Geology and Evolution of the Mineral Deposits in the Hillsboro District, Sierra County, New Mexico

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ABSTRACT

Unlike many porphyry copper deposits in southwestern United States, the Hillsboro district, in central New Mexico, is well exposed, with minimal erosion, and offers an excellent opportunity to examine a relatively intact magmatic-hydrothermal system with multiple zones of different mineral deposit types. New geochemical, geochronological, and geological data, combined with earlier published studies, have provided a refinement of the evolution of mineralization in the district. Past production has been predominantly from the polymetallic veins and placer gold deposits, although minor production has occurred from the porphyry copper and carbonate-hosted Pb-Zn and Ag-Mn replacement deposits. The geology of the Hillsboro district is dominated by Cretaceous andesite flows (75.4±3.5 Ma, ^{40}Ar/^{39}Ar), breccias, and volcaniclastic rocks that were erupted from a volcano. The Copper Flat quartz monzonite porphyry stock (CFQM, 74.93±0.66 Ma, ^{40}Ar/^{39}Ar) intruded the vent of the volcano and hosts porphyry copper mineralization. The unmineralized Warm Springs quartz monzonite (74.4±2.6 Ma, ^{40}Ar/^{39}Ar) and a third altered, but 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. Hydrothermal alteration of the igneous rocks consists of locally intense biotite-potassic, potassic, sericitic, propylitic, and argillic alteration. Large jasperoid bodies, as well as smaller masses of skarn and marble, replaced limestones in the southern part of the district. The porphyry copper deposit is characterized by low-grade hypogene mineralization that is concentrated within a breccia pipe in the CFQM stock. Polymetallic veins hosted by many of the latite/quartz latite dikes trend outward radially from the Copper Flat porphyry copper deposit. Carbonate-hosted replacement deposits (Ag, Pb, Mn, V, Mo, Zn) are found in the southern and northern parts of the district, distal to the Copper Flat porphyry copper deposit. Collectively, the evidence suggests that the mineral deposits found in the Hillsboro district were formed by large, convective magmatic-hydrothermal systems related to the Copper Flat volcanic/intrusive complex. The Copper Flat porphyry copper deposit exhibits very little supergene alteration and enrichment, in contrast to the extensive supergene alteration and enrichment at the Santa Rita and Tyrone, New Mexico and Morenci, Arizona porphyry copper deposits. This may be a result of a lower pyrite content (<2%) at Copper Flat, thereby preventing the supergene enrichment process from occurring. Another explanation for this difference is that the Copper Flat porphyry copper deposit remained buried in the subsurface until uplift at about 21-22 Ma (Kelley and Chapin, 1997), whereas the Santa Rita, Tyrone, and Morenci deposits were exposed to multiple periods of surface erosion, alteration, and supergene enrichments.

INTRODUCTION

The Copper Flat porphyry copper 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-monzonite porphyry stock (CFQM) intruded the vent facies of an andesitic volcanic/intrusive complex and hosts porphyry copper mineralization. Polymetallic veins are associated with latite/quartz latite dikes and both radiate outwards from the CFQM, and are flanked by distal carbonate-hosted Pb-Zn and Ag-Mn replacement deposits to the south and north. Miocene-Holocene placer gold deposits occur in arroyos draining the CFQM and vein deposits. The Copper Flat porphyry copper deposit is a low sulfur system with little supergene enrichment compared to many of the larger porphyry copper deposits in the belt.

This is the second of a series of reports on the Hillsboro mining district. The first paper presented new geochemical and geochronological data and, combined with earlier studies, provided a refinement of the model for the evolution of the mineralization in the Hillsboro district (McLemore et. al., 1999b). The purpose of this second paper is to summarize previous work, characterize the petrology and mineralogy of the various magmatic, mineralizing, and alteration systems; define the genetic relationship among the four distinct types of mineral deposits; and refine a model for the evolution of the Copper Flat volcanic/intrusive magmatic-hydrothermal system.

Although, numerous geologists have examined the Hillsboro area, very few have studied the entire magmatic-hydrothermal system. Lindgren et al. (1910), Harley (1934), and Reeves (1963) described the vein deposits. Kuellmer (1955) first described the 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 replacement of Paleozoic limestones south of the Copper Flat volcano. Hedlund (1977, 1985) and Seager et al. (1982) provided geologic mapping of the area. Geochemical data used for this report are by Korzeb
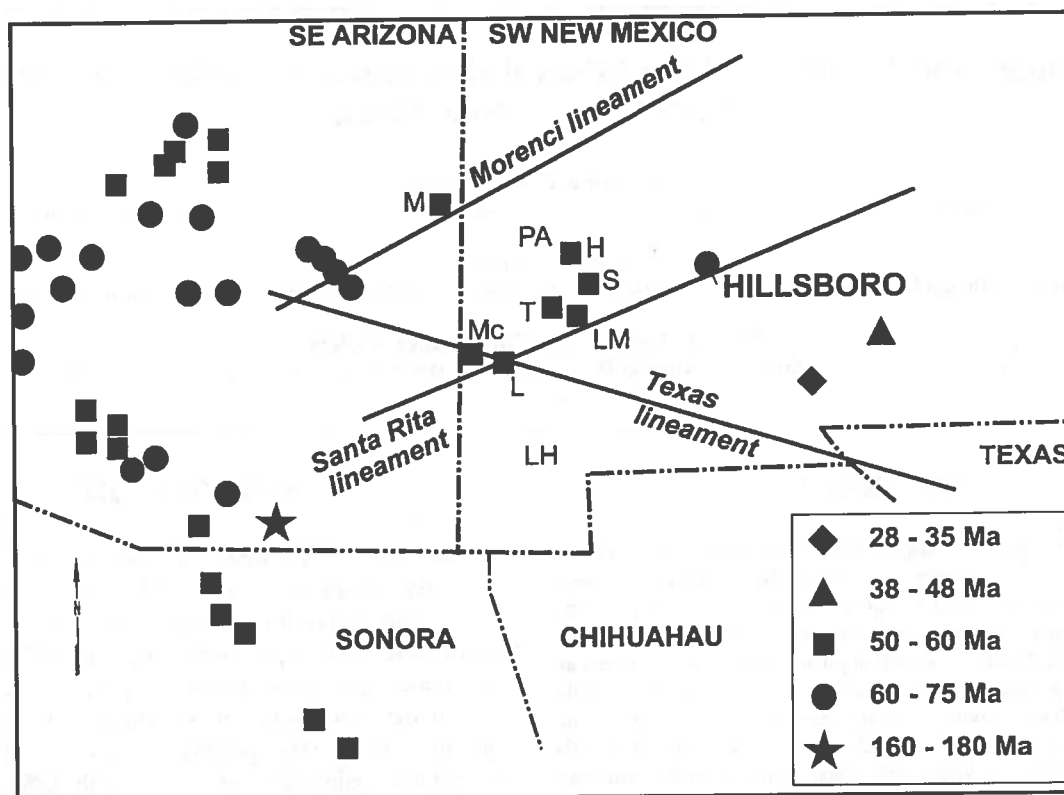
FIGURE 1. Porphyry copper deposits in Arizona, Sonora, and New Mexico, including selected Laramide intrusions in New Mexico. M-Morenci, Mc-McGhee Peak, L-Lordsburg, PA-Piños Altos, H-Hanover-Hermosa, G-Georgetown, T-Tyrone, S-Santa Rita, LM-Lone Mountain, LH-Little Hatchet Mountains. Ages from Keith and Swan (1995) and additional references cited in Table 1.

TABLE 1. Laramide porphyry copper deposits in New Mexico and eastern Arizona (Fig. 1). Does not include porphyry copper deposits associated with Mid-Tertiary alkaline igneous rocks at Organ Mountains, Orogrande, and Cerrillos in central New Mexico.

Porphyry Copper Deposit	Age Ma	Commodities Produced	Comments
Copper Flat (Hillsboro)	75 (this report)	Cu, Au, Ag	Being permitted
Santa Rita (Chino)	56-58 (Phelps Dodge Corp. unpublished data)	Cu, Au, Ag, Mo	Active.
Tyrone (Burro Mountains)	53-56 (DuHamel et al., 1995; Cook 1994))	Cu, Au, Ag	Currently mined for copper leach.
Hanover-Hermosa Mountains (Fierro-Hanover)	57 (McLemore et. al., 1996)	Cu	Skarn deposits produced, mine closed early 1999. Exploration continues.
Lone Mountain	51 (P. B Hubbard and P. G. Dunn, unpublished report, 1983)	None	Inactive. Deposit drilled in 1975-1989.
McGhee Peak (Peloncillo Mountains)	?	None	Inactive. Deposit drilled in 1970s-1990s.
Morenci-Metcaff	55.2 (Keith and Swan, 1995)	Cu, Mo, Au, Ag	Active
Dos Pobres	60-69 (Keith and Swan, 1995)	Not in production	Single-cycle enrichment
San Juan	63 (Keith and Swan, 1995)	Not in production	
Lone Star	?	Not in production	Single-cycle enrichment
Sanchez	?	Not in production	
Bisbee	163-176 (Creasey and Kistler, 1962)	Cu, Ag, Au	

and Kness (1994), Korzeb et al. (1995), Fowler (1982), Hedlund (1985), and Munroe (1999). McLemore et al. (1999b) integrated new geochemical and geochronological data with older published and unpublished data to refine the model for the evolution of the mineralization in the Hillsboro district.

