



ELSEVIER

Journal of Geochemical Exploration 67 (1999) 167–189

**JOURNAL OF  
GEOCHEMICAL  
EXPLORATION**

www.elsevier.com/locate/jgeoexp

# Geochemistry of the Copper Flat porphyry and associated deposits in the Hillsboro mining district, Sierra County, New Mexico, USA

Virginia T. McLemore<sup>a,\*</sup>, Erik A. Munroe<sup>b</sup>, Matt T. Heizler<sup>a</sup>, Christopher McKee<sup>a</sup>

<sup>a</sup> *New Mexico Bureau of Mines and Mineral Resources, New Mexico Tech, Socorro, NM 87801, USA*

<sup>b</sup> *Department of Earth and Environmental Sciences, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA*

Accepted 23 August 1999

## Abstract

New geochemical, geochronological, and geological data, combined with earlier studies, have provided a refinement of the evolution of mineralization in the Hillsboro district in central New Mexico. Laramide (polymetallic) vein, placer gold, carbonate-hosted Ag–Mn and Pb–Zn, and porphyry-copper deposits are found in this district. The Hillsboro district is dominated by Cretaceous andesite flows ( $75.4 \pm 3.5$  Ma), breccias, and volcanoclastic rocks that were erupted from a volcano. The mineralized Copper Flat quartz-monzonite porphyry (CFQM,  $74.93 \pm 0.66$  Ma) intruded the vent of the volcano. The unmineralized Warm Springs quartz monzonite ( $74.4 \pm 2.6$  Ma) and a third altered, unmineralized quartz monzonite intruded along fracture zones on the flanks of the volcano. Younger latite and quartz-latite dikes intruded the andesite and CFQM and radiate outwards from the CFQM; the polymetallic vein deposits are associated with these dikes. The igneous rocks are part of a differentiated comagmatic suite. Alteration of the igneous rocks consists of locally intense silicification, biotite, potassic, phyllic, and argillic alteration. Large jasperoid bodies have replaced the El Paso Formation, Fusselman Dolomite, Lake Valley Limestone, and Percha Shale in the southern part of the district. Many workers in the district have recognized district zoning. The low-sulfur (<7%) porphyry-copper deposit forms the center. Trending radially from the CFQM are Laramide Au–Ag–Cu veins. Carbonate-hosted replacement deposits (Ag, Pb, Mn, V, Mo, Zn) are located in the southern and northern parts of the district, distal from the center. Collectively, the evidence suggests that the deposits found in the Hillsboro district were formed by multiple convective hydrothermal systems related to the Copper Flat volcanic/intrusive complex. © 1999 Elsevier Science B.V. All rights reserved.

**Keywords:** porphyry-copper deposit; New Mexico; polymetallic veins

## 1. Introduction

The Copper Flat deposit at Hillsboro in the Animas Mountains in central New Mexico is one of the older Laramide porphyry-copper deposits in the Arizona–Sonora–New Mexico porphyry-copper belt (Fig. 1, Table 1). The Copper Flat quartz-monzo-

nite porphyry (CFQM) hosts porphyry-copper mineralization, which intruded the vent facies of a volcanic/intrusive complex. Laramide polymetallic vein and Miocene–Holocene placer gold deposits radiate outwards from the CFQM, which are flanked by distal carbonate-hosted Ag–Mn and Pb–Zn replacement deposits to the south and north. The CFQM deposit is “hypothesized ... as manifesting the dominant geologic style of porphyry-copper envi-

\* Corresponding author. E-mail: ginger@gis.nmt.edu

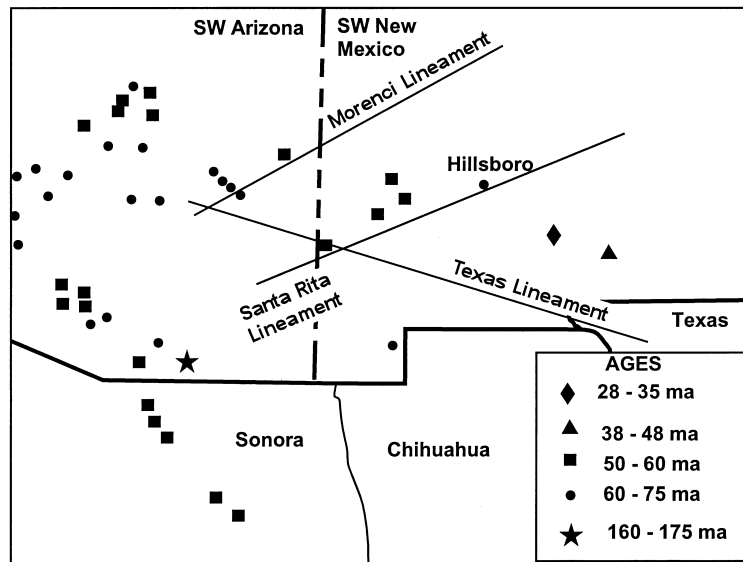


Fig. 1. Porphyry-copper deposits in Arizona, Sonora, and New Mexico.

ronments of Laramide deposits” in the southwestern United States (Titley, 1995). New geochemical, geochronological, and geological data, combined with earlier studies, have provided a refinement of the model for the evolution of the mineralization in the Hillsboro district. The purpose of this study is to (1) chemically define the various magmatic, mineralizing, and alteration systems, (2) date the magmatic events, (3) describe and chemically contrast the four

types of mineral deposits, and (4) chemically characterize the metallogenic zoning. This will ultimately refine exploration models for porphyry-copper deposits.

Although, numerous geologists have examined the Hillsboro area, very few studied the entire magmatic and mineralized system. Lindgren et al. (1910), Harley (1934), and Reeves (1963) described the vein deposits. Kuellmar (1955) first described the

Table 1

Laramide porphyry-copper deposits in New Mexico — does not include porphyry-copper deposits associated with mid-Tertiary alkaline igneous rocks at Organ Mountains, Orogrande, and Cerrillos

Porphyry-copper deposit	Age (Ma)	Commodities produced	Comments
Copper Flat (Hillsboro)	75 (this report)	Cu, Au, Ag	Being permitted
Santa Rita (Chino)	55–56 (Phelps Dodge Corp. unpubl. data)	Cu, Au, Ag	Active
Tyrone (Burro Mountains)	53–56 (DuHamel et al., 1995)	Cu, Au, Ag	Currently mined for copper leach
Hanover-Hermosa Mountains (Fierro-Hanover)	57 (McLemore et al., 1995)	Cu	Skarn deposits produced, mine closed early 1999, exploration continues
Lone Mountain	51 (P.B. Hubbard and P.G. Dunn, unpubl. report, 1983)	None	Inactive, deposit drilled in 1975–1989
McGhee Peak (Peloncillo Mountains)	?	None	Inactive, deposit drilled in 1970s–1990s

porphyry-copper deposit, with later work by Dunn (1982, 1984) and Fowler (1982). Segerstrom and Antweiler (1975) described the Miocene–Holocene placer gold deposits. Lovering (1972) and Lovering and Heyl (1989) briefly described jasperoid in the Paleozoic limestones south of the Copper Flat volcano. Hedlund (1977, 1985) and Seager et al. (1982) provided geologic mapping of the area. Despite previous work, many questions remained, including the age of the volcanic rocks, sequence of geologic events, and the relationship between the four types of mineral deposits and the igneous rocks.

## 2. Methodology

This study involves the incorporation of new detailed geologic mapping by the senior author with new and published geochemical and geochronological data. Several studies have provided geochemical data of the vein and replacement deposits and of the igneous rocks from the Hillsboro district (Table 2). These data are used freely in this report where appropriate. Additional selected samples of the veins, replacement deposits, jasperoids, and associated altered rocks were sampled and analyzed by the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) by X-ray fluorescent spectrometry (XRF). Many of these samples were also analyzed by instrumental neutron activation analysis (INAA) and induced-coupled plasma spectrometry (ICP) methods by commercial laboratories. A summary of these data is given in Table 3.

Additional samples of the igneous rocks were collected and analyzed by XRF for major and trace ele-

ments to determine the magmatic differentiation history (Tables 4 and 5). Major elements were analyzed by XRF on fused glass discs and trace elements were analyzed using pressed powder briquettes. Major elements were analyzed by Uniquant semi-quantitative XRF methods using pressed powder briquettes for samples Hill 3, 84, 85, 86, 87, and 91. Limited major element data by Fowler (1982) and Hedlund (1985) were used where appropriate.

Samples were also submitted to the New Mexico Geochronological Research Laboratory at NMBMMR for age determinations by  $^{40}\text{Ar}/^{39}\text{Ar}$  methods. Laboratory procedures are briefly described by McLemore et al. (1999) or can be obtained from the senior author. It is not practical to present all of these data in this report, but the data are available from the senior author.

## 3. Mining history

The Hillsboro, or Las Animas district, was discovered in 1877 in the Animas Mountains in Sierra County (Fig. 2). Sporadic production has occurred since 1982. Minor production from the Snake mine resumed in 1989/1990. Past production has been predominantly from the Miocene–Holocene placers and Laramide veins, although minor production has occurred from the CFQM porphyry-copper and carbonate-hosted replacement deposits (Table 6). The CFQM deposit, in the northern part of the Hillsboro district, was discovered in 1975 (Dunn, 1982, 1984). Quintana Minerals Corp. began open pit production from the CFQM in early 1982 (Table 6). The mine closed in June 1982 because of low copper prices. Alta Gold Co. is currently applying for mining per-

Table 2  
Summary of geochemical data from the Hillsboro area

Source	Number of samples	Types of samples	Analytical methods
Korzeb and Kness (1994); Korzeb et al. (1995)	142	Veins, replacement deposits	INAA, ICP
Fowler (1982)	8	Andesites, latites, quartz monzonites	XRF
Hedlund (1985, table A-4)	5	Andesite, latite, quartz monzonites	Rapid rock method
This report; V.T. McLemore, unpubl. data	87	Altered and unaltered igneous and sedimentary rocks, veins, replacement deposits, jasperoids	XRF, ICP, INAA

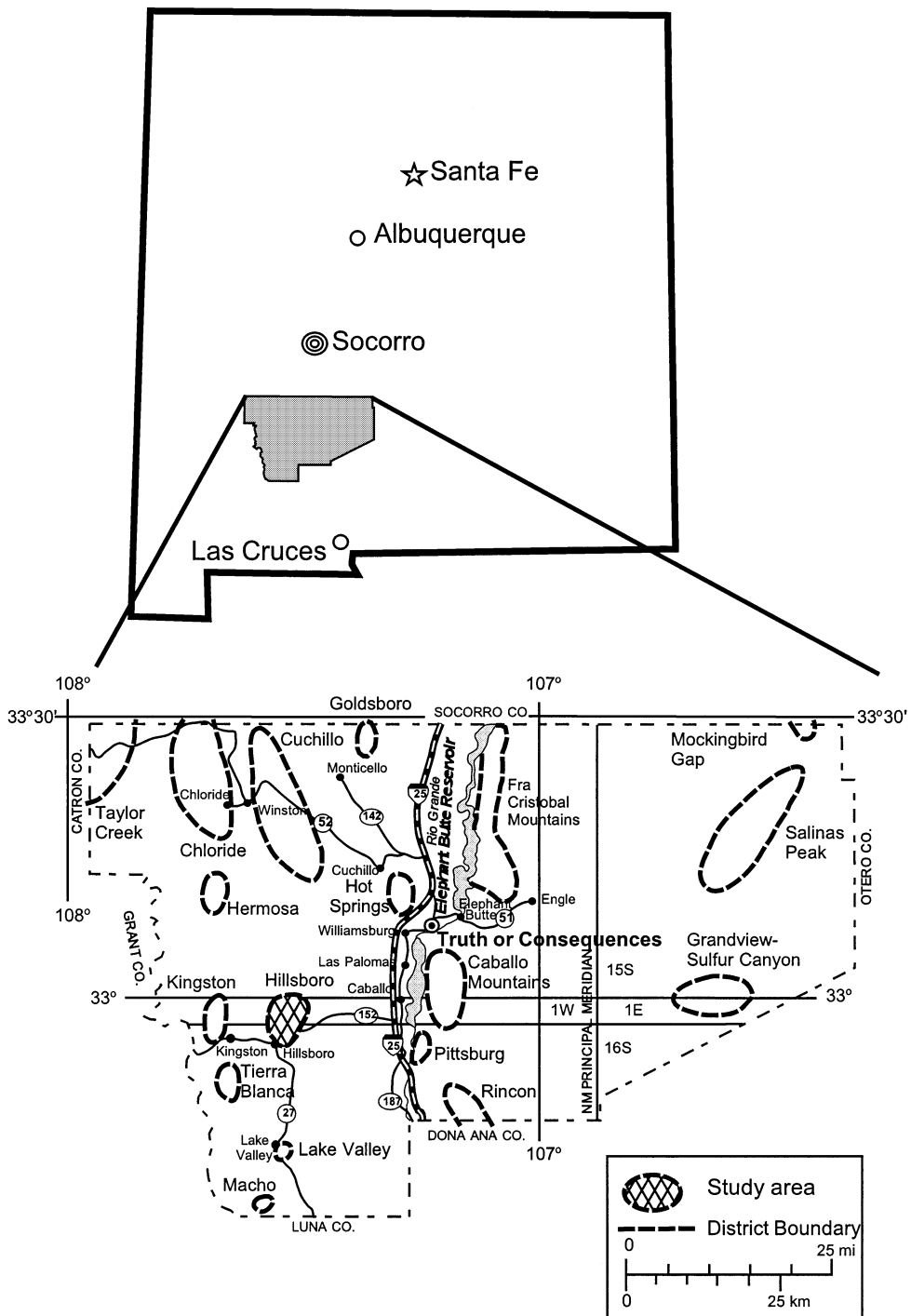


Fig. 2. Location of the Hillsboro mining district, Sierra County, New Mexico.

