Geologic Setting and Characteristics of Mineral Deposits in the Central Wasatch Mountains, Utah

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Abstract

Base- and precious-metal deposits in the central Wasatch Mountains southeast of Salt Lake City were mined for more than 100 years beginning in 1868. Deposits present in the Park City, Little Cottonwood, and Big Cottonwood mining districts include Ag-Pb-Zn ± Cu ± Au replacements and veins, a low-grade porphyry Cu-Au deposit, Cu-bearing skarns, a quartz monzonite-type (low F) porphyry Mo deposit, and high sulfidation (quartz-alunite) Au deposits. Most production came from polymetallic replacement and vein deposits in the Park City mining district, which has a recorded production of more than 1.4 million oz Au, 253 million oz Ag, 2.7 billion lbs Pb, 1.5 billion lbs Zn, and 129 million lbs Cu from 1872 to 1978. Production in the Little and Big Cottonwood districts, mostly from Pb-Ag replacement deposits, was much smaller.

Most mineral deposits in the central Wasatch Mountains are genetically related to the Wasatch igneous belt, a series of high-K calc-alkaline stocks and cogenetic volcanic rocks that formed about 41(?) to 30 Ma. The mineral deposits mostly formed near the end of magmatic activity between about 36 to 31.4 Ma. A subeconomic porphyry Mo deposit in the Little Cottonwood stock is notably younger having formed about 26 to 23.5 Ma. The intrusive rocks were emplaced mostly along the westward extension of the west-trending Uinta arch during a period of NW-SE-directed extension, and much of the mineralization in the Park City district was controlled by ENE-striking normal faults. About 15 degrees of eastward tilting of the central Wasatch Mountains during Late Cenozoic Basin and Range extension has resulted in progressively deeper levels of exposure from <1 km on the east to about 11 km on the west and in profound variations in the types of mineral deposits exposed in different parts of the range. Most deposits formed at paleodepths ≤5 km, and the most productive deposits in the Park City district formed at depths of 1 to 2 km. The porphyry Mo deposit in the Little Cottonwood stock formed at greater depths of about 6 km.

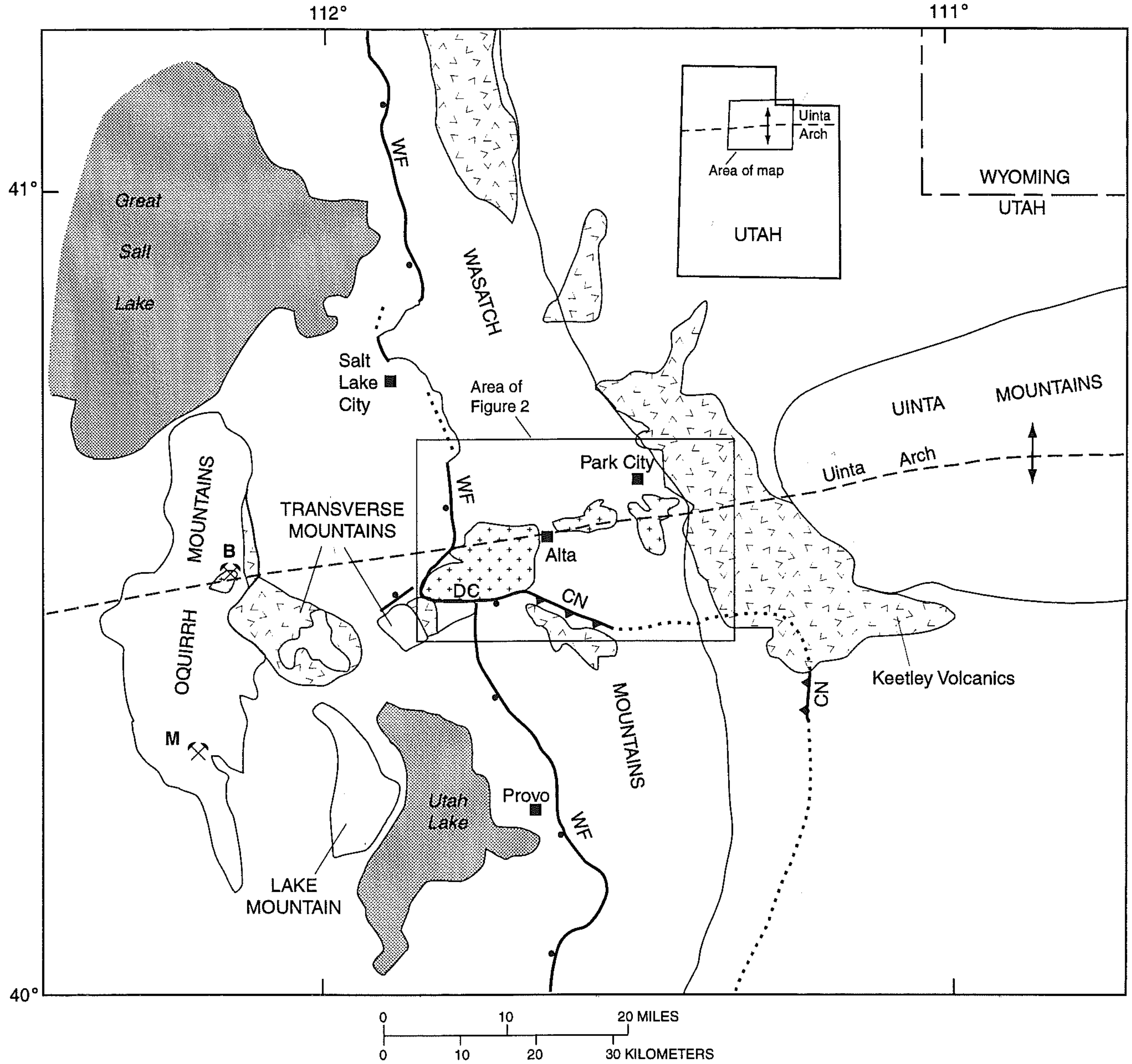
Introduction

The central Wasatch Mountains east and southeast of Salt Lake City, Utah, had a long history of base- and precious-metal mining lasting from the late 1860s to 1978. The range contains a wide variety of mineral deposits that appear to be genetically related to mid-Tertiary magmatism which formed the Wasatch igneous belt (Figs. 1 and 2; Vogel et al., 1997). Deposits include the world-class Ag-Pb-Zn vein and replacement deposits of the Park City mining district, which were the largest producers of silver in the United States for many years (Barnes and Simos, 1968).

This paper reviews the geologic setting and characteristics of mid-Tertiary mineral deposits in the central Wasatch Mountains. Important deposits in the Park City mining district on the east side of the range and in the Big and Little Cottonwood mining districts on the west side of the range (Fig. 2) are described. Several deposits that lie east of the main Park City district are also discussed, but smaller deposits in the American Fork mining district on the south side of the Little Cottonwood stock are not discussed. This summary focuses on mineral deposits that are interpreted to be genetically related to mid-Tertiary magmatism; many small deposits whose origins are uncertain, notably occurrences in metamorphic rocks in the western part of the Big Cottonwood mining district, are not described.

Mining activity in the central Wasatch Mountains began in the late 1860s (Heikes *in* Calkins and Butler, 1943). The first production from the Cottonwood district came in 1868 from Ag-Pb deposits in Little Cottonwood Canyon. Rich Ag-Pb ore in the Park City mining district was first discovered in 1869, and the Ontario Silver Mining Co. was organized in 1872 to exploit the Ontario vein.