METHODOLOGY

This report presents unpublished petrographic and mineralogic data and new geologic interpretations. Samples were examined using petrographic microscope and electron microprobe. X-ray diffraction analyses (XRD) were also used to determine mineral species. Standard operating procedures were used to obtain XRD and electron microprobe data (Munroe, 1999). Geochemical and geochronological data are presented in McLemore et al. (1999b). However, the geochronological data are also included in this report for completeness. Laboratory procedures are briefly described by McLemore et al. (1999a, b) or can be obtained from the senior author.

LOCATION AND MINING HISTORY

The Hillsboro or Las Animas district lies in the Animas Mountains (Fig. 2) and was discovered in 1877. The town of Hillsboro, first known as Hillsborough, was also established in 1877. Placer gold was found in the Snake and Wicks gulches in November 1877 and a tent city named Gold Dust was founded in the district in 1881. In 1884, Hillsboro was the Sierra County seat, although with diminishing mining activity and population, the county seat was moved in 1938 to Truth or Consequences (then known as Hot Springs). Only sporadic minor production has occurred since 1938 (Table 2).

Initially, gold was recovered from the ore using arrastras and followed by the stamp milling process prior to 1881. A 10-stamp mill operated at the Bobtail mine on the Snake vein from about 1881 to 1884 and had a capacity of 20-25 tons per day. Placer deposits in Snake Gulch were also mined by hydraulic mining methods. Mills operated at the Richmond (1890-1892), Bonanza (1890-1910), Ready Pay/Porter (1898-1913), Snake (1910), and Wicks mines. A copper-matte smelter (30 tons per day) was built in 1892 in the town of Hillsboro, but operated for only a few years. Manganese was produced from the carbonate-hosted Ag-Mn replacement deposits and used in the Hillsboro smelter as flux (Wells, 1918). A small amount of vanadium was also produced from the carbonate-hosted Pb-Zn replacement deposits (Lindgren et al., 1910).

The Copper Flat porphyry copper deposit in the northern part of the Hillsboro district was discovered in 1975 by Quintana Minerals Corp. (Castellano et al., 1977; Dunn, 1982, 1984). Alteration and mineralization features in the area suggested to earlier geologists that a porphyry copper deposit should occur in the district (Kuellmer, 1955). Approximately 200 short tons of copper oxide were mined from the poorly developed oxide cap between 1911 and 1931 (Sternberg shaft; Hedlund, 1974). A copper leach plant operated in the mid-1950s, but production figures are unknown. Quintana Minerals Corp. produced approximately 7.4 million pounds of copper from March through June 1982, prior to closure of the open-pit mine (Table 2). Alta Gold Co. is
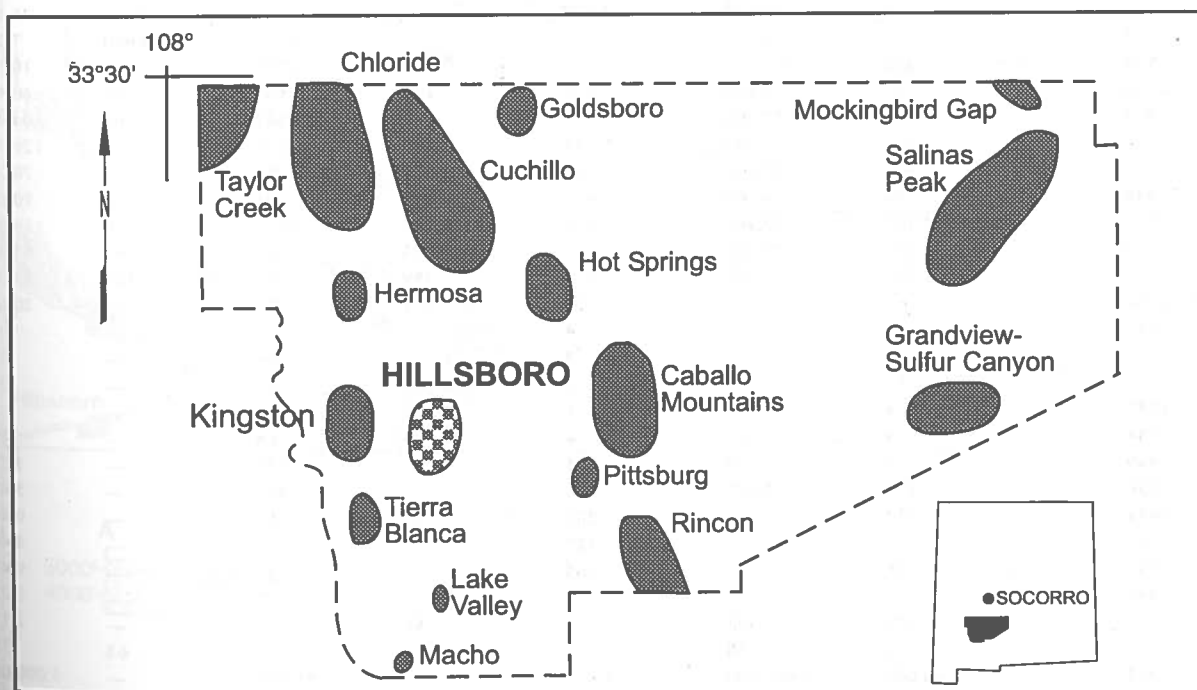

FIGURE 2. Location of the Hillsboro mining district, Sierra County, New Mexico.

TABLE 2. Metals production from the Hillsboro district, Sierra County (U.S. Geological Survey, 1902-1927; U.S. Bureau of Mines, 1927-1990; Harley, 1934; Alta Gold Co., Form 10K, 1999; NMBMMR, unpublished data). *Includes production from Tierra Blanca district in 1939 and from the Caballo district in 1957. Production from 1902-1932 is estimated from unpublished records.

Year	Ore (Short Tons)	Copper (Lbs)	Lode Gold (Oz)	Placer Gold (Oz)	Silver (Oz)	Lead (Lbs)	Value ($)
1877-1904	—	—	134,000	104,000	—	—	6,750,000
1891	—	—	—	—	—	—	253,000
1892	—	—	—	—	—	—	354,424
1893	—	—	—	—	—	—	458,388
1894	26,225	310,000	16,785	—	112,500	80,000	432,680
1902	1,428	3,400	988	—	1,508	—	20,500
1903	8	—	6	—	—	—	1
1904	1,000	16,000	2,400	—	8,001	—	52,000
1905	3,464	35,984	552	—	3,644	—	12,800
1906	3,200	5,000	684	—	3,733	—	15,500
1907	602	4,255	236	—	1,311	—	5,000
1908	827	7,124	551	—	12,157	73	17,000
1909	194	15,523	401	—	1,755	860	8,900
1910	5,530	1,747	94	—	1,585	296	1,880
1911	2,570	4,555	92	—	1,005	422	1,840
1912	90	2,918	90	—	510	94	1,800
1913	4	352	13	—	34	—	280
1914	6	939	11	—	43	—	220
1915	10	1,442	32	—	197	129	640
1916	56	5,621	71	—	889	246	1,400
1917	38	5,377	63	—	3,835	4,616	4,300
1918	14	3,693	—	—	4	—	700
1919	58	3,044	160	—	524	5,945	3,700
1920	688	17,278	428	—	2,500	—	11,000
1921	9	73	30	—	1	—	600
1922	38	4,939	111	—	688	—	2,300
1923	53	2,845	210	—	415	725	4,200
1925	61	5,210	79	—	830	—	1,600
1926	52	5,878	143	—	1354	2500	3,000
1927	656	13,658	436	—	1306	4333	8,800
1928	34	2,000	123	—	306	—	2,500
1929	41	3,222	79	—	50	—	1,600
1930	109	7,302	159	—	563	—	3,300
1931	469	4,100	4,278	—	525	7700	85,600
1932	497	9,000	342	—	1204	16000	7,100
1933	272	3,000	239	221	1,277	600	10,177
1934	761	14,100	462	1,139	4,647	700	60,109
1935	666	22,000	1,098	1,761	2,561	18,400	104,481
1936	983	34,980	1,638	1,620	4,571	—	120,788
1937	469	17,400	357	1,234	2,587	—	70,309
1938	268	13,900	425	2,073	2,104	—	90,138
1939*	1,160	29,900	868	2,271	3,427	100	115,306
1940	1,084	25,000	684	1,688	2,219	3,300	87,588
1941	4,581	20,000	432	989	1,562	1,100	53,269
1942	11	—	16	582	79	—	20,811
1943	—	—	4	—	—	—	70
1944	—	—	8	—	—	—	175
1946	12	400	7	—	83	—	377
1947	4	—	1	—	3	—	20
1948	6	—	4	—	65	—	199
1949	11	1,000	35	—	338	—	1,728
1950	111	3,600	121	—	491	—	5,428
1951	1,214	—	289	—	52	—	0,162
1952	563	—	125	—	30	—	4,402
1953	1,230	—	265	—	51	—	9,426
1955	10	400	2	3	11	—	2,259
1957*	304	3,300	4	58	4	—	1,138
1961	16	118	12	—	17	63	350
1982	1,200,000	7,400,000	2,301	—	55,996	—	5,000,000
ESTIMATED TOTAL 1877-1982	1,236,000	8,000,000	156,300	120,000	134,000	154,000	13,000,000

currently applying for mining permits to reopen the Copper Flat mine. The Copper Flat deposit has proven and probable reserves of 45,650,000 metric tonnes of ore at an average grade of 0.45% Cu, 0.137 ppm Au, 2.26 ppm Ag and 0.015% Mo (December 31, 1998), with a total contained metal resource of approximately 203,200 kg Cu, 696,000 g Au, 102,6000,000 g Ag and 6,696,000 kg Mo (Alta Gold, Form 10K, 1999).