Table 3

Summary of chemical analyses of samples from porphyry-copper, Laramide vein, carbonate-hosted replacement and jasperoid deposits<sup>a</sup>

	Au	Ag	Cu	Pb	Zn	Mo	As	Sb	Ba	Bi	Mn	V
<i>Porphyry-copper deposits</i>												
Maximum	8,810	2.6	>9,999	250	1,032	475	9	30	1,000	23	2,415	173
Minimum	<2	<2	4	<5	14	<2	<0.6	<0.6	140	<10	19	<2
Average	620	0.8	1,806	34	170	35	2	2	613	14	320	46
<i>N</i>	24											
<i>Laramide vein deposits</i>												
Maximum	64,600	590	57,337	9,175	17,026	68	8,560	43	3,000	4,958	59,796	626
Minimum	<2	<2	<2	<5	11	<2	<0.6	<0.6	<100	<10	5	2
Average	3,921	28	3,428	770	863	12	120	3	671	231	2,954	13
<i>N</i>	194											
<i>Replacement deposits</i>												
Maximum	99	64	196	10,000	>20,000	160	388	26	20,000	104	49,430	>2,000
Minimum	<2	<2	7	<5	227	<2	1.6	<0.6	<100	11	149	25
Average	48	32	110	5,151	12,665	39	93	14	5,238	52	15,254	352
<i>N</i>	8											
<i>Jasperoids</i>												
Maximum	19	<2	49	49	268	2	21	na	301	na	176	131
Minimum	<5		2	8	10	<2	0.8		21		52	2
Average	13		11	28	66	2	7		123		110	26
<i>N</i>	8											

<sup>a</sup> Analyses for Au, Sb, and Ba by INAA or XRF; other elements were determined using ICP or XRF. Analyses in ppm (parts per million) except for Au which is in ppb (parts per billion). *N* = number of samples; na = not available. Geochemical data from Korzeb and Kness (1994), Korzeb et al. (1995), and V.T. McLemore (unpubl. data).

mits to reopen the Copper Flat mine; reserves are in Table 6.

#### 4. Geology

The Hillsboro mining district lies on the eastern edge of the Laramide Arizona–Sonora–New Mexico porphyry-copper belt (Fig. 1). The 75 Ma CFQM porphyry-copper deposit is the oldest in the state (Table 1). Although the Piños Altos pluton (ca. 71–75 Ma; McDowell, 1971) and a Georgetown monzonite dike (ca. 71 Ma; McLemore, 1998) have associated Cu–Au–Ag skarn or Ag carbonate-hosted replacement deposits, porphyry-copper deposits are not known to occur in these areas. The possibility exists that undiscovered porphyry-copper deposits may occur in the subsurface in these areas. The Laramide orogeny and the porphyry-copper deposits in Arizona–Sonora–New Mexico are a product of magmas generated during subduction of the Farrallon plate beneath North America about 75 to 50 Ma

(Titley, 1995; Keith and Swan, 1996). The Laramide orogeny in New Mexico was followed by mid-Tertiary volcanism that resulted in extensive caldera formation and eruption of associated ignimbrites. Basin and Range faulting followed from 35 Ma to the present time.

The local geology of the Hillsboro district is dominated by Cretaceous andesite flows, breccias, and volcanoclastic rocks that were erupted from the Copper Flat volcano, which forms the Animas Mountains. The circular outcrop area of the andesite is approximately 6 km in diameter (Fig. 3) and it is at least 830 m thick as determined from drill core data (Hedlund, 1977). The andesite is bounded by Paleozoic sedimentary rocks on the north, south, and southwest across normal faults, and is unconformably overlain on the east by Quaternary alluvial fan deposits. The surrounding rocks include Paleozoic sedimentary rocks and Quaternary alluvial fan deposits (Hedlund, 1977).

The andesite is typically green-gray to brown-gray, holocrystalline and porphyritic with a fine-

Table 4  
Major element analyses in percent (XRF) of igneous rocks from the Copper Flat volcanic complex<sup>a</sup>

Sample	Lat.	Long.	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> (T)	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	LOI	Total
<i>Andesites</i>														
Animas 1 <sup>b</sup>	32 51 15	107 32 05	58.9	0.56	17.07	6.13	0.14	1.86	4.92	4.04	2.73	0.36	3.51	100.17
Hill 5 <sup>b</sup>	32 57 59	107 32 17	50.28	1.16	16.50	12.32	0.21	7.87	4.42	3.20	2.52	0.59	1.77	100.84
Hill5A <sup>b</sup>	32 57 59	107 32 17	51.83	0.98	17.09	9.81	0.20	6.24	4.24	3.73	2.99	0.53	2.07	99.71
Hill 6 <sup>b</sup>	32 58 50	107 31 20	51.02	1.03	19.29	9.86	0.21	7.54	3.31	3.08	2.04	0.61	1.80	99.79
Hill 14	32 56 32	107 33 14	54.53	0.70	15.81	6.67	0.17	5.30	2.44	3.39	4.83	0.45	5.53	99.82
Hill 60	32 56 45	107 33 30	62.79	0.62	14.38	8.09	0.14	0.89	1.00	0.26	3.65	0.27	6.66	98.75
Hill 78	32 55 35	107 31 30	53.41	0.87	14.63	8.62	0.17	3.37	5.95	2.88	5.03	0.65	4.11	99.69
Hill 93 <sup>b</sup>	32 57 59	107 32 05	53.24	1.07	16.39	9.83	0.22	3.44	6.76	3.61	2.43	0.47	2.26	99.72
Hill 92 <sup>b</sup>	32 57 58	107 31 55	56.52	0.94	17.42	8.56	0.18	2.25	6.37	4.33	2.53	0.60	1.11	100.80
Hill 600 <sup>b</sup>	32 57 46	107 31 05	47.24	1.98	15.65	13.09	0.19	6.29	8.72	3.42	1.56	0.59	1.12	99.84
<i>Quartz monzonite</i>														
Hill 36	32 58 02	107 31 53	70.67	0.33	15.23	1.79	ND	0.31	0.40	2.98	6.33	0.06	1.55	99.64
Hill 85	32 58 11	107 32 07	62	0.56	20.8	3.61	0.01	0.77	0.55	2.02	7.2	0.15	4.3	101.97
Hill 2 <sup>b</sup>	32 57 58	107 32 02	52.61	0.90	17.97	9.45	0.12	7.19	3.11	3.83	1.39	0.69	1.61	98.87
Hill 3	32 57 58	107 31 57	48.4	1.19	16.4	13.9	0.1	3.17	4.6	2.64	5	0.87	6.04	102.31
Hill 4 <sup>b</sup>	32 57 59	107 32 00	61.93	0.48	17.57	5.12	0.06	0.86	3.23	4.05	5.83	0.21	1.22	100.56
Hill 7 <sup>b</sup>	32 58 38	107 31 44	64.16	0.34	17.70	3.49	0.08	1.69	0.39	4.67	6.28	0.09	0.78	99.67
Hill 94 <sup>b</sup>	32 59 08	107 31 34	63.68	0.32	17.41	3.43	0.15	0.50	1.85	4.71	6.54	0.11	0.63	99.33
Hill 15 <sup>b</sup>	32 56 17	107 33 00	60.26	0.81	15.61	7.05	0.14	5.28	2.61	3.26	3.18	0.41	1.06	99.67
Hill 39 <sup>b</sup>	32 58 05	107 31 47	60.57	0.50	16.90	5.63	0.05	2.40	1.02	3.76	5.32	0.21	1.81	98.17
Hill 45	32 58 07	107 32 47	66.61	0.38	16.55	3.11	<0.01	0.73	0.41	3.68	5.28	0.08	2.94	99.77
Hill 84 <sup>b</sup>	32 58 12	107 32 05	62.8	0.46	15.9	3.45	0.04	0.46	3.59	2.12	8.5	0.17	2.89	100.38
Hill 86	32 58 10	107 32 07	58.8	0.61	18.5	2.92	0.04	0.68	5.5	2.65	6.8	0.23	3.36	100.09
Hill 89 <sup>b</sup>	32 56 05	107 32 55	64.33	0.53	16.09	4.98	0.13	1.19	3.87	3.67	3.90	0.25	0.84	99.78
Hill 49 <sup>b</sup>	32 55 33	107 32 23	61.98	0.64	15.37	4.99	0.09	4.03	1.84	3.95	4.73	0.29	1.42	99.33
Hill 19 <sup>b</sup>	32 59 41	107 30 40	59.52	0.66	16.98	5.99	0.19	5.83	1.67	3.54	2.87	0.36	1.71	99.32
Hill 54 <sup>b</sup>	32 56 06	107 32 47	57.45	0.83	15.38	7.52	0.14	5.04	2.36	3.91	4.02	0.50	1.66	98.81
Hill 83	32 58 13	107 32 03	70.65	0.17	14.87	1.73	0.01	0.25	0.97	3.08	7.00	0.05	1.61	100.39
Hill 88	32 56 05	107 32 55	74.29	0.17	13.25	1.76	0.04	0.34	1.11	3.77	4.43	0.06	0.64	99.86
Hill 11	32 56 05	107 33 06	67.93	0.45	14.74	3.76	0.07	2.35	1.01	3.78	4.29	0.16	1.04	99.58
<i>Latite dike</i>														
Hill 23	32 58 49	107 31 23	66.03	0.28	17.53	0.65	<0.01	0.30	0.29	3.05	9.08	0.07	2.07	99.35
Hill 91	32 57 58	107 31 55	61.2	0.65	19	3.78	0.04	0.72	1.66	2.72	9.1	0.29	1.39	100.55
Hill 44	32 57 59	107 32 17	61.74	0.31	16.45	4.07	0.03	0.39	0.35	2.59	8.25	0.08	4.67	98.93
Hill 21	32 59 36	107 31 51	61.56	0.44	16.87	3.70	0.11	2.55	1.10	3.23	6.99	0.18	3.61	100.34
Hill BT1 <sup>b</sup>	32 57 25	107 33 20	46.69	2.06	15.68	12.04	8.51	5.54	3.62	1.90	0.55	2.20	2.25	101.04
Hill 1	32 57 59	107 32 03	69.21	0.25	17.22	1.46	<0.01	0.34	0.14	4.30	6.67	0.02	1.04	100.64
Hill 43	32 57 59	107 32 17	59.79	0.29	16.93	3.73	0.04	1.78	0.48	2.69	8.68	0.09	3.82	98.32
Hill 87	32 57 45	107 31 04	60.4	0.84	20.4	2.68	0.01	0.32	1.08	2.47	10.2	0.6	2.15	101.15
Hill 95 <sup>b</sup>	32 58 58	107 01 58	56.83	0.63	17.28	5.38	0.13	1.85	4.02	3.58	5.60	0.32	3.88	99.51
Hill 13	32 56 32	107 33 14	60.87	0.36	17.45	2.55	0.17	3.30	0.57	3.23	6.30	0.10	4.55	99.44
Hill 17	32 56 42	107 33 26	60.23	0.39	17.64	4.06	0.24	2.88	0.58	3.72	6.24	0.13	3.52	99.62
Hill 56 <sup>b</sup>	32 56 40	107 32 35	51.92	0.87	15.19	8.27	0.22	2.65	5.57	3.51	4.80	0.56	5.59	99.15
Hill 29	32 56 03	107 31 47	61.75	0.66	16.83	4.43	0.13	1.70	1.35	3.62	6.18	0.31	3.01	99.97

<sup>a</sup> Total iron reported as Fe<sub>2</sub>O<sub>3</sub>(T). Latitude, longitude in degrees, minutes, and seconds.<sup>b</sup> Denotes fresh sample as determined by Fig. 4 and LOI < 3%.