Continuous mining occurred in the Park City mining district, one of the great bonanza camps of the West from 1872 through 1978 (Boutwell, 1912; Barnes and Simos, 1968). Production from the principal mines in the Park City mining district through 1978 totaled more than 16.7 million tons of ore containing 1.45 million oz Au, 253 million oz Ag, 2.7 billion lbs Pb, 1.5 billion lbs Zn, and 129 million lbs Cu (Bromfield, 1989). Production through 1967 from the Big and Little Cottonwood mining districts was much smaller, totaling about 830,000 tons of ore that contained about 30,670 oz Au, 17.3 mil-



EXPLANATION

- Volcanic rocks (Tertiary)
- Plutonic rocks (Tertiary)
- Normal fault—Dotted where concealed. Bar and ball on downthrown side
- Thrust fault—Dotted where concealed. Sawteeth on upper plate
- Anticline

FIG. 1. Index map showing the location of the Wasatch Mountains and the distribution of Tertiary igneous rocks in north-central Utah. (B, Bingham mine; CN, Charleston-Nebo thrust; DC, Deer Creek fault; M, Mercur mine; WF, Wasatch fault).

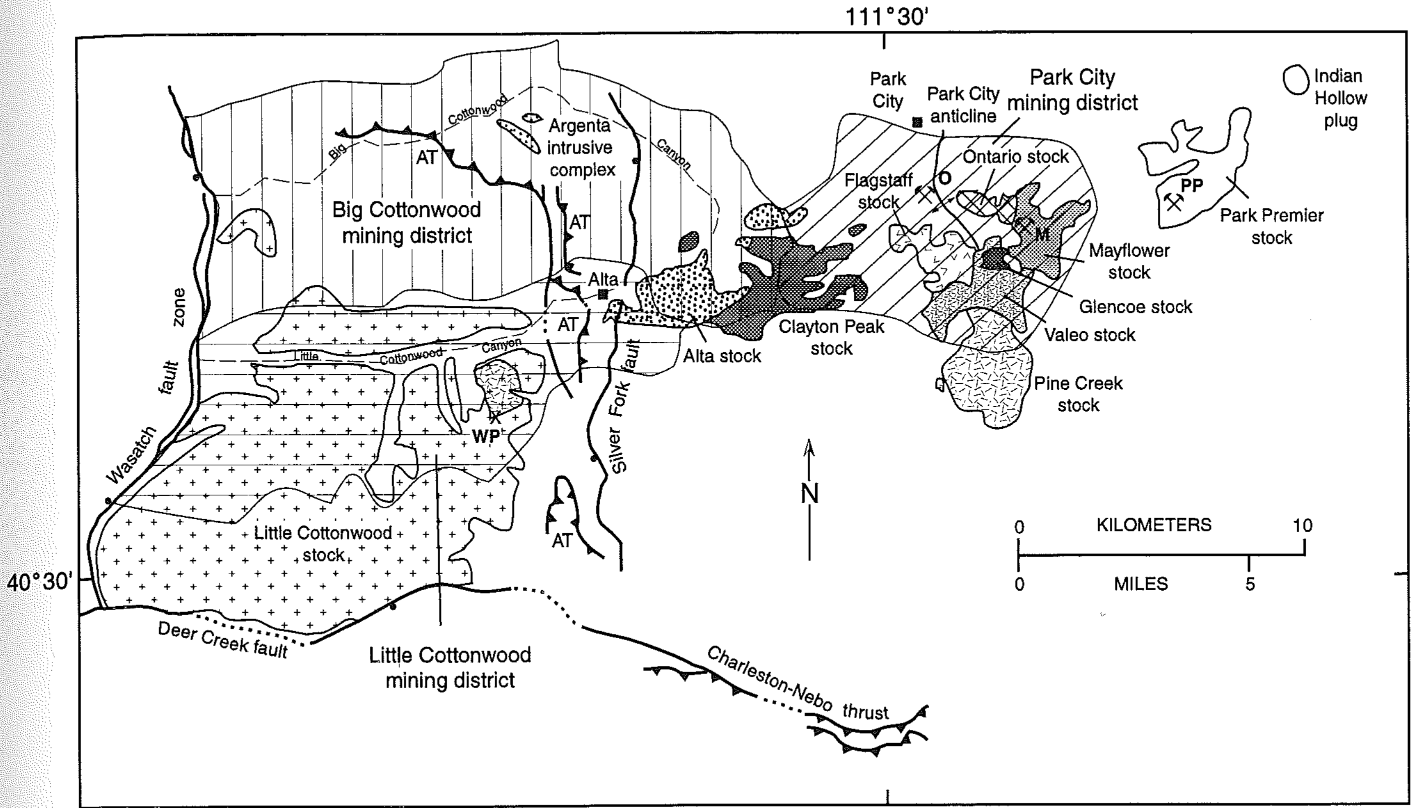


FIG. 2. Generalized geologic map of the central Wasatch Mountains showing mid-Tertiary intrusive rocks, major structural features, and approximate outlines of mining districts discussed in this paper. (AT, Alta-Grizzly thrust; M, Mayflower mine; O, Ontario mine; PP, Park Premier mine; WP, White Pine Fork porphyry molybdenum deposit).

lion oz Ag, 18.1 million lbs Cu, 252 million lbs Pb, and 12.4 million lbs Zn (Stowe, 1975; James, 1979). No production has been recorded in these districts since 1967. At the present time, no mines are operating in the central Wasatch Mountains, and many of the patented mine claims in the Park City district have been bought by ski resorts. On the east side of the Park City mining district, several small mines and prospects were flooded by the filling of Jordanelle Reservoir in the early 1990s, including much of the Park Premier porphyry system. Boutwell (1912), Butler and Loughlin (1916), Calkins and Butler (1943), Barnes and Simos (1968), Erickson (1968), Garmoe and Erickson (1968), Quinlan and Simos (1968), James (1979), Bromfield and Patten (1981), and Bromfield (1989) provide descriptions of the mines and mining history of the central Wasatch Mountains.

Geologic Setting of the Central Wasatch Mountains

The north-trending Wasatch Mountains lie at the junction of the Basin and Range and the Colorado Plateau provinces. The Wasatch fault bounds the west side of the Wasatch Mountains (Fig. 1). The central part of the Wasatch Mountains, called the Cottonwood area by Crittenden (1977), had undergone a long and varied sedimentary and structural history from the Early Proterozoic through the early Tertiary prior to mid-Tertiary igneous activity and formation of the mineral deposits reviewed here.

Sedimentary and Metamorphic Rocks

Sedimentary and metamorphic rocks ranging in age from Early Proterozoic(?) to Late Mesozoic are exposed in the central Wasatch Mountains and host many of the mineral deposits, notably replacement deposits in the Park City mining district. Descriptions of the pre-Cenozoic stratigraphy include those in Boutwell (1907, 1912), Calkins and Butler (1943), Crittenden et al. (1952), Bromfield (1968), and Crittenden (1977). Table 1 presents a composite stratigraphic section for the central part of the Wasatch Mountains based on these descriptions.