GEOLOGY

The Hillsboro mining district lies on the eastern edge of the Laramide Arizona-Sonora-New Mexico porphyry copper belt (Fig. 1) and the 75 Ma Copper Flat porphyry copper deposit is the oldest in the state (Table 1). Although, the Piños Altos pluton (ca. 71-75 Ma, McDowell, 1971), a Georgetown monzonite dike (ca. 71 Ma, McLemore, 1998), Lordsburg granodiorite (58.8 Ma, $^{40}Ar/^{39}Ar$, biotite, McLemore et al., 2000) and andesite sills in the Little Hatchet Mountains (71.44±0.19 Ma, $^{40}Ar/^{39}Ar$, hornblende; Lawton et al., 1993) have associated polymetallic veins, Cu-Au-Ag skarn, or carbonate-hosted Ag replacement deposits (Fig. 1), porphyry copper deposits are not presently known to occur in these areas. The Laramide orogeny and the porphyry copper deposits in Arizona-Sonora-New Mexico are a product of magmas generated during the subduction of the Farallon plate beneath the North American plate between 75 and 50 Ma (Titley, 1995; Keith and Swan, 1996). In New Mexico, the Laramide orogeny was followed by mid-Tertiary volcanism that resulted in extensive caldera formation and eruption of associated ignimbrites. Basin and Range faulting began at about 35 Ma and continues to the present time.

The Hillsboro district consists of a circular outcrop block of Late Cretaceous andesite, the Copper Flat volcano, that is developed in and is surrounded by Paleozoic sedimentary rocks and partially covered by Pliocene basalt flows and Quaternary alluvial fan deposits (Fig. 3). The CFQM intruded the center of the Copper Flat volcano. Latite, quartz latite, and monzonite dikes intruded the andesite and quartz monzonite and are radially distributed around the central CFQM.

The oldest rocks are andesite flows and breccias that erupted from the volcano. The andesite is at least 830 m thick from drill core data (Hedlund, 1977). It is porphyritic, typically green-gray to brown-gray in color, with a holocrystalline, fine-grained matrix, and consists of essential plagioclase, orthoclase, blue-green to brown hornblende, magnetite, olivine, and trace amounts of biotite, clinopyroxene, quartz,
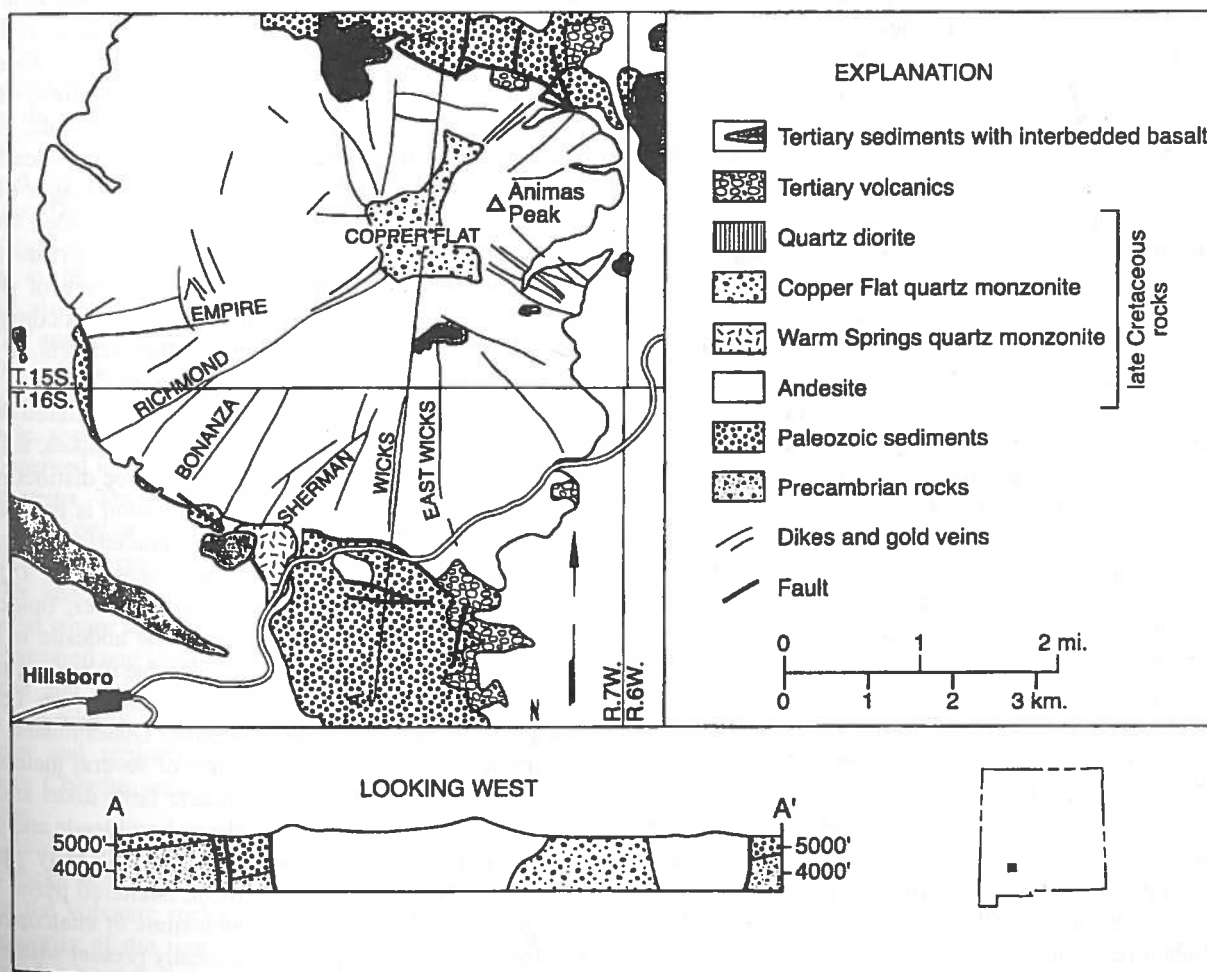

FIGURE 3. Generalized geologic map of the Hillsboro mining district (modified from Dunn, 1982; Hedlund, 1985).

rutile, apatite, and zircon. A trachytic texture is present locally. An andesite flow breccia is exposed on the road to the Snake mine that contains large fragments (as much as 30 cm diameter) of latite, quartz latite, and quartz monzonite, suggesting that the Copper Flat volcano was active after intrusion of the CFQM and latite/quartz latite dikes. However, reconstruction of the volcanic stratigraphy is not possible because of erosion and faulting.

The CFQM intruded andesite flows, breccias, and associated volcaniclastic rocks. A second intrusion, the Warm Springs quartz monzonite is exposed south of the CFQM (Fig. 3) and is relatively unaltered and unmineralized. The CFQM intruded the vent of the volcano, whereas the unmineralized Warm Springs quartz monzonite intruded the andesite south of the CFQM. A third altered, but unmineralized quartz monzonite crops out in the northern part of the district. These two latter intrusions most likely represent small, satellite stocks that intruded along fracture zones on the flanks of the volcano.

The CFQM is medium- to coarse-grained, holocrystalline, porphyritic intrusion and consists of quartz, K-feldspar, plagioclase, hornblende, biotite, and trace amounts of magnetite, apatite, zircon, and rutile with local concentrations of pyrite, chalcopyrite, and molybdenite. Monzonite and quartz monzonite dikes intruded the CFQM stock and the andesite. The Warm Springs quartz monzonite is similar in texture to the CFQM and is medium to coarse grained, holocrystalline, and porphyritic. It is less altered than the CFQM and contains quartz, K-feldspar, plagioclase, hornblende, apatite, magnetite, and zircon.

At least 34 latite, quartz latite, and monzonite radial dikes intruded the andesite and CFQM, but did not intrude the Warm Springs quartz monzonite. The dikes are gray to tan, typically hypocrystalline to holocrystalline and porphyritic. In outcrop the dikes are 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/quartz latite dikes occur: a porphyritic latite with large orthoclase phenocrysts (several centimeters long) and an aphanitic latite. The dikes contain quartz, K-feldspar, plagioclase, biotite, magnetite, and locally hornblende, pyrite, apatite, and rutile. Most dikes exhibit varying degrees of alteration. The polymetallic veins are subparallel to the dikes and trend outwards from the CFQM in a radial pattern similar to spokes of a wheel. Paleozoic sedimentary rocks, including sandstones, siltstones, shales, and limestones are in fault contact with the andesite north and south of the volcano (Fig. 3).

The Kneeling Nun Tuff (ca. 34 Ma) and Sugarlump Tuff (ca. 35 Ma) unconformably overlie the andesite flows locally (Hedlund, 1977). The tuffs were erupted from the Emory caldera and indicate 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±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 basalt dikes intruded the andesite and quartz monzonite. These dikes are relatively unaltered and are probably associated with the Pliocene alkali basalt flows (4 Ma, Seager et al., 1982) capping many of the peaks of the Animas Mountains.