Table 5

Trace element analyses (XRF, except for Au and Ag by ICP) in parts per million (ppm) (except for Au which is in ppb) of igneous rocks from the Copper Flat volcanic complex<sup>a</sup>

Sample	Au	As	Ag	Ba	Cr	Cu	Ga	Mo	Nb	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr	S, %	
<i>Andesite</i>																					
Animas 1	<2	2	<0.5	877	47	28	20	<2	6	8	12	102	671	9	2	79	24	77	169	Nd	
Hill 5	<5	3	<2	686	17	19	21	2	<2	16	11	161	897	11	3	294	28	96	110	0.01	
Hill 5A	Nd	3	Nd	685	43	84	19	<2	<2	14	12	183	899	9	2	215	25	82	109	Nd	
Hill 6	7	1	<2	466	18	70	24	1	3	9	14	132	642	9	2	210	34	117	155	0.15	
Hill 14	<5	1	<2	848	28	15	18	3	10	14	10	200	664	18	4	149	30	96	217	0.01	
Hill 60	514	15	<2	381	34	350	19	1	5	8	79	222	64	11	4	135	33	2200	210	<0.01	
Hill 78	Nd	4	Nd	1119	83	87	20	<2	2	16		189	1020	18	3	153	31	78	219	Nd	
Hill 93	Nd	3	Nd	635	8000	93	21	24	3	590	8	102	623	7	2	224	32	104	156	Nd	
Hill 92	Nd	2	Nd	822	43	942	22	3	4	6	12	114	750	8	2	113	37	103	198	Nd	
<i>Quartz monzonite</i>																					
Hill 36	69	<2	<2	615	58	2200	17	55	12	5	12	279	362	28	5	31	272	25	272	0.14	
Hill 85	Nd	2	Nd	618	85	65	20	9	13	5	9	246	288	18	6	42	36	51	243	Nd	
Hill 2	14	2	<2	451	22	827	23	1	<2	10	5	120	776	5	<2	167	28	74	124	<0.01	
Hill 3	75	2	<2	694	101	2800	25	8	4	13	15	268	731	12	4	206	36	70	219	6.24	
Hill 4	8	2	<2	914	26	154	21	4	7	6	14	224	922	15	5	60	34	37	205	0.06	
Hill 7	9	2	<2	876	13	18	20	2	10	5	28	219	716	19	5	21	30	45	323	<0.01	
Hill 94	Nd	2	Nd	823	8000	55	20	25	9	536	27	230	606	16	3	54	35	63	285	Nd	
Hill 15	9	1	<2	1083	14	32	19	2	10	14	19	110	705	15	4	126	40	76	206	0.01	
Hill 39	29	2	<2	776	64	499	20	3	7	7	16	293	751	21	5	63	30	41	237	0.42	
Hill 45	17	<2	<2	817	89	69	20	4	10	6	13	251	527	27	9	33	21	16	244	2.12	
Hill 84	Nd	<2	Nd	433	115	2900	19	44	14	5	17	321	280	24	11	33	32	32	297	Nd	
Hill 86	Nd	1	Nd	670	78	1300	20	11	11	4	15	222	472	20	6	39	31	35	226	Nd	
Hill 89	Nd	2	Nd	1100	108	13	19	<2	7	6	21	152	645	14	2	48	36	75	201	Nd	
Hill 49	20	2	<2	1066	18	43	18	1	4	9	29	159	569	15	4	81	34	56	223	0.01	
Hill 19	5	2	<2	966	<2	4	19	1	4	5	9	115	784	11	3	63	34	69	221	0.27	
Hill 54	18	2	<2	911	13	69	18	2	5	10	21	155	663	15	4	157	36	93	217	0.35	
Hill 83	Nd	1	Nd	469	119	2300	18	4	10	4	13	316	381	41	12	15	25	20	182	Nd	
Hill 88	Nd	<2	Nd	450	122	7	17	<2	12	5	19	184	230	35	6	15	21	36	99	Nd	
Hill 11	<5	1	<2	1121	18	7	17	2	7	10	13	185	450	23	4	45	35	35	178	<0.01	
<i>Latite dike</i>																					
Hill 23	11	7	<2	939	5	31	15	1	9	5	15	371	374	17	7	23	24	17	324	<0.01	
Hill 91	Nd	2	Nd	896	47	904	20	3	10	4	20	259	605	15	3	37	25	61	304	Nd	
Hill 44	77	9	<2	34	37	4000	18	3	8	7	56	357	301	51	8	34	26	295	330	2.02	
Hill 21	16	3	<2	796	<2	38	18	1	8	6	9	264	364	16	5	55	27	48	298	<0.01	
Hill BT1	56	5	<2	482	197	52	18	2	36	97	11	38	776	9	3	187	27	127	182	0.01	
Hill 1	12	1	<2	361	8	13	23	4	14	3	16	248	208	20	4	10	24	17	400	0.02	
Hill 43	51	5	<2	768	38	237	17	5	9	7	46	382	291	22	3	32	23	175	337	0.96	
Hill 87	Nd	2	Nd	985	39	642	22	2	10	4	11	355	478	14	5	58	62	45	303	Nd	
Hill 95	Nd	5	Nd	794	9000	87	19	45	8	689	12	217	1092	18	5	118	26	64	237	Nd	
Hill 13	14	1	<2	728	3	5	19	4	10	4	6	264	336	17	5	29	23	49	268	0.14	
Hill 17	8	1	<2	873	3	5	19	2	7	4	17	245	421	19	8	37	31	69	267	0.46	
Hill 56	16	1	<2	737	15	108	20	5	9	10		170	361	14	3	211	35	127	224	0.02	
Hill 29	<5	3	2	1019	19	35	18	1	7	12	219	249	786	19	5	67	29	709	240	<0.01	

<sup>a</sup> Nd = not analyzed for.

grained matrix. It consists of essential plagioclase, orthoclase, blue-green to brown hornblende, magnetite, and trace amounts of biotite, clinopyroxene,

quartz, rutile, apatite, and zircon. Along the road to the Snake mine, an andesite flow breccia is exposed that contains large clasts (as much as 30

Table 6

Summary of production and reserves from the Hillsboro district (from Hedlund, 1985; Alta Gold, Form 10K, 1999; V.T. McLemore, unpubl. data)

**Production.** An estimated 270,000 troy ounces Au (from placer and lode deposits), 134,000 troy ounces Ag, 24.4 million pounds Cu, and 154,000 pounds Pb were produced from the district 1877–1982.

The Copper Flat mine produced 1.2 million short tons of ore containing 7.4 million pounds Cu, 2301 troy ounces Au and 55,966 troy ounces Ag March–June 1982.

**Reserves.** The Copper Flat deposit has proven and probable reserves of 50,210,000 short tons of ore at an average grade of 0.45% Cu, 0.004 oz/ton Au, 0.066 oz/ton Ag and 0.015% Mo as of December 31, 1998.

Contained metal is approximately 447,872,000 pounds Cu, 223,900 ounces Au, 3,299,500 ounces Ag and 14,762,000 pounds Mo.

cm in diameter) of latite, quartz latite, and quartz monzonite, suggesting that the Copper Flat volcano was active after intrusion of the quartz-monzonites and latite dikes. However, reconstruction of the vol-

canic stratigraphy is not possible because of erosion and faulting.

The CFQM intrudes the vent of the volcano, whereas the unmineralized Warm Springs quartz

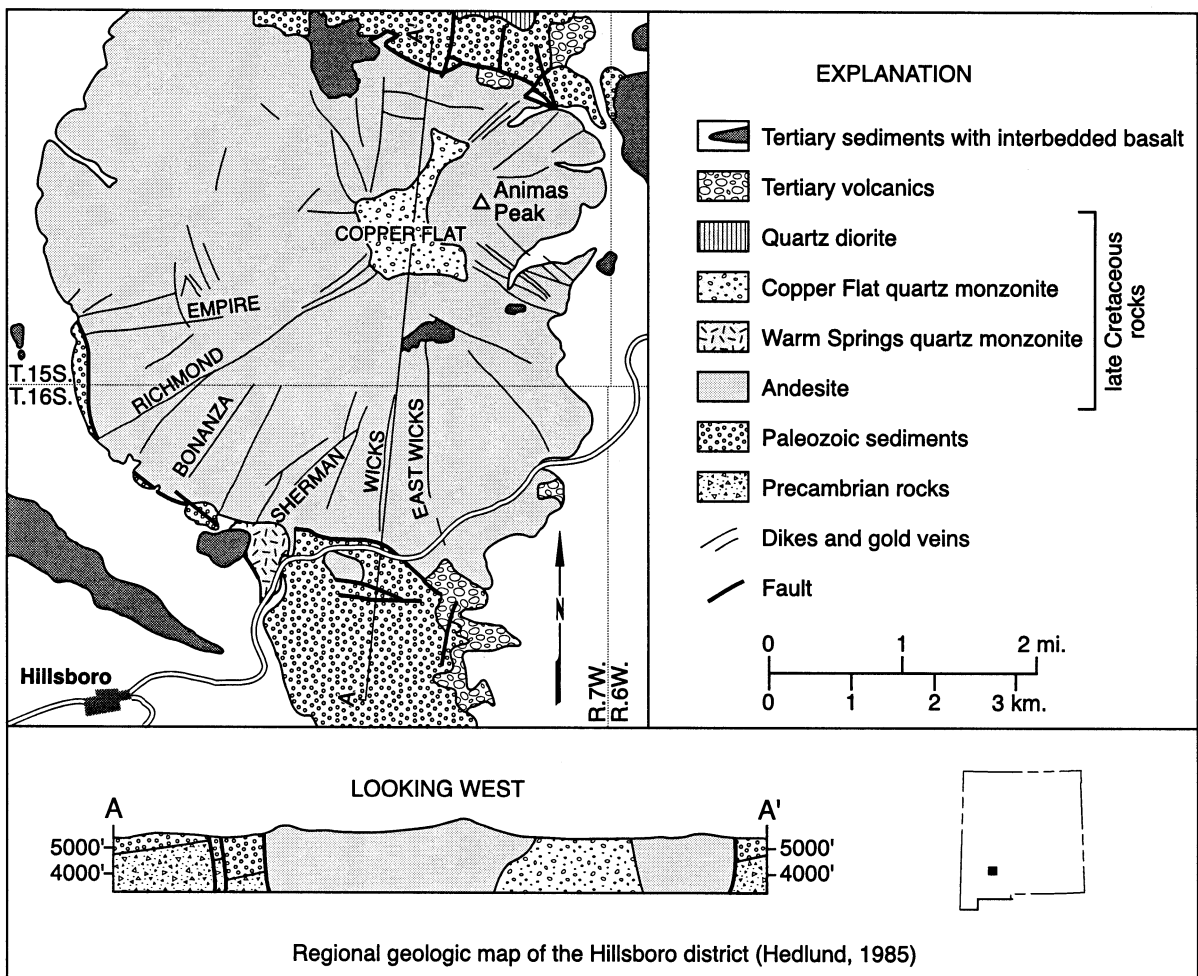


Fig. 3. Generalized geologic map of the Hillsboro mining district (modified from Dunn, 1982 and Hedlund, 1985).



monzonite intrudes the andesite south of the CFQM. A third altered, but unmineralized quartz monzonite crops out in the northern part of the district. These latter two intrusions most likely represent small, satellite stocks that intruded along fracture zones on the flanks of the volcano.

At least 34 latite, quartz latite, and monzonite radial dikes intruded the andesite and CFQM, but do not intrude the Warm Springs quartz monzonite. The dikes are gray to tan, typically porphyritic, linear to sinuous along strike, as much as 1.6 km long, and range in thickness from 1 to 38 m. Two types of latite dikes occur: (1) a porphyric latite with large orthoclase phenocrysts, and (2) a fine-grained aphanitic latite. The Laramide polymetallic veins are subparallel to the dikes and trend outwards from the CFQM similar to spokes of a wheel.

The Kneeling Nun Tuff (ca. 34 Ma) and Sugarlump Tuff (ca. 35 Ma) unconformably overlie the andesite flows locally (Hedlund, 1977), indicating that the Copper Flat volcanic/intrusive complex was buried during the Oligocene. Fission track data on apatite from the quartz monzonite indicates that the Copper Flat complex was uplifted during the Miocene at  $21.7 \pm 3.6$  Ma (Kelley and Chapin, 1997). It is possible that the Love Ranch basin may have buried the Copper Flat volcano until Miocene uplift. Black, scoriaceous basaltic dikes intruded the andesite and quartz monzonite. These dikes are relatively unaltered and are probably associated with the alkali basalt flows capping many of the peaks of the Animas Mountains. These alkali basalts are of Pliocene age (4 Ma; Seager et al., 1982).

