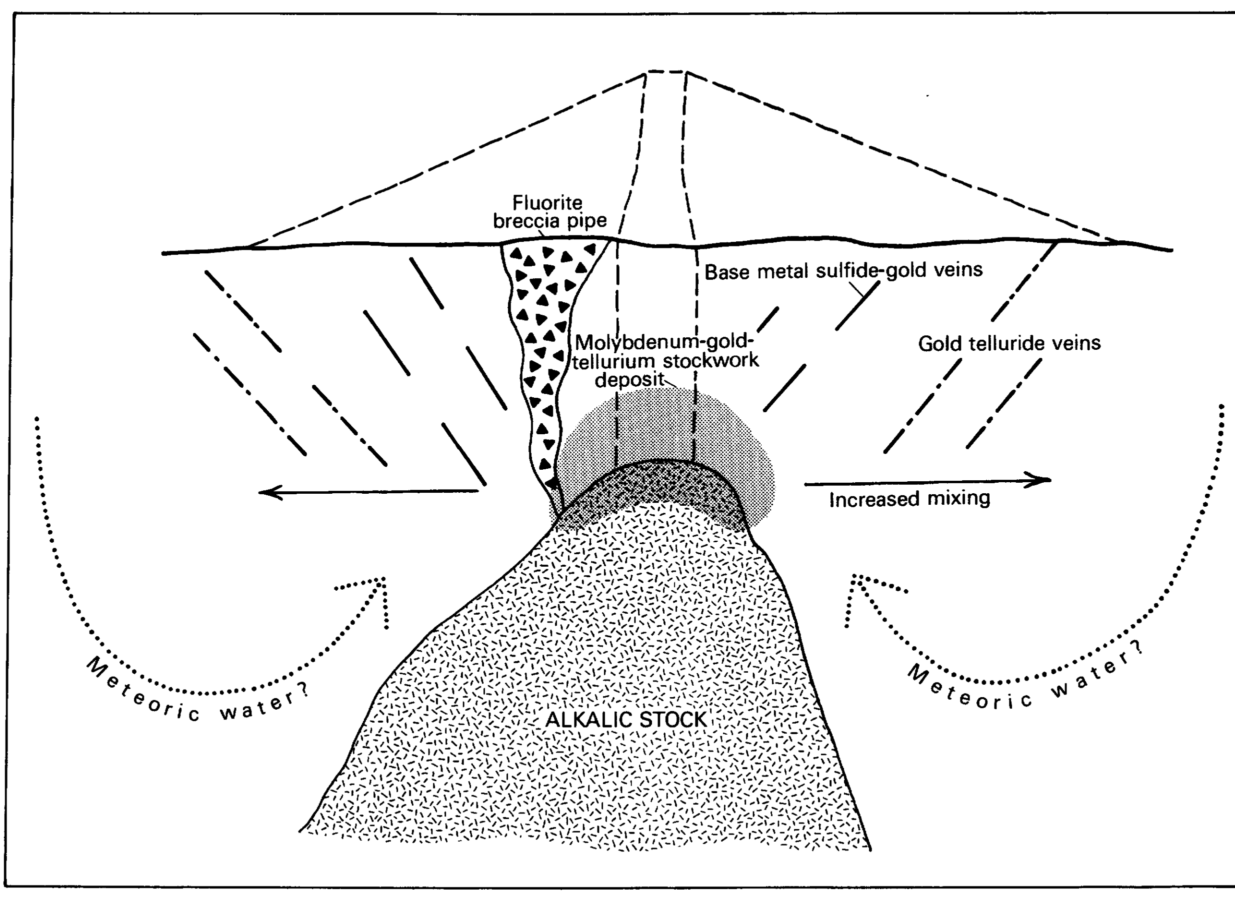

Figure 122. Sketch of interpreted features characteristic of the formation of gold and associated deposits in the Jamestown subdistrict.

cooling history. In the former case, the ore could have formed a considerable distance above the magma chamber, as has been suggested for some of the gold-telluride veins in the La Plata district (Werle and others, 1984; Saunders and May, 1986). Recent studies in the Central City district indicate that breccia-pipe and vein gold ores there are spatially related to an inferred Laramide stockwork molybdenum deposit of alkalic affinity (Rice and others, 1985; Dickin and others, 1986). The bulk of the gold in the Central City district came from base metal sulfide ores, although some production came from late-stage gold-telluride veins. Fluid-inclusion and isotopic studies of the Central City gold ores by Rice and others (1985) and Dickin and others (1986) document significant components of magmatic fluids in several of the various stages of mineralization. However, late-stage telluride deposits likely precipitated from meteoric water-dominated fluids.

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