HYDROTHERMAL ALTERATION OF IGNEOUS ROCKS

Three types of mineral assemblages are recognized in the Copper Flat porphyry copper deposit: biotite-potassic, potassic, and sericitic alteration (Table 3, Fowler, 1982). Biotite-potassic alteration coincides with the highest copper grades in the Copper Flat porphyry copper deposit and is characterized by secondary hydrothermal biotite, K-feldspar, quartz, and pyrite as veinlets and large crystals replacing the monzonite. Potassic alteration is peripheral to the porphyry copper deposit and is characterized by large K-feldspar crystals and rimming of plagioclase by K-feldspar along with chlorite, quartz, and pyrite (Fowler, 1982). Sericitic alteration forms the outer most alteration zone of the Copper Flat deposit and is characterized by replacement of biotite and feldspar by sericite. Quartz-sericite (±pyrite) veinlets are also common.

The latite/quartz latite dikes, which are nearly always associated with polymetallic quartz veins, are extensively altered (Table 3). Propylitic alteration is adjacent to the mineralized veins and is characterized by quartz, K-feldspar, chlorite, pyrite, and locally epidote, which have replaced biotite, hornblende, feldspars, and the groundmass. Sericitic alteration consisting of quartz and sericite is also locally common. Pyrite is common in most dikes. Two stages of pyrite are common; early pyrite is altered and corroded and later fresh, unaltered pyrite. Some of the younger pyrites contain small inclusions of chalcopyrite. A third stage of pyrite is locally present as inclusions within younger chalcopyrite and quartz veinlets. Many dikes contain thin veinlets of quartz, quartz-sericite, and quartz-chalcopyrite.

The andesite is typically hydrothermally altered adjacent to the quartz monzonite, latite/quartz latite dikes, and polymetallic veins, and is characterized by three distinct mineral assemblages (Table 3). Propylitic alteration is present 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. Epidote and chlorite locally replace plagioclase. The andesite is locally bleached to a light greenish-gray color due to replacement by chlorite. Epidote-pyrite and pyrite veinlets are common along fractures within the andesite. Disseminated pyrite occurs in the andesite for a distance of several meters away from the contact with the latite/quartz latite dikes and polymetallic veins. Pyrite locally replaces hornblende and olivine grains. Two stages of pyrite are common; early pyrite is altered and corroded and later fresh, unaltered pyrite. Some younger pyrites contain small inclusions of chalcopyrite. A third stage of pyrite deposition is locally present where pyrite is included within younger chalcopyrite and quartz veinlets.

TABLE 3. Summary of hydrothermal alteration assemblages associated with mineralization in the Hillsboro district (Fowler, 1982; Hedlund, 1985; McLemore et. al., 1999b).

Host Rock/Type Of Mineral Deposit	Alteration Mineral Assemblage	Alteration Type
Quartz monzonite/porphyry copper deposit	Biotite, K-feldspar, quartz, pyrite	1-biotite-potassic
	K-feldspar, chlorite, quartz, pyrite	2-potassic
	Sericite, quartz, pyrite	3-sericitic
Andesites adjacent to the latite dikes and polymetallic veins	Epidote, chlorite, sericite, pyrite, magnetite	4-propylitic
	Sericite, calcite, chlorite, quartz, pyrite	5-argillic
	Chlorite, kaolinite, sericite, calcite, quartz, pyrite	6- propylitic
Latite/quartz latite dikes associated with the polymetallic veins	Quartz, K-feldspar, pyrite, epidote, chlorite	4-propylitic
	Quartz, sericite, chlorite, pyrite	5-sericitic
Limestones, dolostones	Garnet, epidote, magnetite, quartz	6-skarn
	Marble, recrystallized limestone	7-marble
	Quartz, iron and manganese oxides	8-jasperoid

The propylitic alteration zone is intermittent and varies in thickness from less than a centimeter up to a meter thick along strike of the dikes and veins.

Adjacent to, and overlapping, the propylitic alteration zone is the argillic alteration zone, which is characterized by sericite, calcite, chlorite, quartz, and pyrite. Chlorite has replaced mafic minerals and the groundmass within the andesite. Disseminated pyrite is locally pervasive in the andesite. Rare chlorite veinlets form along fractures. Calcite occurs as thin veins and also replaces feldspar crystals. Sericite also replaces K-feldspar crystals.

The andesite is locally altered adjacent to a few polymetallic veins to a second propylitic mineral assemblage consisting of white to greenish-gray fault gouge of chlorite, kaolinite, sericite, calcite, quartz and pyrite. These zones are best observed in the underground workings and are adjacent to the veins. They are locally thicker where polymetallic veins pinch out or where they formed several small veinlets of quartz and pyrite.

The andesite exhibits a variable propylitic to argillic alteration where adjacent to the CFQM. The andesite is typically fractured and locally contains local thin veinlets of chalcopyrite and pyrite in association with chrysocolla, malachite, and azurite. Epidote is rare, but locally forms fracture coatings and replacements of mafic minerals within the andesite. Chlorite, sericite, and iron oxides are common in the andesite.

Deuteric alteration refers to the interaction between volcanic rocks and magmatic-hydrothermal fluids during cooling of the volcanic rocks. Deuteric alteration has affected the majority of the igneous rocks in the Hillsboro district and is distinguished from hydrothermal alteration by its overall pervasiveness, lack of fracture control, and the presence of primary minerals that are only partially replaced by 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.

HYDROTHERMAL ALTERATION OF SEDIMENTARY ROCKS

Three distinct types of alteration of the sedimentary rocks occur in the Hillsboro district (Table 3). Limestone south of the Copper Flat volcano is altered to jasperoid. Elsewhere, the limestones, sandstones, and shales have been metamorphosed to skarns and marble.

JASPEROIDS

Large jasperoid bodies have replaced the limestones of the El Paso Formation (Ordovician), Fusselman Dolomite (Silurian) and 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 developed in the Fusselman Formation and Percha Shale (V. T. McLemore, unpublished mapping), indicating a pre-Oligocene and pre-Emory caldera age (ca. 34 Ma, Seager et al., 1982) for the jasperoids. Andesitic volcanic rocks also overlie jasperoids in the El Paso Formation.

The jasperoids vary from white to gray to reddish brown to yellowish brown, are brecciated, and are typically

aphanitic to fine grained texture. Numerous thin (less than 1 cm) white quartz veins cut the jasperoid. Typically, a single stage of brecciation occurred where the younger brown jasperoid cemented the older, white to gray, brecciated jasperoid. Locally, two stages of brecciation occurred where the brown jasperoid cemented the older brecciated white to gray jasperoid and was then recemented by a younger red jasperoid. Jigsaw-puzzle breccias are common. The jasperoid is locally vuggy with drusy quartz filling the vugs. In thin section, the jasperoids vary from aphanitic to fine-grained, sugary textures. The jasperoids typically form sharp contacts with the host limestone. The limestone adjacent to or underlying the jasperoids is locally brecciated or partially recrystallized, and cut by calcite-iron oxide veins. Some of these veins are continuous into the jasperoids. Locally, thin, poorly developed jasperoid bodies occur within the Percha Shale, especially near the contact with the underlying Fusselman Dolomite. Small carbonate-hosted Ag-Mn replacement deposits occur beneath the jasperoid in these areas.

The jasperoids consists predominantly of quartz and iron and manganese oxides. Trace amounts of pyrite, dolostone, calcite, magnesite, sericite, fluorite, and altered feldspar are locally present. The 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. A maximum of 19 ppb Au and 12 ppm As are reported from eight jasperoid samples from the Hillsboro district (McLemore et. al., 1999b).

SKARNS

Poorly developed, unmineralized skarn deposits occur in limestone north and south of the andesite volcanic/intrusive complex. The skarns are typically small replacement pods consisting of garnet, epidote, and magnetite with fine-grained hornfels and thin beds of white to gray marble adjacent to barren limestone or sandstone. Pyrite is rare, although locally as much as 3% pyrite is present, typically as thin quartz-pyrite veinlets. Precious and base metals concentrations are typically low (<0.2 ppm Au, <2 ppm Ag, and <50 ppm Cu, V. T. McLemore, unpublished data). The skarns generally occur within less than a kilometer of the intrusive contacts (Fig. 3), and are thought to be genetically related to the quartz monzonite intrusions.

MARBLE

Marble occurs sporadically adjacent to and within the skarns. The marble is typically white and locally contains disseminations of pyrite, garnet, and epidote. Recrystallized limestone is also common adjacent to skarns and jasperoids. Iron oxide minerals are common in the recrystallized limestone.

SUMMARY OF GEOCHEMISTRY OF IGNEOUS ROCKS

It is beyond the scope of this paper to present the geochemical data and only a summary is presented here; the reader is referred to McLemore et al. (1999b). Like samples from many porphyry copper systems, the samples from Hillsboro exhibit varying degrees of alteration. The least altered andesites are metaluminous and alkaline; the least altered quartz monzonites and latites are metaluminous to peraluminous and alkaline to subalkaline. The linear variation in Na_2O+K_2O/SiO_2, V/TiO_2, SiO_2 vs. TiO_2, and SiO_2 vs. Zr/TiO_2, and SiO_2 vs. other major elements suggests that the igneous rocks are comagmatic. 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. These plots also indicate that the latite/quartz latite dikes are closely related to the intrusion of the three quartz monzonite porphyry intrusions. The igneous rocks are classified as Syn-collision to Volcanic Arc granites (Pearce et al., 1984). These data are consistent with highly evolved arc magmatism related to subduction of the Farallon plate (Keith and Swan, 1996). The Copper Flat porphyry copper deposit is a low-sulfur system with total sulfur contents less than 7% (V.T. McLemore, unpublished data) and pyrite contents of typically less than 2%, although higher concentrations of pyrite occur locally. Collectively, these data also 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.