## 5. Alteration

### 5.1. Igneous rocks

Hydrothermal alteration is extensive in the Hillsboro district. Alteration is a general term describing the mineralogic, textural, and chemical changes of a rock as a result of a change in the physical, thermal, and chemical environment in the presence of water, steam, or gas (Bates and Jackson, 1980). Alteration halos surrounding ore deposits are typically more widespread and easier to recognize than some of the ore bodies themselves (Guilbert and Park, 1986).

Eight types of alteration mineral assemblages are recognized in the Hillsboro district (Table 7); these types are dependent upon the host rock type and overlap in both time and space.

Three types of alteration assemblages are recognized in the CFQM, i.e. biotite–potassic, potassic, and sericitic alteration (Table 7; Fowler, 1982). Biotite–potassic alteration corresponds to the highest copper grades in the CFQM and is characterized by secondary biotite and K-feldspar as veinlets and large crystals replacing the monzonite. Potassic alteration is peripheral to the CFQM copper-porphyry deposit and is characterized by large K-feldspars and rimming of plagioclase by K-feldspar (Fowler, 1982). Sericitic alteration forms the outermost alteration zone of the CFQM deposit and is characterized by replacement of biotites and feldspars by sericite. Quartz-sericite veinlets are also common.

The latite and quartz-latite dikes are extensively altered as they are nearly always associated with quartz veins that typically contain precious and base metals. Two types of alteration assemblages are present (Table 7). Phyllic alteration is adjacent to the mineralized veins and is characterized by quartz, K-feldspar, chlorite, and locally epidote, which have replaced biotite, hornblende, feldspars, and the groundmass. Potassic alteration consisting of quartz and sericite is also locally common. Pyrite is common in most dikes in both types of alteration assemblages.

The andesite is typically hydrothermally altered adjacent to the quartz-monzonite, latite dikes, and Laramide polymetallic veins. It is characterized by three types of alteration assemblages (Table 7). Phyllic alteration is adjacent to the mineralized veins and is characterized by epidote, chlorite, sericite, pyrite, and, locally, magnetite. Typically, pyrite and magnetite are altered to iron oxides. Sericite, epidote, and chlorite locally replace plagioclase. The andesite is locally bleached to a light greenish gray due to replacement by chlorite. Epidote–pyrite and pyrite veinlets are common along fractures within the andesite. Disseminated pyrite occurs throughout the andesite adjacent to the latite dikes and Laramide veins for a distance of several meters from contacts. Two stages of pyrite are common; early altered and corroded cubes and later fresh, unaltered cubes. The phyllic alteration zone is intermittent and

Table 7

Summary of hydrothermal alteration assemblages associated with the mineralization in the Hillsboro district (Fowler, 1982; Hedlund, 1985; this report)

Host rock/type of mineral deposit	Alteration mineral assemblage	Alteration type
Quartz monzonite/porphyry-copper deposit	Biotite, K-feldspar, quartz, pyrite	1 – biotite–potassic
	Chlorite, K-feldspar, quartz, pyrite	2 – potassic
	Sericite, quartz, pyrite	3 – sericitic
Andesites adjacent to the latite dikes and polymetallic veins	Epidote, chlorite, sericite, pyrite, magnetite	4 – phyllic
	Chlorite, sericite, calcite, quartz, pyrite	5 – argillic
	Sericite, calcite, chlorite, quartz, pyrite	5 – argillic
Latite/quartz-latite dikes associated with the polymetallic veins	Quartz, K-feldspar, pyrite, epidote, chlorite	4 – phyllic
	Quartz, sericite, chlorite, pyrite	5 – potassic
Limestones, dolomites	Garnet, epidote, magnetite, quartz	6 – skarn
	Marble, recrystallized limestone	7 – marble
	Quartz, iron and manganese oxides	8 – jasperoid

varies in thickness along the strike of the dikes and veins from less than a centimeter to up to a meter thick.

The argillic alteration zone is adjacent to and overlaps the phyllic zone. Argillic alteration is characterized by chlorite, sericite, calcite, pyrite, and quartz. Chlorite has replaced mafic minerals and the groundmass within the andesite producing a green color in the andesite. Disseminated pyrite is locally pervasive in the andesite. Rare chlorite veinlets form along fractures.

Locally, the andesite is altered to a second argillic mineral assemblage along Laramide veins that consists of sericite, calcite, pyrite, chlorite, and quartz in white to greenish-gray fault gouge. These zones are best observed in the underground workings where they are adjacent to the veins. These zones locally thicken where a polymetallic vein has pinched out or has split into several small veinlets of quartz and pyrite.

The andesite exhibits either a variable phyllic or argillic alteration adjacent to the CFQM. Fractures in the altered andesite contain local thin veinlets of chalcopyrite and pyrite, as well as chrysocolla, malachite and azurite. Epidote is rare, but locally forms fracture coatings and replaces mafic minerals within the andesite. Chlorite and iron oxides are common in the andesite.

Deuteric alteration reflects the interaction between igneous rocks and magmatic-hydrothermal fluids during cooling. Deuteric alteration has af-

ected the majority of the igneous rocks in the Hillsboro district and is distinguished from hydrothermal alteration by its pervasiveness, lack of fracture control, and presence of primary minerals that are only partially replaced by subsequent alteration minerals. Sericite and clay minerals commonly replace plagioclase phenocrysts. K-feldspar phenocrysts are commonly replaced by sericite. Biotite, hematite, and chlorite replace hornblende. The groundmass is altered to sericite and chlorite. Pyrite is absent.

### 5.2. Sedimentary rocks

Two distinct types of alteration of the sedimentary rocks occur in the Hillsboro district. Carbonates and locally shales south of the Copper Flat volcano are altered to jasperoid. Elsewhere, the limestones, sandstones, and shales have been metamorphosed to skarns and marble.

### 5.3. Jasperoids

Large jasperoid bodies have replaced the limestones of the El Paso Formation (Ordovician), the Fusselman Dolomite (Silurian), Lake Valley Limestone (Mississippian) and the Percha Shale (Devonian) south of the Copper Flat volcano in T16S, R7W (Fig. 3). A thin andesite flow and the Sugarlump Tuff (ca. 35 Ma; Seager et al., 1982) unconformably overlie jasperoid in the Fusselman Formation and Percha Shale, indicating a pre-Oligocene and pre-Emory

caldera age (ca. 34 Ma; Seager et al., 1982) for the jasperoids. Volcanic rocks also overlie jasperoids in the El Paso Formation.

The jasperoids vary from white to gray to reddish brown to yellowish brown and are typically aphanitic to fine grained and brecciated. Typically, one stage of brecciation occurred. However, locally the jasperoids are characterized by two stages of brecciation. The jasperoid is locally vuggy with drusy quartz filling the vugs. The jasperoids typically form sharp contacts with the host limestone. Locally, thin, poorly developed jasperoid occurs within the Percha Shale, especially near the contact with the underlying Fusselman Dolomite. Small Ag–Mn carbonate-hosted replacement deposits occur beneath the jasperoid in these areas (Fig. 3).

The jasperoids consist predominantly of quartz with iron and manganese oxides. Trace amounts of pyrite, dolomite, calcite, magnesite, sericite, fluorite, and altered feldspar are locally found in the jasperoids. Pyrite is typically altered to iron oxides. Drusy quartz, calcite, iron and manganese oxides

fill vugs in the jasperoid. Visible pyrite is rare to absent; however, in thin section, many jasperoids contain trace amounts of finely disseminated pyrite that is commonly altered to hematite and goethite. The jasperoids are depleted in trace elements and metals relative to the vein, replacement, and porphyry-copper samples (Tables 8–10).

#### 5.4. Skarns

Poorly developed, unmineralized skarn deposits occur in limestones north and south of the andesite volcanic/intrusive complex. The skarns are typically small replacement pods adjacent to barren limestone or sandstone and consist mainly of garnet, epidote, and magnetite, with fine-grained hornfels layers and thin beds of white to gray marble. Pyrite is rare and precious and base metals concentrations are low (V.T. McLemore, unpubl. data). The skarns are most likely related to the quartz-monzonite intrusions, because they generally occur less than a kilometer from the intrusive contact (Fig. 3).

Table 8  
Chemical analyses in percent (XRF) of jasperoids from the Hillsboro district <sup>a</sup>

Sample	Lat.	Long.	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub> (T)	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	LOI	Total
Hill 33	32 55 10	107 31 35	95.42	0.04	0.87	1.25	0.02	0.47	0.09	0.03	0.18	0.37	0.87	99.61
Hill 34	32 55 43	107 31 43	97.49	0.07	0.23	0.32	0.01	0.06	0.02	0.04	0.04	0.03	0.42	98.73
Hill 46	32 55 25	107 32 30	97.57	0.02	0.44	0.27	0.02	0.09	0.05	0.01	0.04	0.24	0.55	99.29
Hill 47	32 55 20	107 32 31	98.60	0.08	0.35	0.19	0.01	0.11	0.07	0.03	0.04	0.04	0.31	99.83
Hill 48	32 55 18	107 32 29	79.13	0.08	0.91	0.58	0.03	0.29	9.65	0.03	0.25	0.04	8.02	99.00
Hill 50	32 55 43	107 32 27	91.10	0.10	2.39	0.60	0.02	1.36	0.08	0.09	1.52	0.10	1.68	99.04
Hill 77	32 55 35	107 31 30	88.30	0.01	0.24	0.54	0.12	0.29	5.62	0.02	0.03	0.02	4.56	99.75
Hill 80	32 55 37	107 31 35	92.68	0.02	0.50	3.07	0.35	0.16	0.71	0.04	0.09	0.04	1.30	98.96

<sup>a</sup> Total iron reported as Fe<sub>2</sub>O<sub>3</sub>(T).

Table 9  
Trace elements of jasperoids (XRF, except for Au and Ag, which were by ICP) <sup>a</sup>

Sample	Au	As	Ag	Ba	Cr	Cu	Ga	Mo	Nb	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr
Hill 33	6	16	<2	77	6	6	5	<2	<2	8	50	13	22	2	<2	19	6	119	11
Hill 34	<5	<2	<2	19	<2	<2	<2	<2	<2	2	42	3	8	2	1	10	<2	23	46
Hill 46	19	2	<2	62	5	4	<2	<2	<2	3	8	3	13	<2	<2	<2	<2	15	7
Hill 47	15	1	<2	60	6	<2	<2	2	<2	2	14	3	1	<2	<2	6	3	10	65
Hill 48	13	12	<2	84	13	3	4	<2	2	4	18	15	28	2	2	16	3	38	38
Hill 50	14	3	<2	125	9	4	7	<2	<2	4	20	40	85	1	2	6	2	16	42
Hill 77	Nd	11	Nd	301	223	11	<2	2	<2	10	29	<2	37	<2	1	21	6	20	2
Hill 80	Nd	<2	Nd	250	253	49	3	2	<2	13	Nd	6	10	7	3	131	30	268	12

<sup>a</sup> Analyses are in ppm, except for Au, which is in ppb.

Table 10  
Pearson correlation coefficients of jasperoids<sup>a</sup>

	Cu	Pb	Zn	As	Ba	Mn	V
Pb	0.11						
Zn	<b>0.89</b>	<b>0.74</b>					
As	<b>0.61</b>	<b>0.65</b>	<b>0.85</b>				
Ba	<b>0.64</b>	-0.07	0.41	0.30			
Mn	-0.27	<b>0.87</b>	0.18	0.49	-0.40		
V	<b>0.99</b>	<b>0.61</b>	<b>0.92</b>	<b>0.91</b>	<b>0.60</b>	-0.16	
Rb	-0.14	-0.13	-0.10	0.05	-0.06	-0.08	-0.15

<sup>a</sup> Significant correlations > 0.6 are highlighted.

## 6. Geochemistry of the igneous rocks

One of the problems in determining the magmatic differentiation history of a porphyry-copper system is that most of the rocks exposed exhibit varying degrees of alteration that affect the major and trace element compositions. Many methods of differentiating altered versus unaltered rocks have been proposed using geochemical variation diagrams (Leitch and Lentz, 1994; Stanley and Madeisky, 1994; Wilt, 1995; Keith and Swan, 1996). Like many porphyry-copper systems, the samples from Hillsboro exhibit varying degrees of alteration (Table 7). In this study, the alteration filter diagrams proposed by Wilt (1995) and Keith and Swan (1996) were used to identify altered versus relatively fresh samples from the Hillsboro district (Fig. 4). Unaltered samples also tend to have LOI (loss on ignition) values of less than 3%.