The central Wasatch Mountains were the "hingeline" of the Cordilleran miogeocline from the Proterozoic through the Paleozoic, resulting in thin sequences of sedimentary rocks deposited on the shelf and craton east of the hingeline and much greater thicknesses of age-equivalent rocks deposited to the west (Crittenden, 1977). For example, Pennsylvanian-Permian rocks of the western Oquirrh Mountains facies are 10 to 12 times thicker than age-equivalent rocks of the Weber Canyon facies in the

TABLE 1. Summary composite stratigraphic section for the Park City and Big and Little Cottonwood mining districts, central Wasatch Mountains, Utah

Unit	Age	Maximum thickness (m)	Lithology	Comments
Surficial deposits	Quaternary	0-30	glacial and alluvial deposits	
			Unconformity	
Keetley Volcanics	Oligocene-Eocene (38?-33 Ma)	500	intermediate composition lava flows and flow breccias, minor volcaniclastic and pyroclastic rocks	
			Unconformity	
Nugget Sandstone	Jurassic	250	cross-bedded sandstone	
Ankareh Formation	Early to Late Triassic	450	red sandstone, mudstone, and conglomerate	
Thaynes Formation	Early Triassic	550	marine limestone, limey sandstone, and siltstone	
Woodside Shale	Early Triassic	200-250	red shale, siltstone, and fine-grained sandstone	
Park City Formation	Permian	170-200	limestone, dolomite, sandstone, cherty sandstone and siltstone, phosphatic mudstone and shale, calcareous sandstone	main host rock for replacement deposits in Park City mining district
Weber Quartzite	Pennsylvanian	400-500	fine-grained sandstone and quartzite, minor limestone	main host for vein deposits in Park City mining district
Round Valley Limestone	Early Pennsylvanian	60-100	limestone, minor sandy limestone and quartzite	
Doughnut Formation	Late Mississippian	30	shale, sandstone, silty limestone	
Humbug Formation	Mississippian	60	limestone, dolomite, sandstone	host rock for replacement deposits in Ontario mine
Deseret Limestone	Mississippian	250-280	cherty limestone and dolomite	
Gardison Limestone	Early Mississippian	140	cherty limestone and dolomite	
Fitchville Formation	Early Mississippian	45	dolomite	main host rock for replacement deposits in Little Cottonwood mining district
			Unconformity	
Maxfield Limestone	Middle Cambrian	300	dolomite, limestone, nodular shale	
Ophir Formation	Middle Cambrian	130	micaceous sandstone and siltstone, shale	
Tintic Quartzite	Early-Middle Cambrian	200-400	fine- to coarse-grained quartzite	
			Unconformity	
Mutual Formation	Late Proterozoic	370	shale, quartzite, conglomerate	
Mineral Fork Tillite	Late Proterozoic	180	graywacke, conglomeratic graywacke, minor sandstone	
			Unconformity	
Big Cottonwood Formation	Late Proterozoic	5,000	quartzite, shale	
			Unconformity	
Little Willow Formation	Early Proterozoic	1,100-1,250	amphibolite, schist, gneiss, metaquartzite, metaconglomerate	

See text for sources of data.

central Wasatch Mountains. These two sequences of rocks were juxtaposed by Late Cretaceous to earliest Tertiary thrust faults during the Sevier orogeny (Crittenden, 1977).

Several major unconformities are present in the central Wasatch Mountains, including ones between the strongly metamorphosed Early Proterozoic(?) Little Willow Formation and the weakly metamorphosed Late Proterozoic Big Cottonwood Formation on the west side of the range, and between the Cambrian Maxfield Limestone and the Mississippian Fitchville Formation near Alta (Table 1). The latter unconformity is part of a regional unconformity of Late Devonian age which extends across Utah. Crittenden (1977) noted that this unconformity is particularly evident in Little Cottonwood Canyon where the thickness of Cambrian rocks varies in different plates of the Alta thrust. Regionally, the distribution of the Late Devonian unconformity corresponds to an east-trending anticlinal arch whose eastern end was nearly coincident with the axis of the present day Unita arch (Fig. 1).

Tertiary Igneous Rocks

Mid-Tertiary igneous rocks in the central Wasatch Mountains form the west-trending Wasatch igneous belt which parallels the Unita arch (Fig. 1; Vogel et al., 1997). These rocks consist of three equigranular to coarsely porphyritic stocks exposed in the western and central parts of the range (Little Cottonwood, Alta, and Clayton Peak stocks), six porphyry stocks exposed in the middle and eastern parts of the range, mostly in the Park City mining district (Flagstaff, Glencoe, Mayflower, Ontario, Pine Creek, and Valeo stocks), a subvolcanic porphyry complex (Park Premier stock), and coeval volcanic rocks (the Keetley Volcanics), subvolcanic intrusions, and a volcanic neck (Indian Hollow plug) that are exposed on the east side of the range (Figs. 1 and 2). Because of about 15° of Late Cenozoic tilting of the central Wasatch Mountains, a continuum of mid-Tertiary paleodepths is exposed ranging from about 11 km on the west side of the Little Cottonwood stock to the Eocene paleosurface on the east side of the range onto which the Keetley Volcanics were erupted (John, 1989a). The igneous rocks form a high-K calc-alkaline series (Vogel et al., 1997). Most of the intrusive rocks are about 36 to 33 Ma; the Little Cottonwood stock is about 31 to 30 Ma, and several of the porphyry stocks in the Park City district may be 41 to 40 Ma (John et al., 1997). The Keetley Volcanics are about 38(?) to 33 Ma and the composite Park Premier stock is about 35 to 32 Ma. The mid-Tertiary igneous rocks in the central Wasatch Mountains are generally similar in age and composition to late Eocene igneous rocks in the Oquirrh Mountains that formed the Bingham porphyry copper system (Fig. 1; Moore, 1973; Waite et al., 1997).

Structural Setting

The central Wasatch Mountains have a tectonic history dating from the Early Proterozoic (Crittenden, 1977; Presnell, 1997). The dominant structural feature is the west-trending Uinta arch which cuts transversely across the north-trending Wasatch Mountains (Fig. 1). Other important structural features influencing emplacement of the mid-Tertiary intrusions and localization of mineral deposits related to these intrusions are the Park City anticline and, especially, ENE-striking normal faults in the Park City mining district (Figs. 1 and 2). Eastward tilting of the central Wasatch Mountains during Late Cenozoic Basin and Range extension has resulted in progressively deeper levels of exposure from east to west and profound variations in the types of mineral deposits exposed in different parts of the range (John, 1989a). Basin and Range block faulting has also formed the present physiography of the range.

The west-trending Uinta arch is a regional structural feature (Fig. 1) that first formed in Early Proterozoic or earlier time and has been reactivated periodically (e.g., Roberts et al., 1965; Stokes, 1976; Crittenden, 1977; Presnell, 1997). The Unita arch marks the approximate southern boundary of Archean basement rocks of the Wyoming Province (Bryant, 1988). Uplift along the ancestral Uinta arch during the Devonian resulted in a regional unconformity that is manifested in the central Wasatch Mountains by an absence of rocks between the Middle Cambrian and the Early Mississippian (Table 1). During the Late Cretaceous-early Tertiary Sevier orogeny, periodic uplift along the arch controlled emplacement of thrust plates from the west (Crittenden, 1977). During the mid-Tertiary, a period of crustal extension was oriented approximately perpendicular to the arch, and intrusions that form the Wasatch igneous belt were emplaced along the arch (Fig. 2; Constenius, 1996; Presnell, 1997; Vogel et al., 1997). The Uinta arch projects westward across Salt Lake Valley to the Oquirrh Mountains and may have influenced emplacement of Eocene stocks related to the Bingham porphyry copper deposit (Fig. 1; Babcock et al., 1995; Presnell, 1997). In the central Wasatch Mountains, the Uinta arch presently plunges moderately to the east, in general exposing progressively older and more deeply eroded rocks from east to west across the range.