AGE OF IGNEOUS ROCKS

Hedlund (1974, 1985) reported an age of the CFQM as 75.1±2.5 Ma (biotite, K-Ar). Additional samples of the andesite, quartz monzonite, and quartz latite dikes were collected and analyzed by $^{40}Ar/^{39}Ar$ methods by the New Mexico Geochronological Research Laboratory at NMB-MMR. All of the samples were altered.

The complexity of the hornblende age spectra (Fig. 4) is probably caused by excess argon contamination. Isochron analyses for the three hornblendes yield approximate linear arrays for various heating steps (Fig. 4). Even though the isochron arrays are somewhat disturbed, the data suggest distinct excess argon reservoirs which causes the age spectra complexity (Heizler and Harrison, 1988). The isochron ages (Fig. 5) are the best estimate for the age of the hornblendes and represent 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) are 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
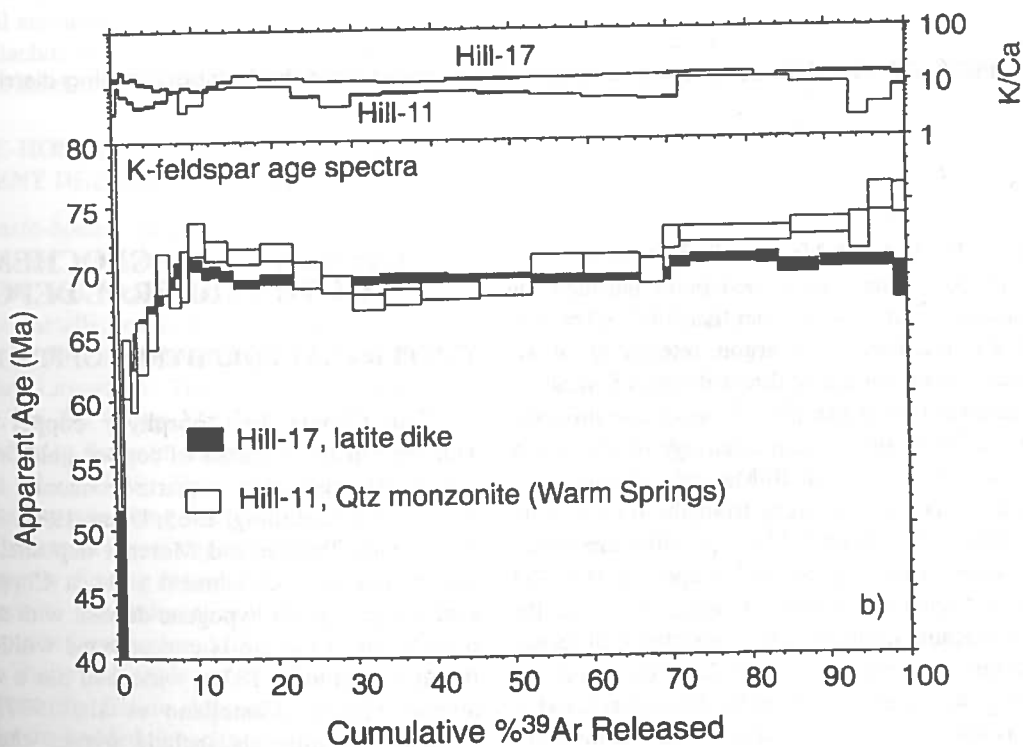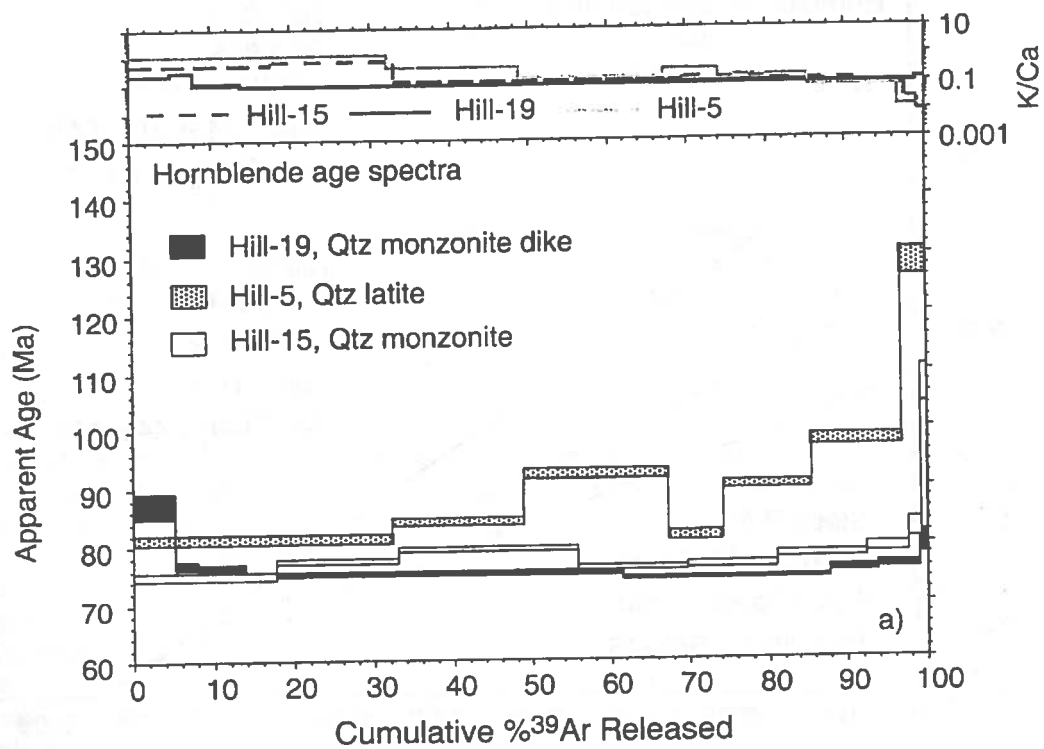
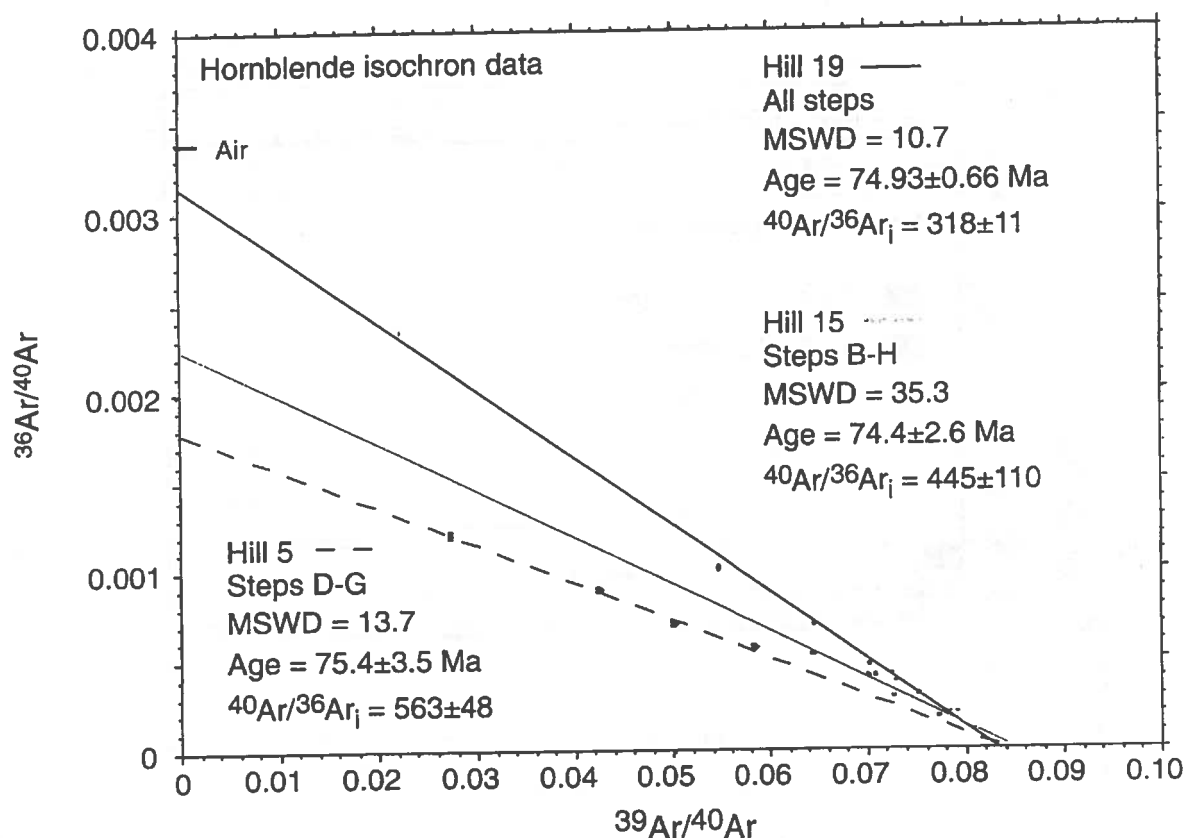**FIGURE 4.** Hornblende (a) and K-feldspar (b) age spectra for samples from Hillsboro mining district.