The unaltered andesites are metaluminous and alkaline; the unaltered quartz monzonites and latites are metaluminous to peraluminous and alkaline to subalkaline. The linear variation in Na<sub>2</sub>O + K<sub>2</sub>O/SiO<sub>2</sub>, V/TiO<sub>2</sub>, SiO<sub>2</sub> vs. TiO<sub>2</sub>, and SiO<sub>2</sub> vs. Zr/TiO<sub>2</sub>, and various major elements suggests that the igneous rocks are comagmatic (Fig. 5). Pearce element plots of Na/Zr vs. Al/Zr and (K + Na)/Mg vs. Al/Mg indicate that magmatic differentiation was controlled in part by feldspar fractionation (Fig. 6). These plots also indicate that the quartz-latite dikes are closely related to the intrusion of the three quartz-monzonite porphyry and quartz-diorite intrusions. The igneous rocks are classified as Syn-collision to Volcanic Arc granites (Fig. 7; Pearce et al., 1984). These data are consistent with highly evolved arc

magmatism related to subduction of the Farrallon plate (Keith and Swan, 1996). The CFQM is a low-sulfur system with total sulfur content less than 7% (Table 5; V.T. McLemore, unpubl. data; Williams and Forrester, 1995) and pyrite contents that are typically less than 2%, although higher concentrations of pyrite occur locally. Collectively, these data suggest that the igneous rocks are part of a differentiated comagmatic suite. The composition of the altered rocks is consistent with the alteration mineral assemblages and reflects the dominance of potassic alteration (Fig. 4).

## 7. Age of igneous rocks

Hedlund (1974, 1985) reported an age for the CFQM of 75.1 ± 2.5 Ma (biotite, K–Ar). Additional samples of the andesite, quartz-monzonite, and latite dikes were collected and analyzed by <sup>40</sup>Ar/<sup>39</sup>Ar methods by the New Mexico Geochronological Research Laboratory at NMBMMR. All samples were altered.

The complexity of the hornblende age spectra (Fig. 8) is probably caused by excess argon contamination. Isochron analyses for the three hornblendes yield approximately linear arrays for various heating steps (Fig. 8). Even though the isochron arrays are somewhat disturbed, the data suggest distinct excess argon reservoirs as the cause of the age spectra complexity (Heizler and Harrison, 1988). The isochron ages (Fig. 9) provide the best estimate for the age of the hornblendes and this represents the age of the rocks from which they were separated due to the expected rapid cooling of these igneous intrusions. Fission track data (long mean track lengths) is consistent with rapid cooling of the CFQM (Kelley and Chapin, 1997). The relatively high uncertainty of the ages does not permit resolution of individual intrusive events, but it appears that the andesite (Hill 5; 75.4 ± 3.5 Ma), CFQM (Hill 15, 19; 74.93 ± 0.66 Ma), and Warm Springs quartz monzonite (Hill 11; 74.4 ± 2.6 Ma) are all about 75 Ma (Figs. 8 and 9; V.T. McLemore, unpubl. data). Since the quartz monzonite intruded the andesite, the andesite cannot be younger than 74.93 ± 0.66 Ma.

Although the relatively low argon retentivity of K-feldspar generally does not allow direct dating

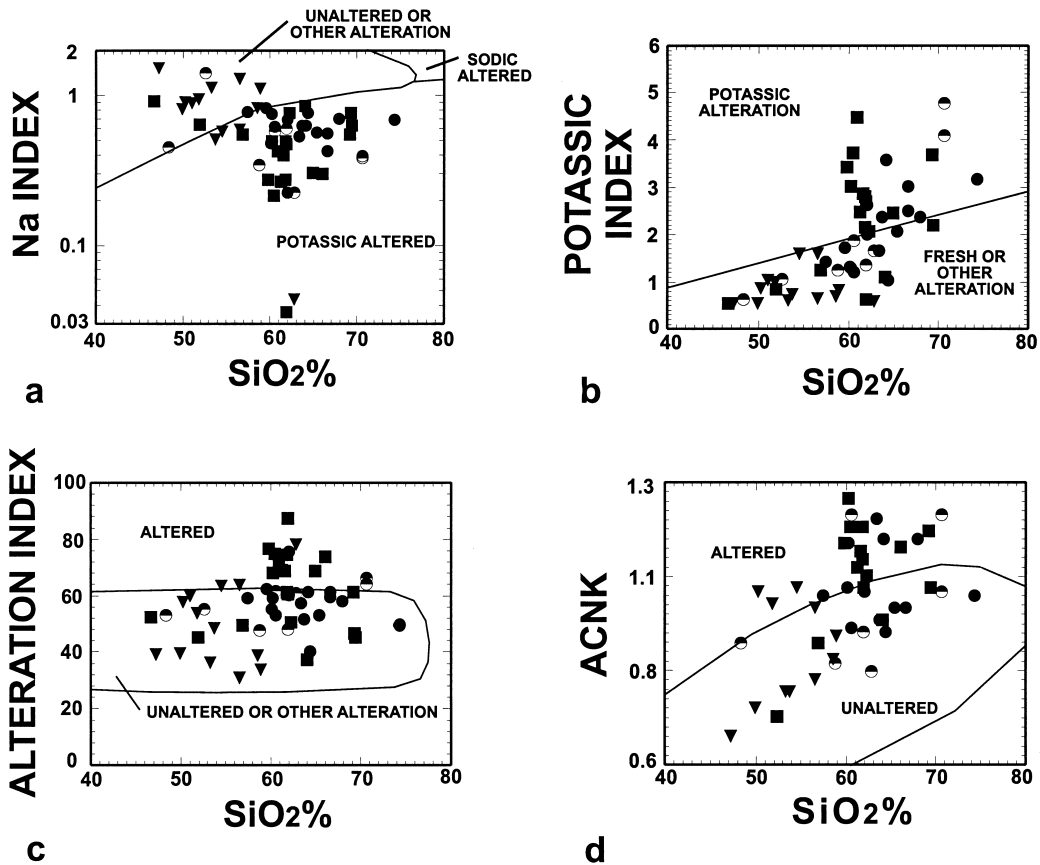


Fig. 4. (a–d) Alteration filter diagrams showing fresh and altered fields (after Wilt, 1995 and Keith and Swan, 1996). Na index (a) is the ratio of  $\text{Na}_2\text{O}$  to the sum of  $\text{K}_2\text{O}$  and ACNK. ACNK is the molecular ratio of  $\text{Al}_2\text{O}_3$  to total  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$  and is calculated by  $[(\text{Al}_2\text{O}_3/102)/(\text{CaO}/56) + (\text{Na}_2\text{O}/62) + (\text{K}_2\text{O}/94)]$ . Potassic index (b) is the ratio of the sum of  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , and  $\text{MgO}$  by the sum of  $\text{CaO}$  and  $(0.9\text{Fe}_2\text{O}_3 + \text{FeO})$ . The alteration index (c) is the ratio of 100 times the sum of  $\text{K}_2\text{O}$  and  $\text{MgO}$  by the sum of  $\text{K}_2\text{O}$ ,  $\text{MgO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{CaO}$ . The scatter in the data is a result of hydrothermal alteration. Filled circles are unmineralized quartz-monzonites and monzonites, half-filled circles are mineralized quartz-monzonites and monzonites, triangles are andesites, and squares are latite and quartz-latite dikes.

of intrusive rocks, K-feldspar results can provide some age information for the quartz-latite dike. The plateau age of the quartz-latite sample (Hill 17) is  $70.21 \pm 0.20$  Ma and is a distinctively younger age than the final heating steps from the Warm Springs quartz-monzonite sample (Hill 11; Fig. 8). A possible interpretation for these results is that the ca. 75 Ma ages for HILL-11 K-feldspar (which equal the hornblende ages), represent the age of quartz-monzonite intrusion. The discordance of its age spectrum is related to argon loss, which may have occurred during the intrusion of the nearby 70 Ma quartz latite. Though somewhat speculative, this interpretation is consistent with the intrusive

relationships. Alternatively, the K-feldspars could simply record a separate cooling event at ca. 70 Ma. If this is true, the true age of the quartz latite remains uncertain.

## 8. Geology and geochemistry of the mineral deposits

### 8.1. Porphyry-copper deposit

Much of the Cu, Au, Mo, and Ag ore of the CFQM porphyry-copper deposit occurs as disseminations and in quartz veins in a breccia pipe in

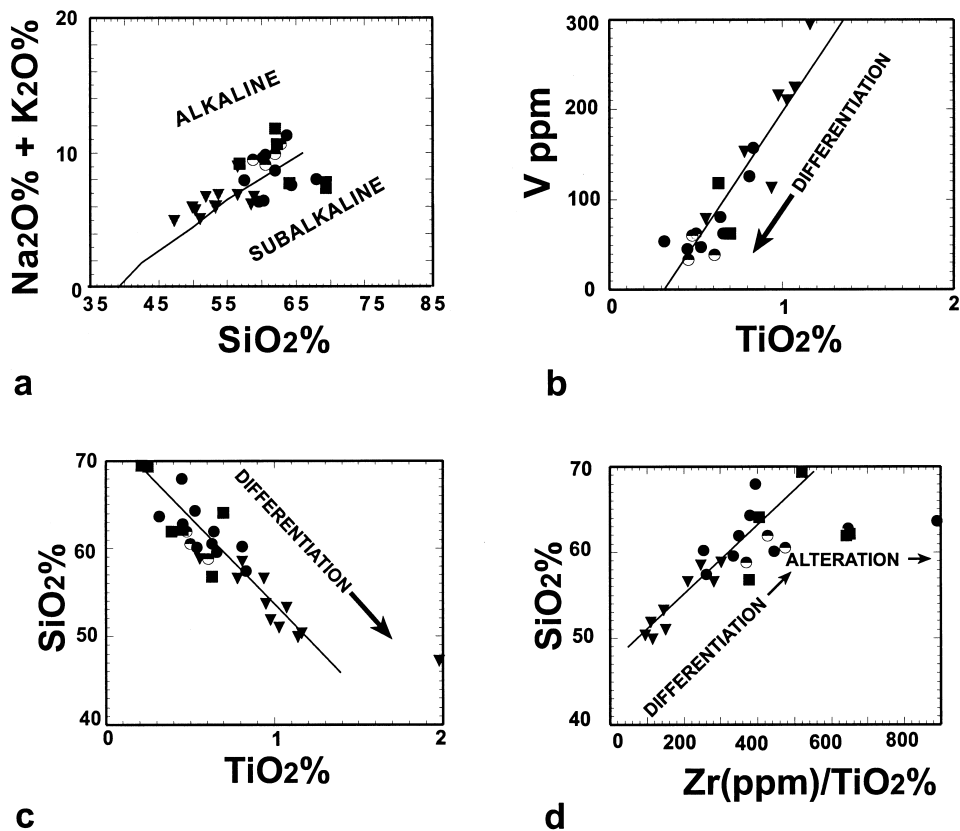


Fig. 5. (a–d) Na<sub>2</sub>O + K<sub>2</sub>O/SiO<sub>2</sub>, V/TiO<sub>2</sub>, SiO<sub>2</sub>/TiO<sub>2</sub>, and SiO<sub>2</sub>/Zr/TiO<sub>2</sub> differentiation diagrams for the Hillsboro igneous rocks. Symbols are explained in Fig. 4.

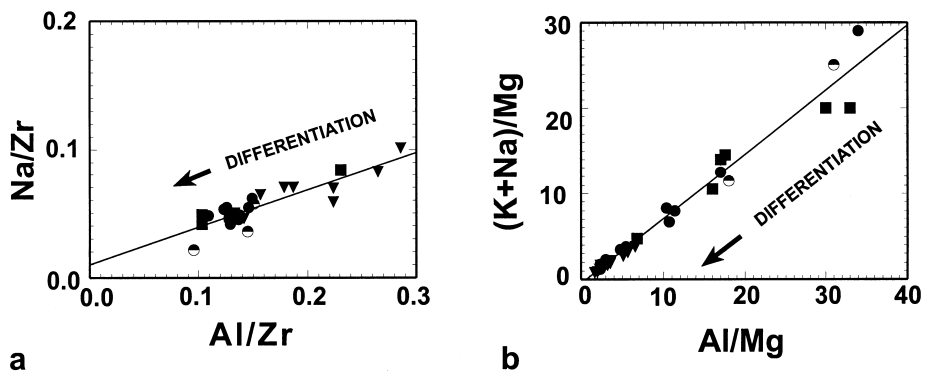


Fig. 6. (a,b) Pearce element plots of Na/Zr vs. Al/Zr and (K + Na)/Mg vs. Al/Mg, in molar concentrations. Symbols are explained in Fig. 4.

the CFQM. The breccia pipe is 396 m long, 183 m wide, and has a vertical extent of almost 518 m (Dunn, 1982, 1984). Predominant minerals include pyrite, chalcopyrite, chalcocite, azurite, malachite,

and cuprite. Unlike the Santa Rita and Tyrone deposits, only a thin supergene enrichment zone occurs at the top of the CFQM porphyry; Copper Flat is predominantly a low-grade hypogene deposit.