The Late Cretaceous to earliest Tertiary Sevier orogeny produced a north-trending fold and thrust belt in Utah, southern Idaho, and western Wyoming (e.g., Crittenden, 1977). In the central Wasatch Mountains, three major thrust faults are recognized, from oldest to youngest, the Alta-Grizzly, Mt. Raymond, and Charleston-Nebo thrusts (Figs. 1 to 3; Crittenden, 1977). These thrust faults acted either as barriers for mineralizing fluids or as channels, where fault brecciation increased permeability (Calkins and Butler, 1943; Barnes and Simos, 1968). Folds formed during the Sevier orogeny include the north-trending Park City anticline, the dominant structural feature in the Park City mining district.

Two periods of Cenozoic extension are recognized in the central Wasatch Mountains: late Eocene to Oligocene and latest Tertiary to Holocene (Constenius, 1996; Presnell, 1997; Vogel et al., 1997). The earlier period of extension was oriented NW–SE to NNW–SSE, approximately perpendicular to the Uinta arch, and was accom-

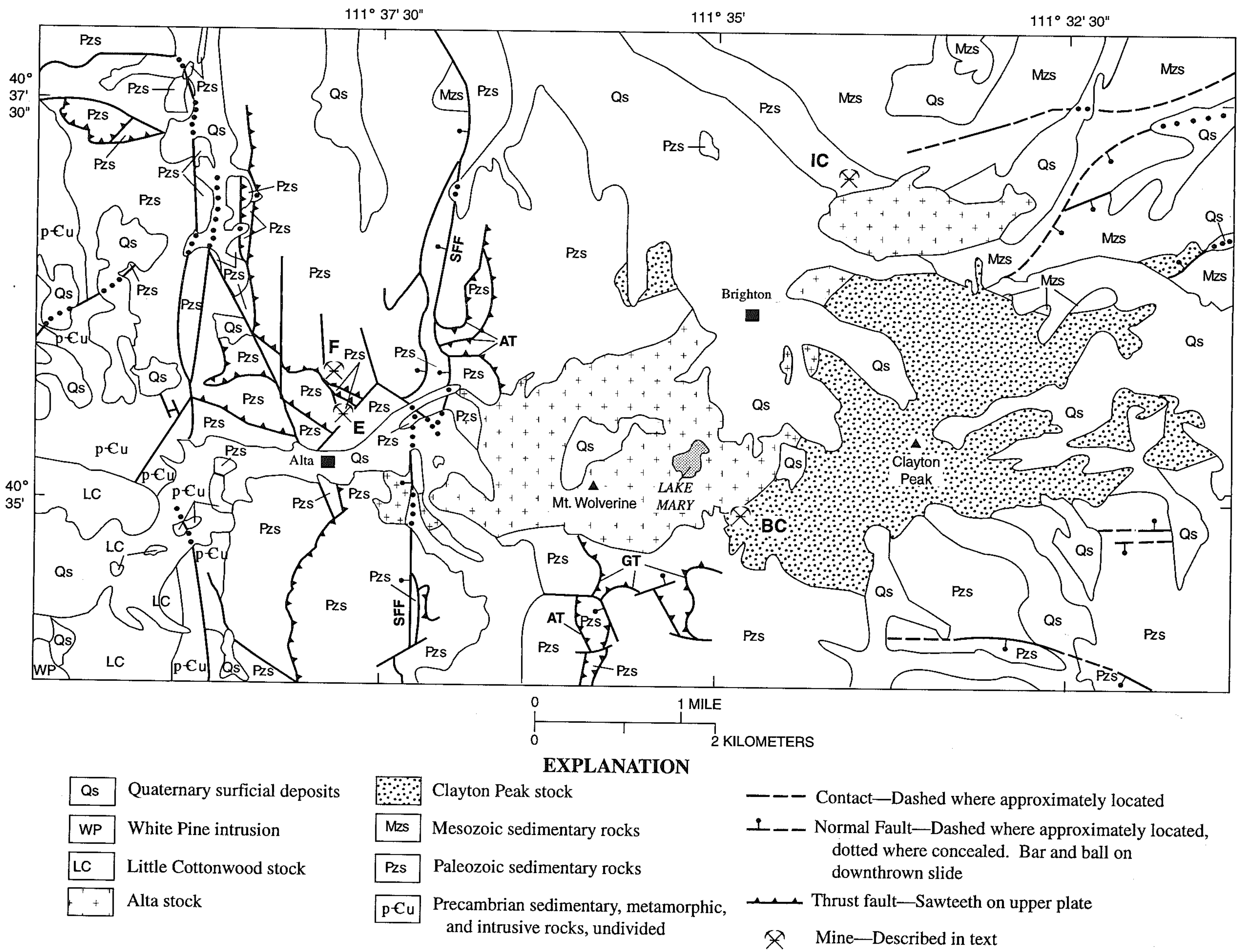


FIG. 3. Generalized geologic map of the Big and Little Cottonwood districts showing principal mines and deposits described in text. Geology simplified from Baker et al. (1966) and Crittenden (1965). (AT, Alta thrust; BC, Big Cottonwood mine and Mountain Lake group; E, Emma mine tunnel; F, Flagstaff mine; GT, Grizzly thrust; IC, Iowa Copper adit; SSF, Silver Fork fault).

panied by emplacement of NE- to ENE-elongated dikes and stocks of the Wasatch igneous belt, by formation of ENE-striking normal faults, including many of the faults that served as conduits for mineralizing fluids in the Park City mining district, by reactivation of Sevier-age thrust faults as normal faults (e.g., Deer Creek fault, Figs. 1 and 2), and by formation of a west-trending half graben south of the Little Cottonwood stock. The later extension involved development of the north-trending physiography of the Wasatch Mountains during the main period of Late Cenozoic Basin and Range extension that uplifted the range as much as 11 km relative to Salt Lake Valley (Zoback, 1983; Parry and Bruhn, 1987) and tilted the range about 15° down to the east (John, 1989a). Basin and Range extension may have began about 17 Ma, although most uplift of the Wasatch Mountains is younger than 10 Ma, and extension continues to the present day (Naeser et al., 1983; Parry and Bruhn, 1986).

Mineral Deposits

A wide variety of mineral deposits related to mid-Tertiary magmatism are present in the central Wasatch Mountains including: (1) a quartz monzonite-type (low F) porphyry Mo deposit; (2) Cu-bearing skarns; (3) Ag-Pb-Zn replacement deposits; (4) polymetallic veins (Ag-Pb-Zn ± Au ± Cu); (5) a Cu-Au porphyry; and (6) high-sulfidation Au deposits. The most productive deposits have been polymetallic vein and replacement deposits in the Park City mining district. The variation in types of mineral deposits across the range in part reflects progressively deeper levels of exposure from east to west, resulting from Late Cenozoic tilting (John, 1989a). These deposit types represent a transition from an epithermal environment on the east (Park Konold mine), to a mesothermal/porphyry environment in the central part of the range (Park City mining district), to the deeper plutonic environment on the west (White Pine Fork porphyry Mo deposit). Estimated mid-Tertiary paleodepths of present exposures range from about 500 m in the Park Premier stock on the east, to 1 to 2 km for replacement and vein deposits in the Park City district, to 4 to 5 km for replacement and skarn deposits in the Big and Little Cottonwood districts, and to about 6 km for the quartz monzonite-type porphyry Mo deposit in the Little Cottonwood stock (John, 1989a).