FIGURE 5. Hornblende isochron diagrams for samples from the Hillsboro mining district.

monzonite (HILL 11, 74.4±2.6 Ma) are all about 75 Ma (Fig. 5; Appendix 1). 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 of intrusive rocks, the K-feldspar results can provide some age information of the quartz latite dike. The plateau age of the quartz latite sample HILL-17 is 70.21±0.20 Ma and is distinctively younger than the final heating steps from the quartz monzonite sample HILL-11 (Appendix 2). 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 occurred during the intrusion of the 70 Ma quartz latite nearby. 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 and thus the true age of the quartz latite remains uncertain.

GEOLOGY AND GEOCHEMISTRY OF THE MINERAL DEPOSITS

COPPER FLAT PORPHYRY COPPER DEPOSIT

The Copper Flat porphyry copper deposit in the Hillsboro district consists of copper, gold, molybdenum, and silver disseminated in a quartz-monzonite stock and in thin quartz veins (Schilling, 1965; Dunn, 1982, 1984). Unlike the Santa Rita, Tyrone, and Morenci deposits, there is only a minor supergene enrichment zone at Copper Flat; Copper Flat is a low-grade hypogene deposit with a low pyrite content. Much of the ore is concentrated within a breccia pipe that is 396 m long, 183 m wide, and has a vertical extent of almost 518 m (Castellano et al., 1977; Dunn, 1982). Predominant minerals include pyrite, chalcopyrite, chalcocite, azurite, malachite, and cuprite. Minor amounts of molybdenite, galena, bornite, tetrahedrite, sphalerite, and fluorite are also present. Chalcopyrite is the predominant copper

mineral. Gold and silver occur as electrum. Molybdenite is the predominant molybdenum mineral. Thin veinlets containing quartz, chalcopyrite, pyrite, bornite, biotite, and epidote cut the CFQM. Oxidation is restricted to the upper 6-9 m of the sulfide zone (Castellano et al., 1977). Overburden ranges from 0 to 6 m.

POLYMETALLIC VEIN DEPOSITS

The polymetallic veins are associated with latite/quartz latite dikes and consist of quartz, pyrite, clay, iron oxides, barite, malachite, pseudomalachite, 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 0.8-3 m wide. They are typically en echelon and pinch and swell. The veins locally grade along strike into an alteration zone of sericite and pyrite with little or no metals concentrations. The veins vary tremendously in chemical composition, but are typically enriched in Au, Ag, Cu, As, Bi, Pb, Zn, Sb, and depleted in Mo relative to the porphyry copper and carbonate-hosted replacement deposits (McLemore et. al., 1999b).

The paragenetic sequence of the minerals within the veins is complex. Typically, quartz and pyrite precipitated first followed by chalcopyrite and pyrite. Some of the pyrite contain inclusions of chalcopyrite. Other pyrite completely surrounds bornite and indicates that bornite is locally a primary mineral. Locally, galena rims pyrite crystals or contains small inclusions of pyrite. Cuprite, digenite, and arsenopyrite are locally present in small amounts. Late veins of hematite with a central core of malachite are found in some areas and may suggest a change in fluid chemistry to more oxidizing fluids.

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 McLemore, in press), small Pb-Zn skarns, and polymetallic veins in Paleozoic limestones and dolostones, of the El Paso Formation, Fusselman Dolomite and Lake Valley Limestone. The replacement deposits are enriched in Pb, Zn, Ba, V, Ag, Mn, Mo, Sb, and depleted in Au and Cu relative to the vein and porphyry copper deposits (McLemore et. al., 1999b). Two styles of mineralization occur: 1) fissure deposits along fracture zones and faults, and 2) tabular bedded replacement deposits. The fissure deposits are irregular, steeply dipping deposits that cut across bedding planes. Adjacent to the mineralized fault zones, tabular, stratabound deposits have replaced limestone. These deposits are irregular in shape and grade into the fissure replacement bodies. Therefore, the fissure deposits are most likely the feeder zones for the bedded deposits.

Two distinct types of mineral deposits are recognized: 1) Pb-Zn and 2) Ag-Mn. Breccia fragments of jasperoid within the deposits indicate that early deposition of jasperoid replacement preceded metals deposition in both types of mineral deposits. Typically in the Pb-Zn deposits, sphalerite, quartz, calcite, and dolostone precipitated next and cement the jasperoid breccia fragments. Locally, sphalerite contains inclusions of galena, pyrite, and iron-oxide minerals. Cerussite and locally anglesite typically occur as rims surrounding galena and filling fractures within the galena. Smithsonite and willemite, when present, typically surround or replace sphalerite grains. Locally, well-crystallized cerussite grains contains pyromorphite inclusions (Munroe, 1999). Garnet and wollastonite are locally present in small amounts. Wulfenite, vanadinite, pyromorphite, hemimorphite, hydrozincite, mottramite, plumbojarosite, argentojarosite, rhodochrosite, cuprite, malachite, azurite, linarite, descloisite, endlichite, franklinite, and mimetite are also late-stage oxidation minerals (Lovering and Heyl, 1989; Munroe, 1999; observations by the authors). Psilomelane and pyrolusite are present in some deposits. Samples of wulfenite, vanadinite, endlichite, melanotekite, and calcite from the district are in the Smithsonian Institute collection (Kimbler, 1981).

In the carbonate-hosted Ag-Mn replacement deposits, early deposition of unidentified silver minerals in association with quartz, siderite, and calcite was followed by a manganese-rich stage. Manganese-oxide minerals, typically psilomelane, pyrolusite, and coronadite occur with manganiferous calcite, hematite, and siderite. Smectite and mixed-layered clay minerals surround some manganese-oxide minerals in places, and are attributed to formation by surface weathering (Munroe, 1999).

PLACER GOLD DEPOSITS

The placer gold deposits in the Hillsboro district is the second most productive of placer gold 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 and accounts for most of the gold production from the district (McLemore, 1994). Placer gold occurs in four gravel units ranging in age from latest Miocene to Holocene (Segerstrom and Antweiler, 1975). The Luxemburg placers were one of the largest producers of placer gold and included alluvial fan and stream gravels near and within the Grayback and Hunkidri Arroyos (Heylmun, 1986). The gold averaged 945-956 fineness and 2.44-24.4 g/m³ Au in deposits as much as 4.5 m thick. Black sand concentrates from the area consist of magnetite, pyrite, hematite, and limonite that were eroded from oxidized pyrite-quartz veins; coarse grained silver-bearing gold occurs in these heavy mineral concentrates (Heylmun, 1986; Lovering and Heyl, 1989). Flour gold, with a low silver content, was derived from the Copper Flat porphyry copper deposit (Lovering and Heyl, 1989). The absence of abundant water has hampered production. The deposits are small and amenable to small-scale placer operations.

SUMMARY OF FLUID INCLUSION DATA

Fluid inclusions from the breccia pipe of the Copper Flat porphyry copper deposit contained numerous daughter minerals, including halite, sylvite, and chalcopyrite. Fowler

(1982) reports homogenization temperatures of 320-360°C for the majority of the inclusions within the breccia pipe with salinities of 10-45 eq. wt.% NaCl. Norman et al. (1989) reports 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 later meteoric fluids flooded the system. These data indicate 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 (226-388°C) than the breccia pipe samples, with salinities of 5.7-33.7 eq. wt% NaCl (Norman et al., 1989). The similarity in chemical composition of fluids in samples from the Wicks vein and the breccia pipe deposit suggest that both types of deposits may have resulted from a similar fluid source, although they are products of different physical and chemical depositional processes (Norman et al., 1989). High salinities are consistent with a magmatic-hydrothermal origin for the vein and the breccia pipe.

DISTRICT ZONING

Many previous workers have recognized district-wide mineral zoning (Harley, 1934; Fowler, 1982; Hedlund, 1985) with the Copper Flat porphyry copper deposit at the center (Fig. 6). Chemical analyses of 24 samples of the porphyry copper deposit show that metal contents range from <2-8810 ppb Au, <2-2.6 ppm Ag, 4->9999 ppm Cu, <2-475 ppm Mo, <5-250 ppm Pb, and 14-1032 ppm Zn (McLemore et al., 1999b). Propagating radially outward from the CFQM are

polymetallic veins hosted by many of the latite dikes. Chemical analyses of 194 vein samples show that metal contents range from <2-64,600 ppb Au, <2-590 ppm Ag, <2-57,337 ppm Cu, <2-68 ppm Mo, <5-9175 ppm Pb, and 11-17,026 ppm Zn. The distal carbonate-hosted replacement deposits (Ag, Pb, Mn, V, Mo, Zn) are found in the southern and northern parts of the district, and chemical analyses of 8 replacement samples show that metal contents ranges of <2-99 ppb Au, <2-64 ppm Ag, 7-196 ppm Cu, <2-160 ppm Mo, <5->10,000 ppm Pb, and 227->20,000 ppm Zn. A crude chemical zonation exists among the two types of carbonate-hosted deposits and reflects the abundance of silver, manganese, and base metals. The carbonate-hosted Ag-Mn replacement deposits occur closer to the CFQM and the fault contact between the andesite and Paleozoic rocks, whereas the carbonate-hosted Pb-Zn replacement deposits are the most distal deposits relative to the CFQM.