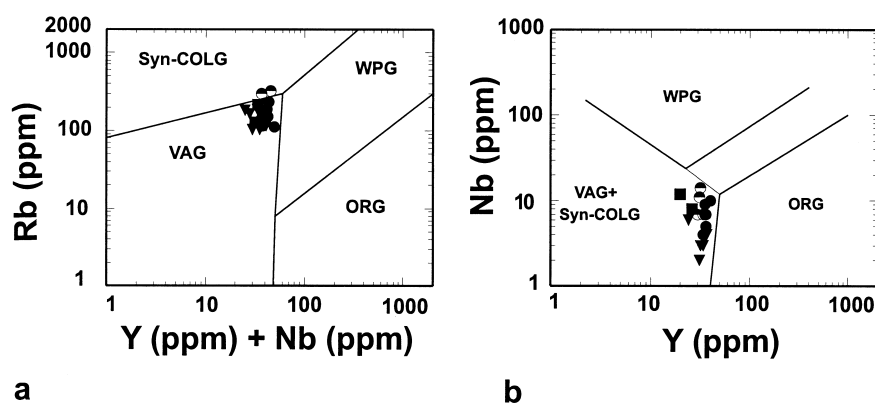


Fig. 7. (a,b) A scatter plot of Rb vs. Y + Nb and Nb vs. Y. Fields are from Pearce et al. (1984). *WPG* = within-plate granites; *ORG* = orogenic granites; *VAG* = volcanic arc granites; *Syn-COLG* = syn-collision granites. Symbols are described in Fig. 4.

Quintana Minerals Corp. analyzed 4246 samples of drill core and cuttings from 149 drill holes for Cu and Mo from the porphyry-copper deposit. The mean of these samples is 0.29% Cu and 0.01% Mo; the maximum concentration is 4.04% Cu and 0.49% Mo. The mean compares well with the grade of 0.432% Cu and 0.014% Mo reported by Alta Gold Corp. Chemical analysis of surface samples indicates that they are enriched in Cu and Mo and depleted in Ag, As, Pb, Zn, Ba, Bi, Mn, and V relative to the vein and replacement deposits (Table 3). Good correlation exists between Cu, As, Ag, and Sb and between Ag, Au, Pb, and As (Table 11). This suggests that these metals are found in similar minerals that may have co-precipitated. Note the very poor correlation between Cu

and Mo (0.06, Table 11). A very poor correlation also exists between Cu and Mo in samples from the drill core and cuttings (Pearson correlation coefficient of 0.10 using 4246 samples). This suggests that Cu and Mo are found in separate minerals (i.e. chalcopyrite, molybdenite) that did not co-precipitate.

## 8.2. Laramide polymetallic vein deposits

The Laramide veins are associated with latite and quartz-latite dikes and consist of quartz, pyrite, clay, iron oxides, barite, malachite, chrysocolla, chalcopyrite, bornite, free gold, galena, and several additional minor minerals (Harley, 1934; Hedlund, 1985). Some veins are as much as 1500 m long and

Table 11

Pearson correlation coefficients for 24 samples from the porphyry-copper deposit (only 13 samples had measurable Au, Ag, Sb, Bi)<sup>a</sup>

	Au	Ag	Cu	Pb	Zn	Mo	As	Sb	Ba	Bi	Mn	V
Ag	<b>0.62</b>											
Cu	0.01	<b>0.66</b>										
Pb	<b>0.96</b>	<b>0.73</b>	0.15									
Zn	0.03	0.34	0.35	0.22								
Mo	-0.03	0.08	0.06	0.11	-0.04							
As	0.52	<b>0.89</b>	<b>0.68</b>	0.47	0.42	-0.02						
Sb	-0.07	0.02	<b>0.83</b>	-0.10	-0.17	0.12	0.18					
Ba	0.01	0.33	-0.15	-0.08	-0.08	-0.33	-0.25	0.12				
Bi	-0.24	-0.09	0.02	-0.28	-0.22	-0.02	-0.10	-0.01	0.12			
Mn	-0.06	0.04	0.17	0.06	<b>0.83</b>	-0.10	0.02	-0.23	-0.02	-0.09		
V	-0.18	-0.42	-0.22	-0.18	-0.27	-0.30	-0.27	-0.14	-0.14	<b>0.74</b>	-0.05	
Rb	0.26	-0.01	0.02	-0.02	-0.27	-0.59	0.20	-0.04	-0.14	-0.11	-0.21	-0.21

<sup>a</sup> Geochemical data from Korzeb and Kness (1994), Korzeb et al. (1995), and V.T. McLemore (unpubl. data). Significant correlations > 0.6 are highlighted.

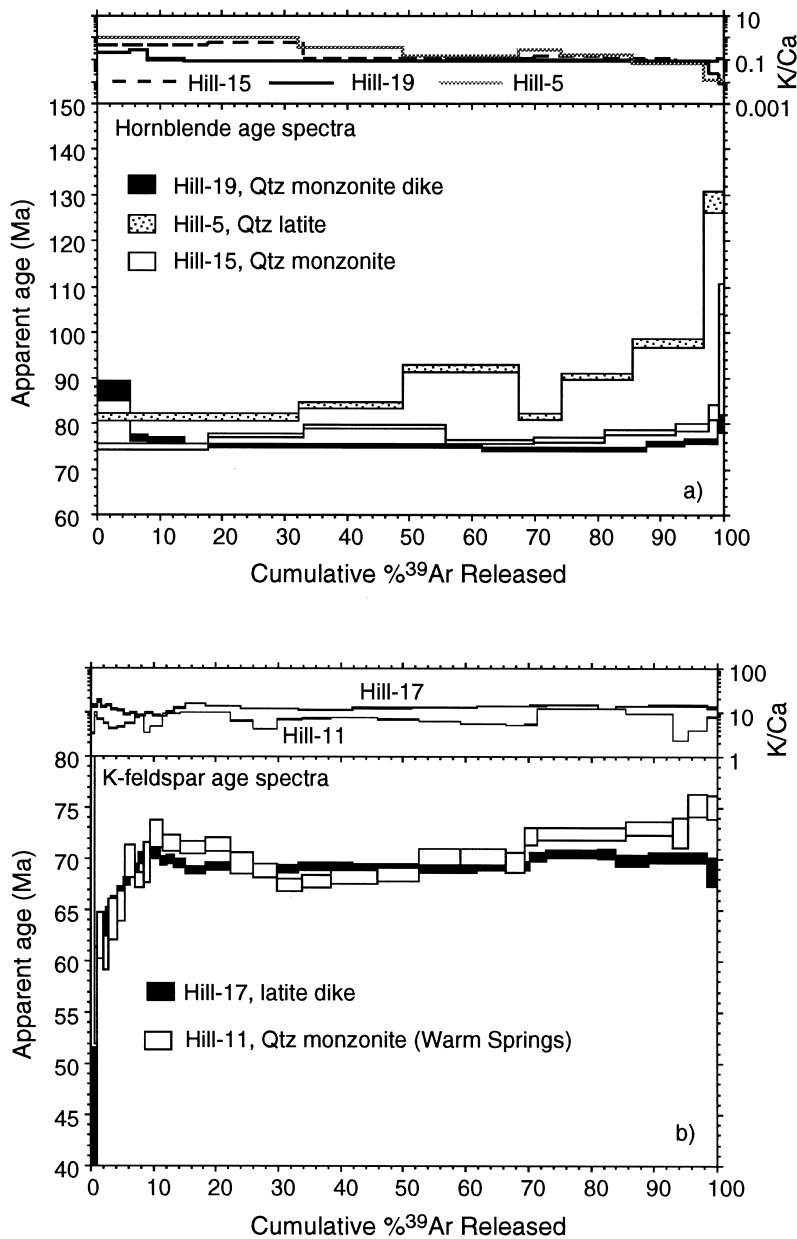


Fig. 8. Hornblende (a) and K-feldspar (b) age spectra for samples from Hillsboro.

0.8–3 m wide. They are typically en echelon and pinch and swell. The veins locally grade along strike into alteration zones of sericite and pyrite with little or no metal concentrations. The veins vary tremendously in chemical composition, but are typically enriched in Au, Ag, Cu, As, Bi, and depleted in Mo

relative to the porphyry-copper and carbonate-hosted replacement deposits (Table 3). Good correlation exists between Au, Ag, and Cu; Bi also correlates with Ag (Table 12). This suggests that these metals are found in similar minerals that may have co-precipitated. The low correlation between Au, Sb and



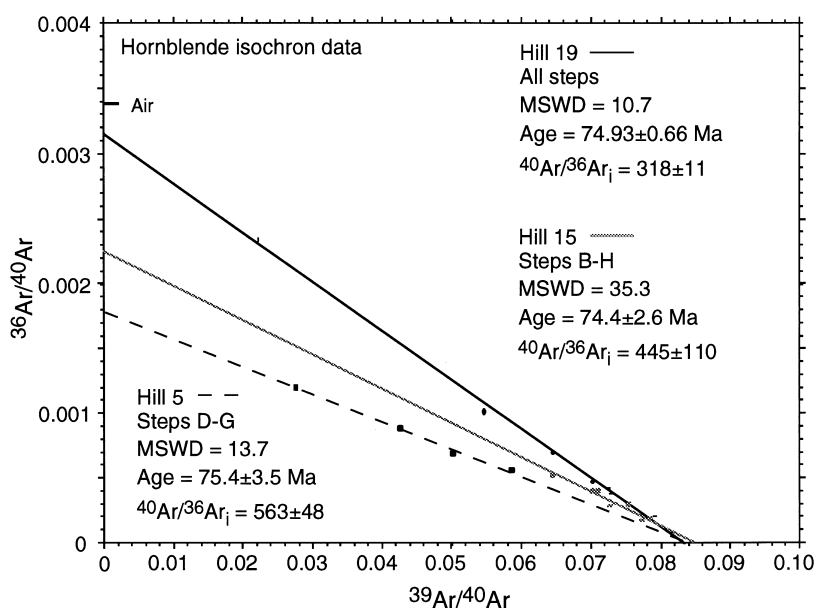


Fig. 9. Hornblende isochron diagrams for samples from the Hillsboro mining district.

Table 12

Pearson correlation coefficients for 195 samples from the vein deposits<sup>a</sup>

	Au	Ag	Cu	Pb	Zn	Mo	As	Sb	Ba	Bi	Mn	V
Ag	<b>0.75</b>											
Cu	<b>0.62</b>	<b>0.63</b>										
Pb	0.17	0.22	0.10									
Zn	0.26	0.38	0.25	0.22								
Mo	0.07	0.05	0.04	0.40	0.01							
As	0.10	-0.01	-0.02	0.30	-0.02	0.11						
Sb	0.01	-0.01	-0.04	<b>0.64</b>	-0.03	<b>0.73</b>	0.37					
Ba	-0.22	-0.22	-0.11	-0.23	-0.13	-0.11	-0.11	-0.12				
Bi	0.33	0.57	0.32	0.14	0.11	0.05	0.08	0.05	-0.13			
Mn	-0.10	-0.01	-0.01	-0.02	0.09	-0.03	-0.05	-0.03	0.33	0.01		
V	-0.03	-0.07	-0.03	<b>0.65</b>	-0.04	0.35	0.38	<b>0.72</b>	0.03	0.02	0.02	
Rb	-0.35	-0.38	-0.23	-0.24	-0.12	-0.27	-0.13	-0.18	0.45	-0.28	-0.07	0.09

<sup>a</sup> Geochemical data from Korzeb and Kness (1994), Korzeb et al. (1995), and V.T. McLemore (unpublished data). Significant correlations > 0.6 are highlighted.

Mo suggests that these metals are found in separate minerals (i.e. gold, molybdenite) that did not co-precipitate. The good correlation between Mo and Sb suggests that Sb occurs in molybdenite. Also note the poor correlations with Au and Ag with As and Sb. This indicates that neither As nor Sb will act as pathfinder (or indicator) elements for the Au–Ag veins in this district.