In the following discussion, deposits in the central Wasatch Mountains are discussed by district from west to east. Summaries of the districts precede short descriptions of important deposits or deposit types within each district that are summarized in Table 2.

Big and Little Cottonwood Mining Districts

The Big and Little Cottonwood mining districts lie on the west side of the range and encompass Little and Big Cottonwood Canyons (Figs. 2 and 3). In terms of past production, the largest deposits in these districts are polymetallic (Ag-Pb ± Zn ± Cu) replacement and fissure deposits in Paleozoic carbonate rocks between the Little Cottonwood and Alta stocks (Fig. 3). Most of these deposits occur in a down-dropped block west of the post-mineral Silver Fork fault (Fig. 3; Calkins and Butler, 1943; James, 1979). Small Cu-bearing skarn deposits related to the Alta and(or) Clayton Peak stocks and a subeconomic porphyry Mo deposit in the eastern part of the Little Cottonwood stock are also present in these districts and are briefly described below.

Polymetallic Replacement Deposits–Emma and Flagstaff Mines

The Emma mine was the first major discovery in the area. The area of the mine was claimed in 1868, the ore body was discovered in 1869, and its main production occurred in the 1870s. Total production of Ag-Pb ore from 1870 to 1918 is estimated to have been worth about $3,825,000 (Calkins and Butler, 1943). Ore was present mostly as replacement of carbonate beds in the Mississippian Fitchville Formation and Gardison Limestone (Fig. 4; Calkins and Butler, 1943). Ore shoots were associated with NE-trending, east-dipping fissures. The Old Emma shoot, the largest ore body developed, was a replacement deposit in a brecciated zone that probably represented a small thrust fault (Fig. 4; Calkins and Butler, 1943). The ore bodies were disrupted and displaced by north-striking normal faults, the largest being the Montezuma fault which displaced the ore zone about 80 m (Fig. 4). Primary ores in the Emma mine consisted mainly of pyrite and galena in a gangue of quartz and unreplaced carbonate. Smaller amounts of sphalerite, tetrahedrite, and tungstenite were also present. Much of the ore was partially oxidized and consisted mainly of Fe oxides which were commingled with Pb, Ag, Cu, and Zn oxides and stolzite.

The Flagstaff mine was another early and rich discovery and, by 1880, it had a total production estimated at $4,550,000 from Ag-Pb ore (Calkins and Butler, 1943). There was also a small amount of production in the early 1900s. Rich ore bodies mined prior to 1874 averaged about 0.5 oz/t Au, 60 oz/t Ag, and 40 percent Pb. Ore formed as replacement of brecciated limestone beds in the Fitchville Formation, and ore formed shoots where limestone beds intersected fissures, most of which trended northeast. Mining was restricted mostly to a single horizon in the limestone. Ore shoots were displaced by north-striking, east-dipping normal faults. Primary ore consisted of pyrite and galena, but most of the ore mined was oxidized and consisted of limonite, lead carbonate with residual galena, and probably plumbojarosite (Calkins and Butler, 1943).

Cu-bearing Skarn Deposits–Mountain Lake Group and Big Cottonwood Mine

Base metal skarn deposits are locally present in Paleozoic carbonate rocks along the margins of the Alta and Clayton Peak stocks. The Mountain Lake group and the adjacent Big Cottonwood mine lie at the head of Big Cottonwood Canyon near contacts between Mississippian

TABLE 2. Characteristics of mineral deposits in the central Wasatch Mountains, Utah

Name	District	Deposit Type	Host Rock	Age (Ma)	Controlling Structures	Production	References
White Pine Fork molybdenum deposit	Little Cottonwood	quartz monzonite-type porphyry molybdenum	Little Cottonwood stock, White Pine intrusion	26-23.5	uncertain	none; estimated resources of 16 mt of 0.1% MoS_2	Sharp, 1958; Bromfield and Patten, 1981; John et al., 1997
Flagstaff mine	Little Cottonwood	polymetallic replacement	Mississippian limestone	approx 33	intersection of northeast-striking fissures with limestone beds	>$4.5 million prior to 1880 of Ag, Au, and Pb	Calkins and Butler, 1943
Emma mine	Little Cottonwood	polymetallic replacement	Mississippian limestone	approx 33	intersection of northeast-striking fissures with limestone beds	1870-1918; approx $3,825,000 of Ag and Pb	Calkins and Butler, 1943
Mountain Lake Group and Big Cottonwood mine	Big Cottonwood	Fe-Cu skarn	Mississippian limestone	approx 33	contact of Paleozoic carbonate beds with Alta and Clayton Peak stocks	1907; small	Calkins and Butler, 1943; James, 1979
Silver King mine	Park City	polymetallic replacement (manto)	Permian Park City Formation (mostly Jenney limestone bed)		intersection east-trending fissures with favorable lithologies	1882-1951; 4,698,609 tons ore; 202,224 oz Au; 86,126,871 oz Ag, 1,334,765,435 lbs Pb; 331,859,041 lbs Zn, 45,801,007 lbs Cu	Boutwell, 1912; Barnes and Simos, 1968; Bromfield, 1989
Ontario mine	Park City	polymetallic vein at surface; polymetallic replacement at depth	vein in Pennsylvanian Weber Quartzite; replacement ores mostly in Mississippian Humbug Formation	34-36	Ontario fault	1875-1978; 2,822,081 tons ore; 50,700 oz Au; 58,119,001 oz Ag, 229,283,401 lbs Pb; 294,044,608 lbs Zn; 6,113,468 lbs Cu	Boutwell, 1912; Barnes and Simos, 1968; Garmoe and Erickson, 1968; Erickson, 1968; Bromfield, 1989
Daly mine	Park City	polymetallic vein	Pennsylvanian Weber Quartzite		Daly fault	1885-1950; 554,088 tons ore; 18,717 oz Au; 12,734,946 oz Ag, 11,166,664 lbs Pb; 10,877,183 lbs Zn; 371,628 lbs Cu	Boutwell, 1912; Barnes and Simos, 1968; Bromfield, 1989
Daly West and Judge mines	Park City	polymetallic vein and replacement (manto)	vein in Pennsylvanian Weber Quartzite; replacement deposits in Permian Park City Formation (mostly Jenney limestone bed, 920 horizon)		intersection of ENE-striking faults (vein zones) with favorable lithologies	1899-1968; 4,265,346 tons ore; 79,051 oz Au; 51,264,289 oz Ag, 744,384,966 lbs Pb; 401,616,365 lbs Zn; 31,831,461 lbs Cu	Boutwell, 1912; Barnes and Simos, 1968; Bromfield, 1989
Park Utah mine	Park City	polymetallic vein	Pennsylvanian Weber Quartzite		Hawkeye-McHenry fault zone (ENE-striking faults)	1920-1951; 1,228,778 tons ore; 168,264 oz Au; 21,690,467 oz Ag, 104,032,694 lbs Pb; 136,311,084 lbs Zn; 6,003,021 lbs Cu	Barnes and Simos, 1968; Bromfield, 1989
Park City Consolidated mine	Park City	polymetallic vein	Pennsylvanian Weber Quartzite		East Crescent Vein fault	1929-1942; 532,155 tons ore; 30,598 oz Au; 8,764,593 oz Ag, 20,966,691 lbs Pb; 32,993,610 lbs Zn; Cu not recovered	Barnes and Simos, 1968; Bromfield, 1989
Mayflower mine	Park City	polymetallic vein; minor polymetallic replacement	mostly in Ontario and Mayflower stocks	33-34	Mayflower-Pearl fault zone (ENE-striking fault)	1936-1972; 2,610,666 tons ore; 904,313 oz Au; 14,644,051 oz Ag, 263,546,534 lbs Pb; 280,141,927 lbs Zn; 38,847,113 lbs Cu	Barnes and Simos, 1968; Quinlan and Simos, 1968; Nash, 1973; Bromfield, 1989
Park Premier mine	East Park City	porphyry copper-gold, copper skarn, polymetallic vein	Triassic Thaynes Formation, Park Premier stock	33.5	porphyry stock	small	John, 1989b; John et al., 1997
Park Konold mine	East Park City	acid-sulfate gold (high sulfidation)	porphyry of Bone Hollow	31.4	ENE-striking, NW-dipping fault	small or none	John, 1989b; John et al., 1997