DISCUSSION AND CONCLUSIONS

Field relationships, geochemical, and geochronological data indicate the igneous rocks are comagmatic and related to a Laramide volcanic/intrusive complex that formed at about 75 Ma. The age of the latite/quartz latite dikes is 70-75 Ma. The sequence of events at Hillsboro is summarized in Table 4. The geochemical data suggest that the igneous rocks are products of highly-evolved arc magmatism and similar in composition to most porphyry copper deposits in southwestern United States (Wilt, 1995; Keith and Swan, 1996; McLemore et. al., 1999b). Lead isotopic data indicate that the source of lead in the Copper Flat porphyry copper deposit is
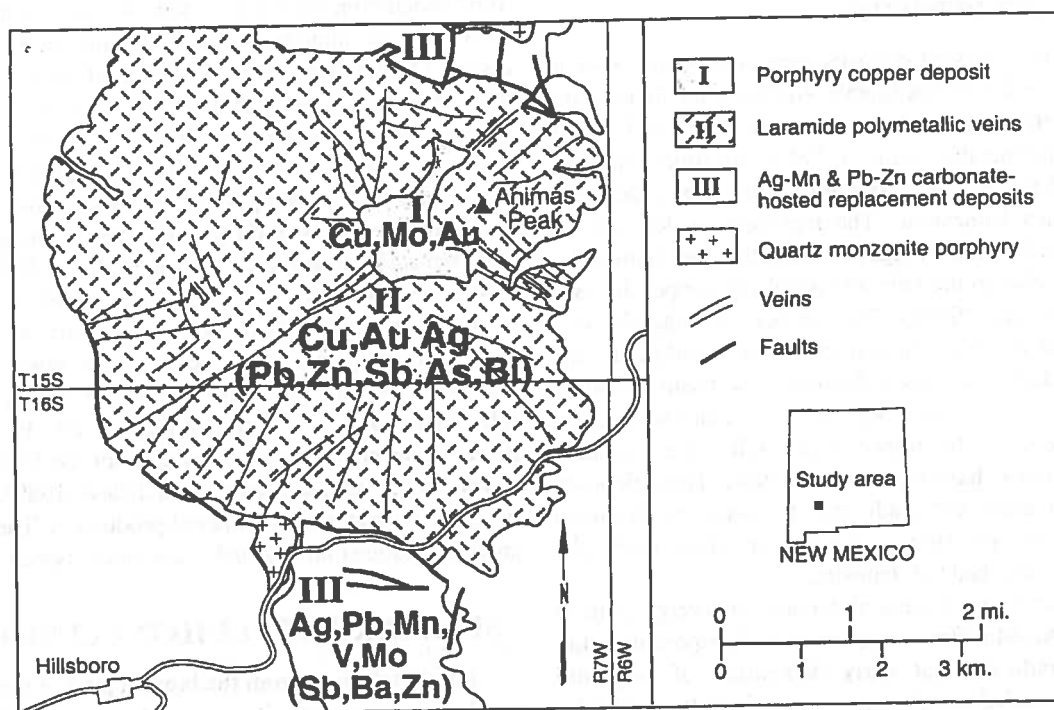

FIGURE 6. District zoning in the Hillsboro mining district (McLemore et. al., 1999b).

TABLE 4. Sequence of events in the Hillsboro mining district. Deposition of the Copper Flat porphyry copper and vein deposits and formation of jasperoids most likely overlapped in time. From McLemore et al. (2000).

Geologic Event	Age	Mineralization And Alteration
Eruption of alkali basalt	4 Ma	None
Uplift of the Copper Flat volcanic/intrusive complex followed by erosion	21-22 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 in the Hillsboro district
Burial? or possibly minor erosion?	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, type 4, 5, and 6 alteration (Table 3)
Intrusion of quartz monzonite porphyry and formation of breccia pipe deposit	75 Ma	Porphyry copper deposits (Cu, Au, Ag, Mo), type 1, 2 and 3 alteration (Table 3), formation of skarn and marble in limestone
Eruption of andesite volcano	75 Ma	None, possible early deuteric alteration

similar to the source for other porphyry copper deposits in New Mexico, and that the source is distinctly different from that for the younger mid-Tertiary mineral deposits in southwestern United States (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 (McLemore et. al., 1999b). Keith and Swan (1996) propose that the Copper Flat volcanic/intrusive sequence at Hillsboro was related to flattening of the subducted Farallon plate.

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 subsequent intrusion of the latite/ quartz latite dikes. These convective hydrothermal systems were shallow, at depths of 1-2 km (Fowler, 1982). Fluid inclusion measurements from the Wicks vein and Copper Flat breccia pipe indicate the fluids had high salinities, and suggest a magmatic-hydrothermal source. Only minor differences exist in the chemical composition of fluid inclusions from the Wicks vein and the Copper Flat breccia pipe, suggesting a common source of mineralizing fluids although different depositional processes controlled mineralization (Norman et al., 1989).

The exact age of the carbonate-hosted replacement deposits is unknown. The deposits are younger than the jasperoids, which formed prior to eruption of the Sugarlump

Tuff at 35 Ma. It is likely that the carbonate-hosted replacement deposits are the distal end-members of the chemically and mineralogically zoned magmatic-hydrothermal system developed around the CFQM, for three reasons. They occur within a few kilometers of the CFQM. The abundance of multiple episodes of silicification in the carbonate-hosted replacement deposits is consistent with a magmatic-hydrothermal source. The mineralogy and textures of the carbonate-hosted Pb-Zn and Ag-Mn replacement deposits are consistent with formation by late-stage oxidizing fluids, although formation by supergene processes can not be completely eliminated.

The similarities in bulk metal chemical composition between the three deposit types (McLemore et. al., 1999b) are consistent with the conclusion that the deposits have a common source, but formed by different depositional processes in different host rocks. Good correlations exist between precious and base metals in the porphyry copper, polymetallic vein, and carbonate-hosted replacement deposits, also support this conclusion. A poor correlation between Cu and Mo in the porphyry copper and vein deposits suggests multiple cycles of mineralizing fluids, possibly as a result of multiple magmatic-hydrothermal systems. The presence of low temperature fluid inclusions in Copper Flat porphyry copper and vein deposits is also consistent with multiple cycles of hydrothermal fluids and influx of meteoric fluids.

Field evidence indicates that the jasperoids were formed prior to deposition of the Sugarlump Tuff 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 Copper Flat porphyry copper or vein deposits. Some jasperoid samples contain anomalous Au and As concentrations (McLemore et. al., 1999b), which suggests formation by distal hydrothermal fluids that formed the porphyry copper and polymetallic vein deposits. Therefore, the carbonate-hosted replacement deposits may represent the final stages of hydrothermal-magmatic mineralization in the Hillsboro district. Erosion and re-concentration of gold from the porphyry copper and vein deposits formed the placer gold deposits during Miocene to Holocene.

Many porphyry copper deposits in Arizona-Sonora-New Mexico porphyry copper belt appear to have a similar geologic history, that involved as many as three stages of supergene enrichment (Cook, 1994). They were erupted and partially eroded during the Eocene, buried by Oligocene volcanic cover, exhumed from the volcanic cover, and weathered again since late Miocene or early Pliocene. However, the Copper Flat porphyry copper deposit exhibits very little supergene alteration and enrichment. One possible explanation for this is that the Copper Flat deposit contains less than 2% pyrite and the more productive deposits elsewhere in the belt contain higher concentrations of pyrite, and more importantly, higher pyrite:chalcopyrite ratios (Titley and Marozas, 1995).

Another explanation for the absence of supergene enrichment at Copper Flat is that the CFQM remained buried in the subsurface until uplift began at about 21-22 Ma (Kelley and Chapin, 1997), whereas the Santa Rita, Tyrone, and Morenci deposits were exposed to multiple periods of surface erosion, alteration, and supergene enrichments. At Tyrone, four episodes of igneous intrusion occurred between 53-56 Ma and were followed by three episodes of supergene enrichment: 1) during the extensive Eocene erosion of the andesite volcanic complex, 2) again during Miocene Basin and Range faulting, and 3) finally during erosion of the Miocene Mangas Conglomerate (DuHamel et al., 1995). At Chino, three stages of supergene enrichment are recognized; Eocene, early Miocene, and the final stage after Basin and Range faulting in late Miocene or early Pliocene (Cook, 1994). At both of these deposits, extensive erosion of the overlying andesite volcano and supergene enrichment of the porphyry copper deposit occurred during the Eocene, prior to Oligocene volcanism. In contrast, very little of the Copper Flat volcano was eroded during the Eocene; much of the erosion occurred after uplift (21-22 Ma) forming the alluvial deposits and placer gold deposits east of Copper Flat.