### 8.3. Carbonate hosted Ag–Mn and Pb–Zn replacement deposits

The carbonate-hosted deposits consist of small pods of Ag–Mn and Pb–Zn replacements (defined by North and McLemore, 1986 and by McLemore, 1999), small Pb–Zn skarns, and veins in Paleozoic limestones and dolomites, typically belonging to the El Paso Formation, Fusselman Dolomite and Lake Valley Limestone. These deposits are typically

Table 13

Pearson correlation coefficients for 8 samples from the carbonate-hosted replacement deposits<sup>a</sup>

	Au	Ag	Cu	Pb	Zn	Mo	As	Sb	Ba	Bi	Mn	V
Ag	<b>0.89</b>											
Cu	<b>0.88</b>	<b>0.75</b>										
Pb	<b>0.94</b>	<b>0.82</b>	<b>0.89</b>									
Zn	<b>0.97</b>	<b>0.89</b>	<b>0.84</b>	<b>0.95</b>								
Mo	-0.10	-0.07	-0.04	0.22	0.05							
As	0.20	0.07	0.25	0.49	0.32	<b>0.91</b>						
Sb	0.45	0.52	0.49	<b>0.69</b>	0.53	<b>0.74</b>	<b>0.73</b>					
Ba	-0.55	-0.45	-0.52	<b>-0.66</b>	<b>-0.66</b>	-0.19	-0.33	-0.50				
Bi	-0.01	0.43	-0.15	-0.10	0.05	-0.01	-0.25	0.13	0.29			
Mn	<b>-0.75</b>	<b>-0.79</b>	<b>-0.76</b>	<b>-0.77</b>	<b>-0.76</b>	-0.19	-0.38	-0.48	0.25	-0.29		
V	-0.03	-0.13	0.04	0.23	0.10	<b>0.95</b>	<b>0.97</b>	<b>0.64</b>	-0.18	-0.23	-0.23	
Rb	-0.17	-0.22	-0.34	-0.36	-0.28	-0.29	-0.25	-0.43	<b>0.75</b>	0.22	0.30	-0.18

<sup>a</sup> Geochemical data from Korzeb and Kness (1994), Korzeb et al. (1995), and V.T. McLemore (unpubl. data). Significant correlations > 0.6 are highlighted.

Ag–Mn or Pb–Zn dominant. Breccia fragments of jasperoid within the deposits indicate that an early deposition of jasperoid preceded metal deposition. The replacement deposits are enriched in Pb, Zn, Ba, V, and depleted in Au and Cu relative to the vein and porphyry-copper deposits. A good correlation exists between Ag, Cu, Pb, and Zn and a negative correlation with Mn (Table 13), which is consistent with the known mineralogy of these deposits. This indicates that the Ag, Cu, Pb, and Zn occur in minerals that co-precipitated (i.e. argentite, chalcopyrite, galena, sphalerite) and that Mn mineralization may be a younger event than the Ag–base metals mineralization. Crosscutting field relationships and petrographic textures also indicate that the Mn mineralization is younger. The good correlation between Mo, V, As, and Sb indicate that these metals occur in minerals that co-precipitated (i.e. molybdenite, wulfenite, vanadinite). The poor correlation between Mo, V, As, and Sb with Ag, Cu, Pb, and Zn indicates that these two metal suites did not co-precipitate. The correlation of Au with Ag, Cu, Pb, and Zn is probably not statistically valid, because Au concentrations are so low.

#### 8.4. Placer gold deposits

The placer gold deposits have made the Hillsboro district the second most productive of all the placer districts in New Mexico (McLemore, 1994). The best deposits were found in drainages and gulches

radiating from the Copper Flat area. Total production from placer deposits is estimated as 120,000 oz Au (McLemore, 1994) but the absence of abundant water has hampered production. Placer gold occurs in four gravel units ranging in age from latest Miocene to Holocene (Seegerstrom and Antweiler, 1975). The deposits are small and amenable to small-scale operations.

### 9. Summary of fluid inclusion data

Fluid inclusions from the breccia pipe of the CFQM deposit contained numerous daughter minerals, including halite, sylvite, and chalcopyrite (Fowler, 1982). Fowler (1982) reports homogenization temperatures of 320–360°C for the majority of the inclusions within breccia pipe with salinities of 10–45 eq. wt% NaCl. Norman et al. (1989) report homogenization temperatures of 179–359°C with salinities of 7.7–34.4 eq. wt% NaCl for additional breccia pipe samples. Low-temperature inclusions (100–150°C) with low salinities were found in all samples, suggesting that later meteoric fluids flooded the system. These data indicate that the deposit was formed at pressures of 127–166 bars at a depth of 1–2 km (Fowler, 1982).

The Wicks vein had higher homogenization temperatures of 226–388°C than the breccia pipe samples, and salinities of 5.7–33.7 eq. wt% NaCl (Norman et al., 1989). The similarity in chemical com-

position of fluids from both the Wick vein and the breccia pipe deposit indicates that the deposits had a similar fluid source but different chemical depositional processes that produced the two kinds of ore deposits (Norman et al., 1989). High salinities are consistent with a magmatic-hydrothermal origin.

### 10. District zoning

Many workers in the district have recognized district zoning (Harley, 1934; Fowler, 1982; Hedlund, 1985). The CFQM porphyry-copper deposit forms the center of mineralization. It is characterized by Cu, Mo, and minor Au (Fig. 10) and depleted in Ag, As, Pb, Zn, Ba, Bi, Mn, and V. Trending outward radially from the CFQM are Laramide Au–Ag–Cu veins hosted by many of the latite and quartz-latite dikes. The veins are variable in chemical composition, but consist predominantly of Cu, Au, and Ag with relatively high values of Pb, Zn, Sb, As, and Bi (Table 3). Carbonate-hosted replacement deposits are found in the southern and northern parts of the district, distal from the center, and contain Ag, Pb,

Mn, V, and Mo and relatively high values of Sb, Ba, and Zn (Table 3). They are lower in Au and Cu concentration relative to the CFQM and vein deposits. Placer gold deposits were formed by erosion of the Laramide polymetallic veins and occur in the drainages and alluvial fans emanating from the Laramide deposits.

Element distribution maps of the available lithochemical data (Table 2) were plotted. The distribution of most elements reflected either the district zoning or local enrichment in certain metals of some of the Laramide veins. Plots of Rb (Fig. 11) and, to a lesser extent, K, defined a halo surrounding the CFQM deposit. Therefore enriched Rb and K may be an indication of alteration surrounding porphyry-copper deposits.

### 11. Discussion and conclusions

Geochemical and geochronological data indicate that the igneous rocks of the Hillboro district are comagmatic and related to a Laramide volcanic/intrusive complex that formed at about 75

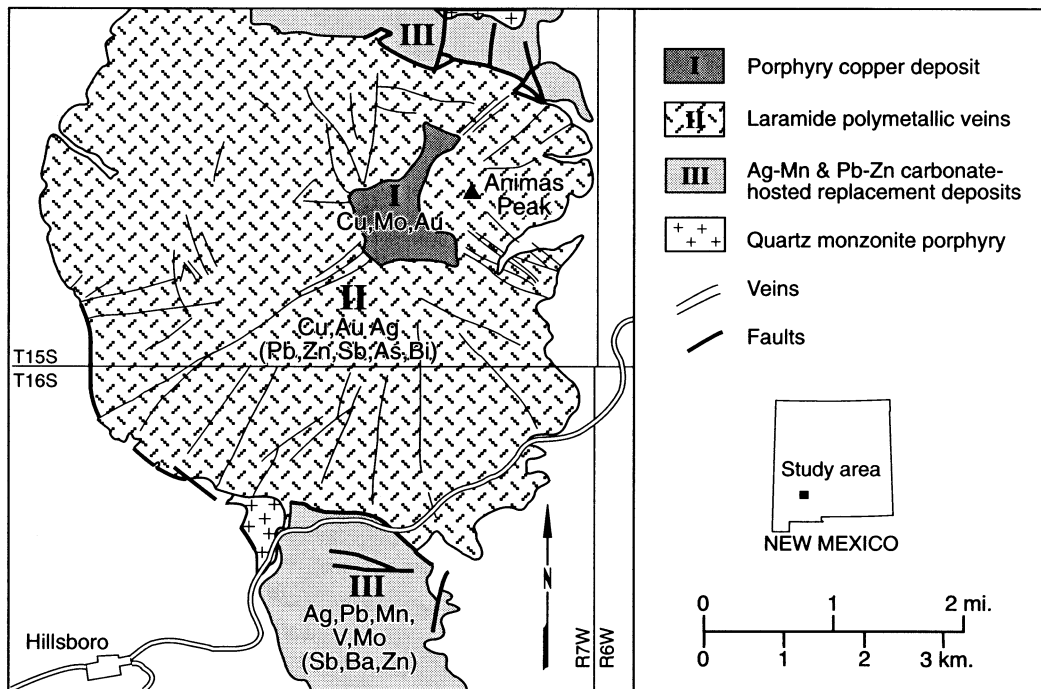


Fig. 10. District zoning in the Hillsboro mining district.

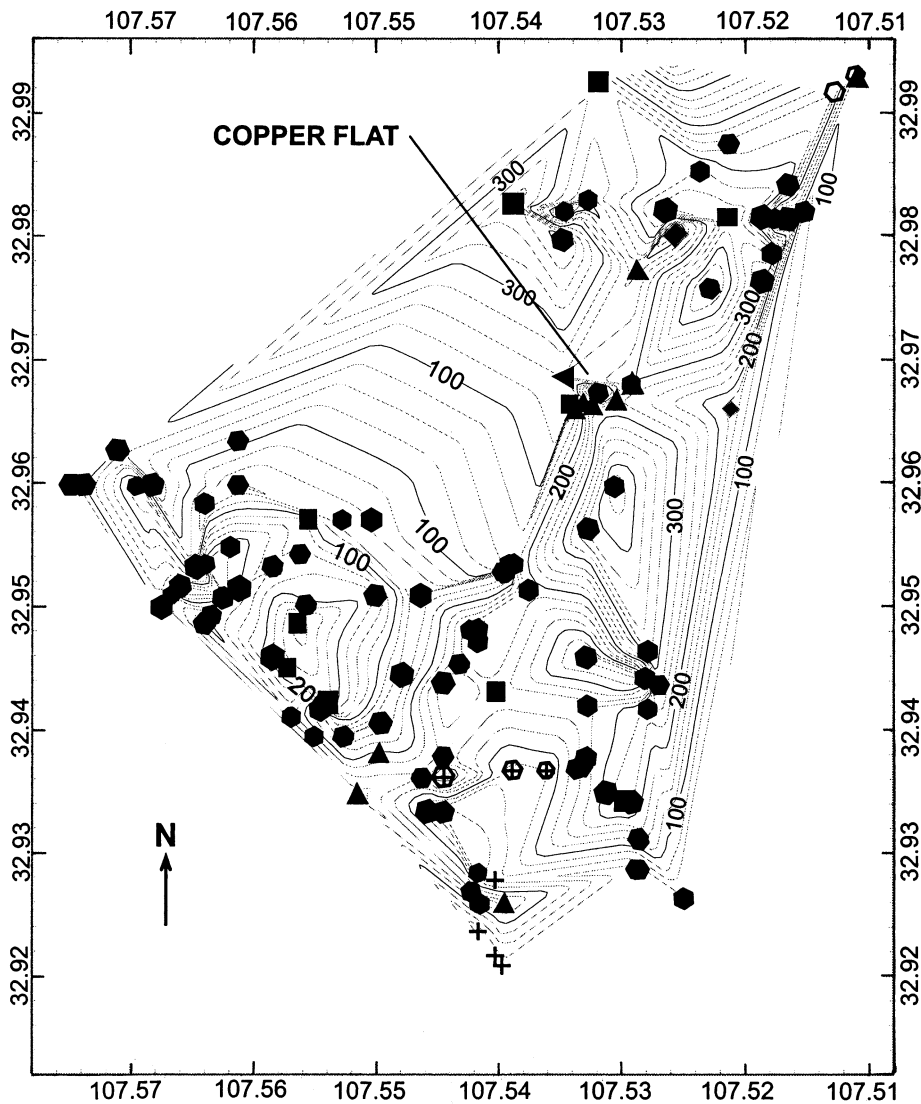


Fig. 11. Rb element distribution map. Triangles, porphyry-copper samples; filled circles, polymetallic vein samples; squares, latite dike samples; diamonds, andesite samples; open circles, sedimentary rock samples; crosses, jasperoid samples.

Ma, whereas the age of the latite dikes is 75–70 Ma. The sequence of events at Hillsboro is summarized in Table 14. The geochemical data suggest that the igneous rocks are products of highly evolved arc magmatism and are similar in composition to most porphyry-copper deposits in the southwestern United States (Wilt, 1995; Keith and Swan, 1996). Lead isotopic data indicate that the CFQM is derived from a similar source as the other porphyry-copper deposits in New Mexico and the source is distinctly differ-

ent from the younger mid-Tertiary mineral deposits (Stacey and Hedlund, 1983). The lead is relatively unradiogenic, suggesting a lower crust or upper mantle source, which is consistent with the geochemical composition of the igneous rocks (Tables 4 and 5).