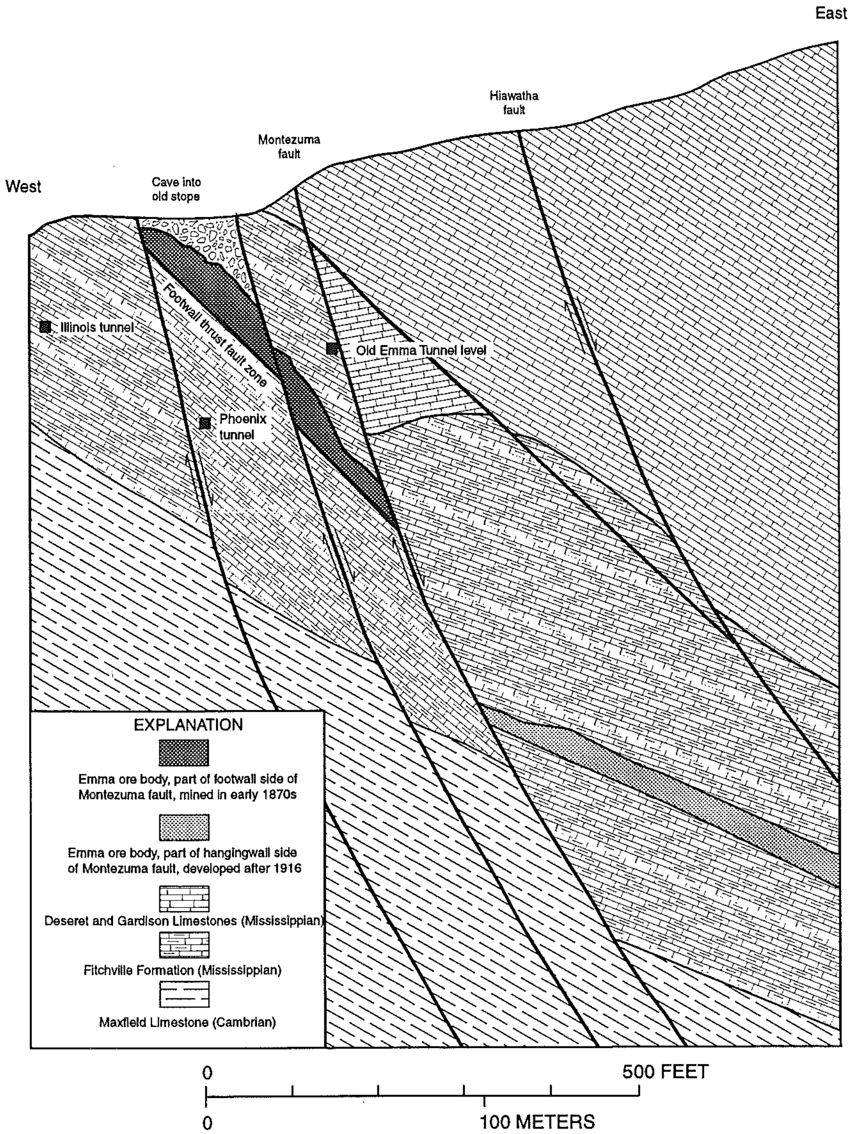


FIG. 4. Cross section of the Emma mine, Little Cottonwood mining district, looking north. Modified from Calkins and Butler (1943, Fig. 5.).

carbonate rocks and these stocks (Fig. 3). Mine workings expose small skarns formed in limestone beds metasomatically replaced by magnetite, ludwigite, and forsterite, with lesser amounts of amphibole, epidote, garnet, pyrite, chalcopyrite, and bornite (Calkins and Butler, 1943; James, 1979). Massive bodies of magnetite + bornite ± chalcopyrite are present locally. The largest skarn mass exposed on the surface has an irregular outline as much as 15 m wide and 60 m long. In 1907, several railroad cars of ore containing as much as 5 percent Cu reportedly were shipped to the smelter at Tintic, Utah (James, 1979).

White Pine Fork Porphyry Molybdenum Deposit

A large area of low-grade Mo mineralization is centered on White Pine Fork in the eastern part of the Little Cottonwood stock (Figs. 2 and 5). Molybdenite in the area has been known for more than 90 years (Hess, 1908; Calkins and Butler, 1943), and Erickson and Sharp (1954) reported scheelite on joint planes peripheral to the molybdenite occurrences. Exploration and drilling by Bear Creek Mining Co. and Midwest Oil Co. in the 1960s and early 1970s was centered on a zone of stockwork quartz veins in the White Pine Fork area and defined a porphyry Mo system which is described in detail by Bromfield and Patten (1981). John (1989a) reported the results of reconnaissance fluid inclusion studies. Crittenden et al. (1973) and John et al. (1997) report K-Ar and Ar-Ar ages of muscovite alteration associated with Mo mineralization.

The area surrounding White Pine Fork is marked by widespread hydrothermal alteration and Fe-staining that contains stockwork quartz veins and scattered occur-