ACKNOWLEDGMENTS

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APPENDIX 1. Argon isotopic data for Hillsboro hornblende samples. Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, but not corrected for interfering reactions. Individual analyses show analytical error only; plateau, isochron, and total gas age errors include error in J and irradiation parameters. N=number of heating steps. K/Ca=molar ratio calculated from reactor produced $^{39}Ar_K$ and $^{37}Ar_{Ca}$. * 2σ error. ** MSWD outside of 95% confidence interval.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_K$ (x 10^{-15} mol.)	K/Ca	$^{40}Ar*$ %	^{39}Ar %	Age (Ma)	±1σ (mA)
HILL-19, hornblende, wt=20.36 mg, J=0.0035361, NM-91, Lab#=9356-01										
A	850	45.14	2.374	106.0	9.38	0.21	31.0	5.2	87.2	1.1
B	950	15.50	1.821	11.27	5.09	0.28	79.3	8.1	76.87	0.38
C	1050	14.21	4.796	7.994	10.4	0.11	86.0	13.9	76.58	0.27
D	1100	12.50	5.975	3.330	85.7	0.085	95.9	61.6	75.22	0.16
E	1130	12.63	5.481	4.046	47.2	0.093	93.9	87.8	74.45	0.18
F	1160	13.75	5.515	7.240	10.7	0.093	87.6	93.8	75.56	0.25
G	1190	13.70	6.092	6.923	9.24	0.084	88.6	98.9	76.12	0.25
H	1220	18.26	4.709	19.82	1.95	0.11	69.9	100.0	79.96	0.93
Total gas age		N=8			179.6	0.10			75.89	0.25
Isochron age		N=8	Steps A-H				MSWD =10.7**		74.93	0.66*
HILL-15, hornblende, wt=8.18 mg, J=0.0035662, NM-91, Lab#=9357-01										
A	850	15.63	1.024	12.94	16.2	0.50	75.9	17.8	74.83	0.35
B	950	12.98	0.7926	2.483	13.9	0.64	94.6	33.0	77.41	0.19
C	1050	13.76	4.271	5.101	20.8	0.12	91.4	55.8	79.42	0.21
D	1100	12.75	4.437	3.649	12.8	0.11	94.2	69.9	75.93	0.21
E	1130	13.27	3.403	4.827	10.3	0.15	91.2	81.1	76.38	0.29
F	1160	14.07	4.571	6.904	10.2	0.11	88.0	92.3	78.23	0.27
G	1190	14.20	7.122	7.568	4.79	0.072	88.2	97.6	79.27	0.38
H	1220	15.30	20.56	13.71	1.45	0.025	84.5	99.2	82.59	0.81
I	1300	20.91	64.28	33.35	0.756	0.008	78.2	100.0	107.4	1.7
Total gas age		N=9			91.2	0.26			77.61	0.28
Isochron age		N=7	Steps B-H				MSWD =35.5**		74.40	2.6*
HILL-5, hornblende, wt=5.30 mg, J=0.0035712, NM-91, Lab#=9358-01										
A	850	18.50	0.4914	18.93	20.8	1.0	69.8	32.3	81.42	0.36
B	950	16.18	1.315	9.904	10.7	0.39	82.4	49.1	84.03	0.30
C	1050	18.95	3.535	15.52	11.9	0.14	77.2	67.5	92.10	0.40
D	1100	14.28	1.867	4.995	4.37	0.27	90.6	74.3	81.56	0.33
E	1150	16.65	3.106	8.613	7.33	0.16	86.1	85.7	90.29	0.38
F	1200	19.61	7.986	16.10	7.23	0.064	79.0	97.0	97.70	0.47
G	1250	29.41	43.55	44.08	1.95	0.012	67.9	100.0	128.4	1.2
Total gas age		N=7			64.3	0.47			88.10	0.40
Isochron age		N=4	Steps D-G				MSWD =13.7**		75.4	3.5*

APPENDIX 2. Argon isotopic results for Hillsboro feldspar samples.

ID	Temp (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ (x 10^{-3})	$^{39}Ar_k$ (x 10^{-15} mol.)	K/Ca	$^{40}Ar*$ %	^{39}Ar %	Age (Ma)	±1σ (mA)
HILL-17, K-feldspar, wt.=12.00 mg, J=0.0035546, NM-91, Lab#=9359-01										
A	500	166.9	0.0368	542.1	10.3	13.9	4.0	1.1	42.4	4.6
B	500	20.46	0.0280	36.04	5.64	18.2	47.8	1.7	61.69	0.58
C	550	13.22	0.0377	11.19	7.77	13.5	74.8	2.5	62.34	0.33
D	550	12.13	0.0358	6.237	6.91	14.2	84.6	3.2	64.66	0.27
E	600	11.70	0.0444	4.089	9.83	11.5	89.5	4.2	65.91	0.21
F	600	11.46	0.0473	2.742	8.70	10.8	92.7	5.1	66.87	0.20
G	650	11.82	0.0563	3.454	11.0	9.1	91.2	6.3	67.82	0.20
H	650	11.61	0.0531	2.251	8.74	9.6	94.1	7.2	68.71	0.20
I	700	12.73	0.0622	6.073	4.40	8.2	85.7	7.7	68.67	0.40
J	750	12.99	0.0604	6.210	9.68	8.4	85.7	8.7	70.01	0.27
K	800	12.23	0.0521	3.339	11.4	9.8	91.8	9.9	70.57	0.20
L	850	12.25	0.0610	3.503	11.0	8.4	91.4	11.0	70.42	0.20
M	900	12.85	0.0622	5.833	10.5	8.2	86.4	12.1	69.84	0.23
N	950	13.26	0.0498	7.174	12.2	10.2	83.8	13.4	69.91	0.22
O	1000	13.40	0.0409	7.846	17.0	12.5	82.5	15.1	69.58	0.23
P	1050	13.15	0.0321	7.365	30.5	15.9	83.3	18.3	68.89	0.20
Q	1100	13.16	0.0365	7.168	53.5	14.0	83.7	23.9	69.30	0.18
R	1100	13.72	0.0424	9.230	89.0	12.0	80.0	33.2	69.01	0.19
S	1100	14.46	0.0443	11.60	83.6	11.5	76.1	41.9	69.27	0.17
T	1100	15.03	0.0409	13.61	89.5	12.5	73.1	51.2	69.14	0.19
U	1100	15.41	0.0385	14.92	100.3	13.2	71.2	61.7	69.09	0.22
V	1100	15.88	0.0367	16.37	80.9	13.9	69.4	70.1	69.30	0.22
W	1180	14.03	0.0357	9.640	26.9	14.3	79.5	72.9	70.16	0.20
X	1230	14.91	0.0348	12.45	78.8	14.6	75.2	81.1	70.46	0.20
Y	1280	16.19	0.0416	16.78	27.1	12.3	69.2	84.0	70.49	0.27
Z	1330	17.19	0.0363	0.55	49.4	14.0	64.5	89.1	69.79	0.28
ZA	1430	15.90	0.0353	15.99	88.3	14.5	70.1	98.3	70.15	0.25
ZB	1680	15.95	0.0389	16.95	15.9	13.1	68.5	100.0	68.72	0.72
Total gas age			N=28		958.8	13.0			69.01	0.27
Plateau age	MSWD =1.86	N=6	Steps W-ZB	286.4	14.1			29.9	70.21	0.20*
HILL-11, K-feldspar, wt.= 7.58 mg, J=0.003575, NM-91, Lab#=9360-01										
A	500	317.1	0.1507	1013.6	2.88	3.4	5.5	0.6	108.9	8.9
BB	500	45.05	0.0563	121.9	1.69	9.1	20.0	1.0	56.6	2.3
C	550	38.85	0.0719	97.68	4.31	7.1	25.7	2.0	62.5	1.1
D	550	23.07	0.0879	45.25	3.81	5.8	42.0	2.8	60.78	0.83
E	600	36.27	0.1155	88.09	6.49	4.4	28.2	4.3	64.1	1.0
F	600	19.84	0.1075	31.79	5.68	4.7	52.6	5.5	65.34	0.72
G	650	27.25	0.0900	54.43	6.45	5.7	40.9	56.9	69.78	0.76
H	650	15.09	0.0609	14.26	6.91	8.4	71.9	8.5	67.96	0.36
I	700	26.84	0.1463	53.13	4.41	3.5	41.5	9.5	69.67	0.98
J	750	26.08	0.1042	49.01	8.68	4.9	44.4	11.4	72.44	0.66
K	800	19.46	0.0543	27.09	13.1	9.4	58.7	14.3	71.51	0.40
L	850	16.73	0.0514	18.11	17.9	9.9	67.9	18.3	71.06	0.30
M	900	17.91	0.0510	21.94	18.4	10.0	63.7	22.4	71.38	0.35
N	950	22.79	0.0774	39.43	16.0	6.6	48.8	25.9	69.58	0.51
O	1000	18.48	0.1176	25.27	17.6	4.3	59.5	29.8	68.84	0.36
P	1050	16.12	0.0727	18.05	17.8	7.0	66.8	33.7	67.40	0.30
Q	1100	16.40	0.0692	18.82	21.1	7.4	66.0	38.4	67.78	0.29
R	1100	17.36	0.0659	21.80	33.3	7.7	62.8	45.8	68.23	0.32
S	1100	18.75	0.0728	26.36	30.0	7.0	58.3	52.5	68.47	0.34
T	1100	20.03	0.0821	29.79	30.1	6.2	55.9	59.2	70.13	0.40
U	1100	21.29	0.0939	34.03	33.1	5.4	52.7	66.5	70.18	0.39
V	1100	22.54	0.0992	38.58	13.1	5.1	49.3	69.4	69.61	0.48
W	1180	17.81	0.0966	21.13	8.93	5.3	64.8	71.4	72.23	0.42
X	1230	17.44	0.0424	19.75	63.4	12.0	66.4	85.4	72.44	0.28
Y	1280	18.93	0.0535	24.49	33.7	9.5	61.6	92.9	72.96	0.34
Z	1330	31.07	0.2200	65.86	10.7	2.3	37.3	95.3	72.58	0.74
ZA	1430	23.32	0.1283	38.13	13.5	4.0	51.6	98.3	75.24	0.54
ZB	1680	20.98	0.0647	30.26	7.58	7.9	57.3	100.0	75.09	0.59
Total gas age			N=28		450.6	7.6			70.48	0.47