Collectively, the geological, geochemical, and fluid inclusion data indicate that the mineral deposits found in the Hillsboro district were formed by convective hydrothermal systems related to the Copper Flat volcanic/intrusive complex and subse-

Table 14

Sequence of events in the Hillsboro mining district — deposition of the CFQM porphyry-copper and vein deposits and formation of jasperoids most likely overlapped in time

Geologic event	Age	Mineralization and alteration
Eruption of alkali basalt	4 Ma	None
Uplift of the Copper Flat volcanic/intrusive complex followed by erosion	22 Ma to present	Minor supergene enrichment of porphyry-copper deposit, placer gold deposits
Eruption of Sugarlump and Kneeling Nun Tuffs (Emory caldera)	35–34 Ma	None
Erosion? or burial?	75 Ma to 35 Ma	Minor supergene enrichment of porphyry-copper deposit?
Formation of jasperoids	75–35 Ma	Followed by deposition of carbonate-hosted replacement Ag–Mn and Pb–Zn deposits
Latite and quartz-latite dikes	75–70 Ma	Vein (Au, Ag, Cu) deposits, types 4, 5, and 6 alteration (Table 7)
Intrusion of quartz-monzonite porphyry and formation of breccia pipe deposit	75 Ma	Porphyry-copper deposits (Cu, Au, Ag, Mo), types 1, 2 and 3 alteration (Table 7), formation of skarn and marble in limestone
Eruption of andesitic volcano	75 Ma	None, possible early deuteric alteration

quent intrusion of the quartz-monzonites and latite and quartz-latite dikes. These convective hydrothermal systems were shallow, with depths of 1–2 km (Fowler, 1982). Fluid inclusions from the Wicks vein and CFQM breccia pipe had high salinities, suggesting a magmatic source. Only minor differences exist in the chemical composition of fluid inclusions from the Wicks vein and the CFQM breccia pipe, indicating that the mineralizing fluids were from a common source and different depositional processes controlled mineralization (Norman et al., 1989). The similarities in bulk metal chemical composition between the three deposit types (Table 3) are consistent with a common source, but formation by different depositional processes in different host rocks. Good correlations exist between precious and base metals in the CFQM, Laramide vein, and carbonate-hosted replacement deposits, which is also consistent with a common source fluid. The poor correlation between Cu and Mo in the porphyry-copper and vein deposits (Tables 11 and 12) supports multiple cycles of mineralizing fluids, possibly as a result of multiple hydrothermal systems. The presence of low-temperature fluid inclusions in CFQM and vein deposits is also consistent with multiple cycles of hydrothermal fluids.

Field evidence indicates that the jasperoids were

formed prior to deposition of the Sugarlump and Kneeling Nun Tuffs at about 35 Ma. The jasperoids were locally brecciated and re-cemented by younger carbonate-hosted replacement deposits, indicating that they are older than the carbonate-hosted replacement deposits. However, there is no field evidence to confirm that the jasperoids are genetically related to the CFQM or Laramide vein deposits. However, some jasperoid samples contain anomalous Au and As concentrations (Tables 8–10), which is permissive for formation from distal hydrothermal fluids that are related to the CFQM and Laramide vein deposits. If this is true, the carbonate-hosted replacement deposits may represent the final stages of hydrothermal-magmatic mineralization in the Hillsboro district. Erosion and re-concentration of material from the CFQM and vein deposits formed placer gold deposits during Miocene to Holocene time.

### Acknowledgements

This report is part of on-going studies of mineral resources in New Mexico, supported by the New Mexico Bureau of Mines and Mineral Resources, Charles Chapin, Director and State Geologist. We would like to thank Robert North, Allan G. Galley

and an anonymous reviewer for commenting on an earlier version of this paper. Discussions with Robert North, William Chavez, and Daniel Hack provided insights on the origin of porphyry-copper deposits. Chris McKee (NMBMMR) analyzed some samples by X-ray-fluorescence using the Phillips PW 2400 instrument purchased with funds from NSF grant EAR-9316467. Lisa Peters and Rich Esser carried out mineral separations and  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations at the New Mexico Geochronology Laboratory at the New Mexico Bureau of Mines and Mineral Resources. Michael O'Neill, USGS, provided some chemical analyses by commercial laboratories. Robert Thompson provided technical assistance. The New Mexico Bureau of Mines and Mineral Resources Cartography Department and Erik Munroe drafted the figures.

## References

- Bates, R.L., Jackson, J.A. (Eds.), 1980. *Glossary of Geology*. American Geological Institute, Alexandria, VA, 751 pp.
- DuHamel, J.E., Cook, S.S., Kolessar, J., 1995. Geology of the Tyrone porphyry-copper deposit, New Mexico. In: Pierce, F.W., Bolm, J.G. (Eds.), *Porphyry-Copper Deposits of the American Cordillera*. *Ariz. Geol. Soc. Digest* 20, pp. 464–472.
- Dunn, P.G., 1982. Geology of the Copper Flat porphyry-copper deposit, Hillsboro, Sierra County, New Mexico. In: Titley, S.R. (Ed.), *Advances in Geology of the Porphyry-Copper Deposits*. Univ. of Arizona Press, Tucson, pp. 313–326.
- Dunn, P.G., 1984. Geologic studies during the development of the Copper Flat porphyry deposit. *Min. Eng.* 36 (2), 151–160.
- Fowler, L.L., 1982. Brecciation, Alteration, and Mineralization at the Copper Flat Porphyry-Copper Deposit, Hillsboro, New Mexico. M.S. Thesis, Univ. of Arizona, Tucson, 133 pp.
- Guilbert, J.M., Park, C.F., Jr., 1986. *The Geology of Ore Deposits*. Freeman, New York, 985 pp.
- Harley, G.T., 1934. The geology and ore deposits of Sierra County, New Mexico. *N.M. Bur. Mines Miner. Resour. Bull.* 10, 220 pp.
- Hedlund, D.C., 1974. Age and structural setting of base-metal mineralization in the Hillsboro–San Lorenzo area, southwestern New Mexico (abstr.). In: Siemers, C.T., Woodward, L.A., Callender, J.F. (Eds.), *Ghost Ranch*. *N.M. Geol. Soc., Guideb.* 25, 378–379.
- Hedlund, D.C., 1977. Geologic map of the Hillsboro and San Lorenzo quadrangles, Sierra and Grant Counties, New Mexico. U.S. Geol. Surv., Misc. Field Stud. Map 900-A, Scale 1:48,000.
- Hedlund, D.C., 1985. Economic geology of some selected mines in the Hillsboro and San Lorenzo quadrangles, Grant and Sierra Counties, New Mexico. U.S. Geol. Surv., Open-File Rep. 85-456, 76 pp.
- Heizler, M.T., Harrison, M., T.M., 1988. Multiple trapped argon isotopic components revealed by  $^{40}\text{Ar}/^{39}\text{Ar}$  isochron analysis. *Geochim. Cosmochim. Acta* 52, 1295–1303.
- Keith, S.B., Swan, M.M., 1996. The great Laramide porphyry-copper cluster of Arizona, Sonora, and New Mexico: the tectonic setting, petrology, and genesis of a world class porphyry metal cluster. In: Coyner, A.R., Fahey, P.L. (Eds.), *Geology and Ore Deposits of the American Cordillera*. Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, pp. 1667–1747.
- Kelley, S.A., Chapin, C.E., 1997. Cooling histories of mountain ranges in the southern Rio Grande rift based on apatite fission-track analysis — a reconnaissance study. *N.M. Geol.* 19, 1–14.
- Korzeb, S.L., Kness, R.F., 1994. Mineral resources in areas of critical environmental concern in the Caballo Resource Area, Otero County, New Mexico. U.S. Bur. Mines, Open-File Rep. MLA 20-94, 72 pp.
- Korzeb, S.L., Kness, R.F., Geroyan, R.I., Ward, D.A., 1995. Mineral resource assessment of the Caballo Resource Area, Sierra and Otero Counties, New Mexico. U.S. Bur. Mines, Open-File Rep. MLA 5-95, 177 pp.
- Kueller, F.J., 1955. Geology of a disseminated copper deposit near Hillsboro, Sierra County, New Mexico. *N.M. Bur. Mines Miner. Resour. Circ.* 34, 46 pp.
- Leitch, C.H.B., Lentz, D.R., 1994. The Gresens approach to mass balance constraints of alteration systems: methods, pitfalls, examples. In: Lentz, D.R. (Ed.), *Alteration and Alteration Processes Associated with Ore-Forming Systems*. *Geol. Assoc. Can., Short Course Notes* 2, 161–192.
- Lindgren, W., Graton, L.C., Gordon, C.H., 1910. *The Ore Deposits of New Mexico*. U.S. Geol. Surv. Prof. Pap. 68, 361 pp.
- Lovering, T.G., 1972. Jasperoid in the United States — its characteristics, origin, and economic significance. *U.S. Geol. Surv. Prof. Pap.* 710, 164 pp.
- Lovering, T.G., Heyl, A.V., 1989. Mineral belts in western Sierra County, New Mexico, suggested by mining districts, geology, and geochemical anomalies. *U.S. Geol. Surv. Bull.* 1876, 49 pp.
- McDowell, F.W., 1971. K–Ar ages of igneous rocks from the western United States. *Isotopes/West* 2, 1–16.
- McLemore, V.T., 1994. Placer gold deposits in New Mexico. *N.M. Geol.* 16, 21–25.
- McLemore, V.T., 1998. Insights into origin of carbonate-hosted Ag and Pb–Zn replacement deposits in the Black Range, Sierra and Grant Counties, New Mexico (abstr.). *N.M. Geol. Soc., Spring Meeting Prog.* *N.M. Geol.* 20, p. 49.
- McLemore, V.T., 1999. Silver and gold resources in New Mexico. *N.M. Bur. Mines Miner. Resour., Resource Map* 21 (in press).
- McLemore, V.T., McIntosh, W.C., Pease, T.C., 1995.  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations of four plutons associated with mineral deposits in southwestern New Mexico. *N.M. Bur. Mines Miner. Resour., Open-File Rep.*, 36 pp.

- McLemore, V.T., McMillan, N.J., Heizler, M., McKee, C., 1999. Cambrian alkaline rocks at Lobo Hill, Torrance County, New Mexico: more evidence for a Cambrian–Ordovician Aulogogen. *N.M. Geol. Soc., Guideb. 50th Field Conf.*, pp. 247–253.
- Norman, D.I., Kyle, P.R., Baron, C., 1989. Analysis of trace elements including rare earth elements in fluid inclusion liquids. *Econ. Geol.* 84, 162–166.
- North, R.M., McLemore, V.T., 1986. Silver and gold occurrences in New Mexico. *N.M. Bur. Mines Miner. Resour., Resource Map 15*, 32 pp.
- Pearce, J.N., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* 25, 956–983.
- Reeves, C.C., 1963. Economic geology of a part of the Hillsboro, New Mexico, mining district. *Econ. Geol.* 58, 1278–1285.
- Seager, W.R., Clemons, R.E., Hawley, J.W., Kelley, R.E., 1982. Geology of northwest part of Las Cruces 1° × 2° sheet, New Mexico. *N.M. Bur. Mines Miner. Resour., Geol. Map 53*, Scale 1:125,000.
- Segerstrom, K., Antweiler, J.C., III, 1975. Placer-gold deposits of the Las Animas district, Sierra County, New Mexico. *U.S. Geol. Surv., Open-File Rep. 75-206*, 39 pp.
- Stacey, J.S., Hedlund, D.C., 1983. Lead–isotopic compositions of diverse igneous rocks and ore deposits from southwestern New Mexico and their implications for early Proterozoic crustal evolution in western United States. *Geol. Soc. Am. Bull.* 94, 43–57.
- Stanley, C.R., Madeisky, H.E., 1994. Lithogeochemical exploration for hydrothermal ore deposits using Pearce element ratio analysis. In: Lentz, D.R. (Ed.), *Alteration and Alteration Processes Associated with Ore-Forming Systems*. *Geol. Assoc. Can., Short Course Notes 2*, 193–212.
- Titley, S.R., 1995. Geological summary and perspective of porphyry-copper deposits in Southwestern North America. In: Pierce, F.W., Bolm, J.G. (Eds.), *Porphyry-Copper Deposits of the American Cordillera*. *Ariz. Geol. Soc. Digest 20*, 6–20.
- Williams, S.A., Forrester, J.D., 1995. Characteristics of porphyry-copper deposits. In: Pierce, F.W., Bolm, J.G. (Eds.), *Porphyry-Copper Deposits of the American Cordillera*. *Ariz. Geol. Soc. Digest 20*, 21–34.
- Wilt, J.C., 1995. Correspondence of alkalinity and ferric/ferrous ratios of igneous rocks associated with various types of porphyry-copper deposits. In: Pierce, F.W., Bolm, J.G. (Eds.), *Porphyry-Copper Deposits of the American Cordillera*. *Ariz. Geol. Soc. Digest 20*, 180–200.