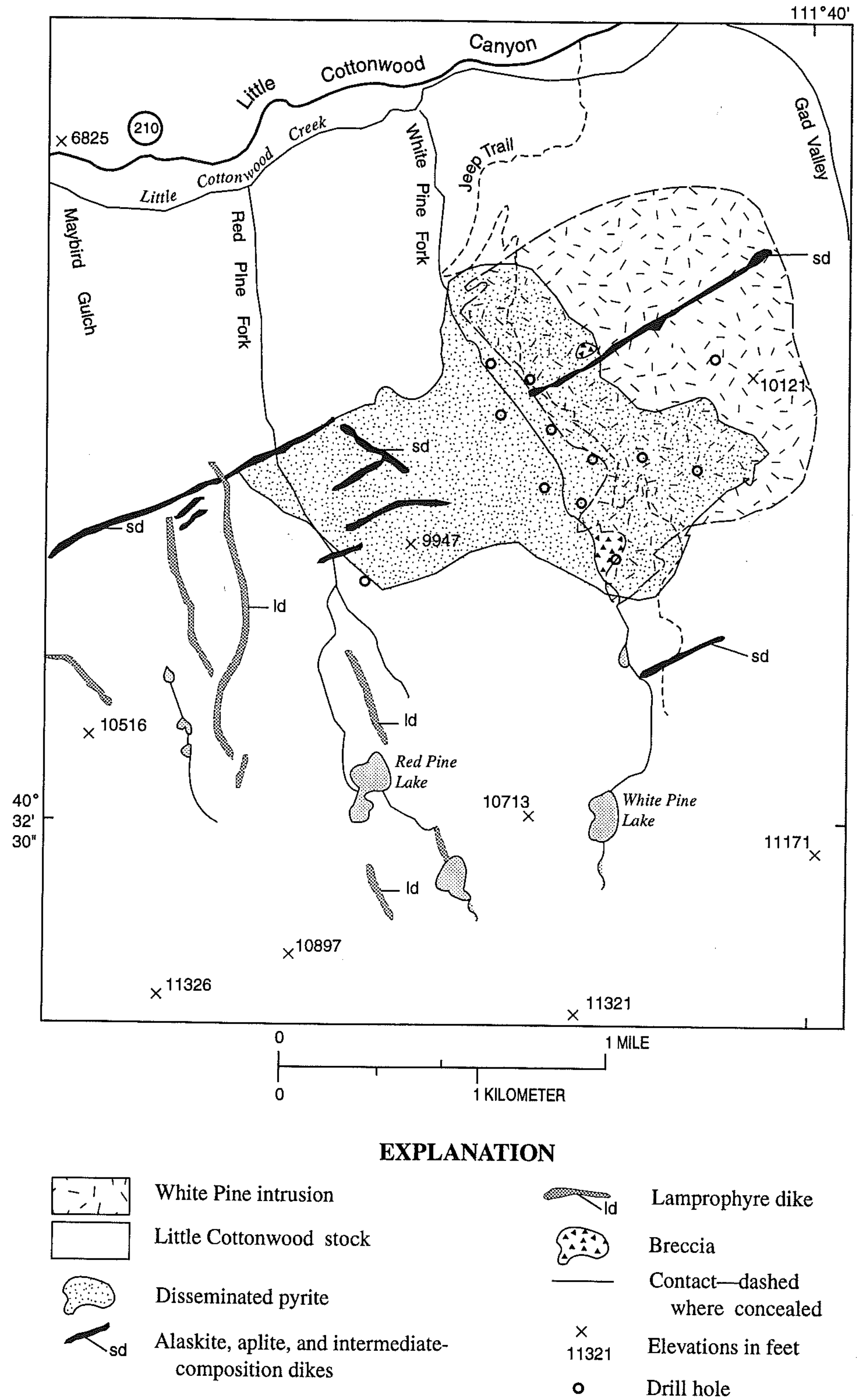


FIG. 5. Geologic map of the White Pine Fork area, Little Cottonwood stock, showing the White Pine intrusion, areas of disseminated pyrite, and surface exposures of the White Pine Fork porphyry molybdenum deposit. Quaternary surficial deposits not shown. Modified from Bromfield and Patten (1981).

rences of molybdenite, scheelite, and powellite (Fig. 5). Hydrothermal alteration is centered on the White Pine intrusion (Fig. 5), a younger, fine-grained, more leucocratic phase of the Little Cottonwood stock (Sharp, 1958; Crittenden, 1965). Contacts between the Little Cottonwood stock and the White Pine intrusion are gradational and often obscured by intense hydrothermal alteration as well as by glacial and talus deposits. Figure 5, modified from Crittenden (1965) and Bromfield and Patten (1981), shows a semi-elliptical shaped intrusion elongated to the northeast, parallel to a set of silicic porphyry dikes that intrude both the White Pine intrusion and the Little Cottonwood stock and which are widespread throughout the central Wasatch Mountains (Crittenden, 1965; Baker et al., 1966; Vogel et al., 1997). North-trending lamprophyre dikes locally cut the silicic porphyry dikes (Fig. 5).

Hydrothermal alteration in the White Pine Fork Mo deposit consists of several types of stockwork veins, widespread fracture-controlled and disseminated pyrite, and local areas of potassic (hydrothermal K-feldspar) and sericitic alteration. John (unpub. data, 1983) distinguished seven major types of veins: (1) pyrite+sericite, (2) vuggy quartz ± pyrite with sericite vein selvages, (3) vuggy quartz ± pyrite without vein selvages, (4) granular quartz ± pyrite, (5) sericite, (6) K-feldspar, and (7) anhydrite veins partly altered to gypsum. Mutually crosscutting relations between different vein types suggests multiple pulses of mineralizing fluids. Pods of green sericite + pyrite ± fluorite ± molybdenite are present locally. The intensity of pyritic alteration is irregular and varies from scattered grains of pyrite in otherwise unaltered rock to intense, texturally destructive quartz-sericite-pyrite alteration. Molybdenite is present in the quartz-bearing veins (types 2, 3, and 4), in sericite vein selvages, as "smears" on fractures, and in pods with coarse-grained green sericite + pyrite ± fluorite.

A knoll of quartz-cemented breccia, about 140 by 200 m in size, near the southern edge of the White Pine intrusion, contains more intense hydrothermal alteration (Fig. 5). The breccia is intensely sericitized and pyritized, and is interlaced with a network of quartz veins that commonly have coarse muscovite selvages and locally contain pink K-feldspar and pyrite. Molybdenite is present in some of the quartz veins, and as joint coatings, and is locally disseminated in the sericitized breccia fragments.

Diamond drill holes by Bear Creek Mining Co. and Midwest Oil Co. ranged from 72 to 923 m deep. Bromfield and Patten (1981) report 3-m drill intercepts containing as much as 0.3 to 0.5 percent MoS_2 and a 40-m-thick zone in 3 drill holes that averaged about 0.1 percent MoS_2. They estimated a resource of 16 million tons with an average grade of 0.1 percent MoS_2.

K-Ar and $^{40}Ar/^{39}Ar$ ages of coarse-grained muscovite associated with quartz veining and molybdenite are 23.5 to 26.2 Ma (John et al., 1997), which suggests that hydrothermal alteration and molybdenite mineralization both formed at least 4 m.y. after emplacement of the Little Cottonwood stock (zircon U-Pb age of 30.5 ± 0.6 Ma; Vogel et al., 1997). The White Pine Fork mineralization is the youngest recognized hydrothermal event associated with mid-Tertiary magmatism in the central Wasatch Mountains (John et al., 1997). The ENE-trending silicic porphyry dikes, that crosscut both the White Pine intrusion and the Little Cottonwood stock (Fig. 5), are hydrothermally altered suggesting that the White Pine intrusion may not have been the source of mineralizing fluids. However, neither the dikes nor the White Pine intrusion have been dated isotopically, and the origin of the Mo mineralization is unclear.

Park City Mining District

The Park City mining district has been the most important mining area in the central Wasatch Mountains and contains several large Ag-Pb-Zn fissure vein (lode) and bedded replacement deposits, some of which were mined for more than 100 years following discovery of the Ontario vein in 1872. Major mines in the district are summarized in Table 2 and some are described briefly below. More complete descriptions of the geology and mineral deposits of the Park City mining district include Boutwell (1907, 1912), Barnes and Simos (1968), Bromfield (1968, 1989), Erickson (1968), Garmoe and Erickson (1968), and Quinlan and Simos (1968).

Two principal types of deposits were present in the Park City district: fissure or lode deposits and bedded replacement or manto deposits. Fissure deposits were discovered first and contained the highest Ag contents. Principal lode ore zones included the Ontario-Daly zone, the Hawkeye-McHenry-Dunyon zone (Park Utah), and the Mayflower-Pearl zone (Figs. 6 and 7). Major replacement deposits included the Silver King, Ontario, Daly, Daly West, and Judge mines (Table 2, Figs. 6 and 7). Bedded replacement deposits typically were larger and contained higher values in Pb and Zn and less Ag. Replacement deposits were the major source of production after early exhaustion of near-surface bonanza ores in the Ontario and Daly Lodes near the beginning of the 20th century.

Stratigraphic and Igneous Setting

Sedimentary rocks exposed in the Park City mining district range in age from Late Proterozoic through Jurassic (Table 1; Boutwell, 1907, 1912; Bromfield, 1968). On the east side of the district, the sedimentary rocks are overlain unconformably by the late Eocene to Oligocene Keetley Volcanics (Fig. 6). Six porphyry stocks, mostly of granodiorite composition, intrude the sedimentary rocks and some of the cogenetic Keetley Volcanics (Fig. 6). Ore zones in the Park City district were hosted primarily by Late Paleozoic sedimentary rocks. Many replacement deposits were hosted by the Jenney bed, a 6-m-thick cherty limestone bed between two thin quartzite beds in the lower part of the Permian Park City Formation (Tables 1 and 2). Fissure deposits in the

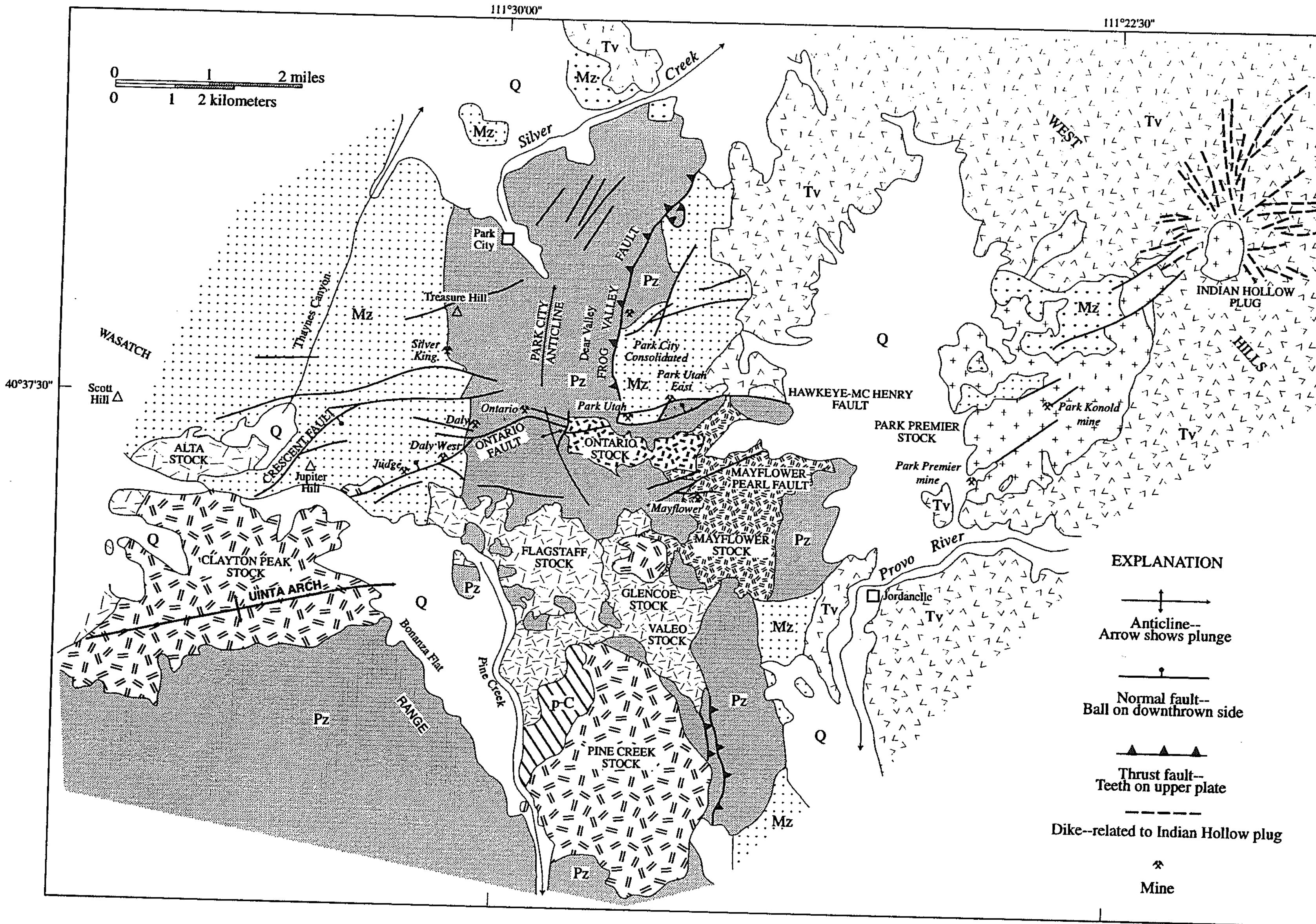


FIG. 6. Generalized geology of the Park City area modified from Bromfield (1989). Q, Quaternary alluvium; Tv, Tertiary Keetley Volcanics; Mz, Mesozoic sedimentary rocks; Pz, Paleozoic sedimentary rocks; p€, Precambrian sedimentary rocks. Tertiary stocks are labeled.

Ontario-Daly and Hawkeye-McHenry zones were hosted primarily by the Pennsylvanian Weber Quartzite.

Structural Setting

Three major structural features localized replacement and fissure deposits in the Park City district: the Unita arch, the Park City anticline, and east- to northeast-striking high-angle normal faults (Fig. 6).

The Uinta arch passes through the southern part of the district and forms a broad structural dome that plunges moderately to the east (Figs. 2 and 6). Most of the intrusions in the central Wasatch Mountains were emplaced along the western extension of the arch, and mid-Tertiary normal faults that were active during emplacement of the intrusions and formation of mineral deposits in the Park City district parallel the arch.

The Park City anticline is the dominant structural feature in the district. It is a broad, flat, north-trending fold whose axis plunges gently to the north (Fig. 6). At the north end of the fold, rocks dip away from the axis about 15 to 25 degrees, whereas dips are generally steeper at the south end of the fold. Much of the southern part of the fold axis has been intruded by mid-Tertiary porphyry stocks. Bromfield (1968, 1989) notes that the Park City anticline is a second-order fold on the northeast flank of the larger east-trending Uinta arch. The anticline was formed during the Late Cretaceous to earliest Tertiary Sevier orogeny. The shapes of many of the replacement deposits, notably the Silver King mine, conform to bedding attitudes in the sedimentary rocks, which are controlled by this fold (Fig. 7).

Rocks of the Park City anticline are cut by numerous east- to northeast-striking normal faults which provided the loci of mineralization for many of the vein and replacement deposits in the district. Some of the more important faults include the Ontario-Daly fault system, which probably connects to the east with the Hawkeye-McHenry fault system, the Crescent fault, and the Mayflower-Pearl fault system, which may extend eastward into the Park Premier stock (Fig. 6). Displacement on these faults ranges from a few m to more than 500 m. The faults were active during and following emplacement of late Eocene to early Oligocene porphyry stocks in the Park City district and probably formed during a period of NW-SE-directed extension (Presnell,1997; Vogel et al., 1997).

Age of Mineralization

K-Ar dating of hydrothermal alteration minerals in the Ontario and Mayflower mines suggest that the Ontario vein was formed between 36 to 34 Ma and the Mayflower vein at about 33 Ma (Bromfield et al., 1977). The isotopic

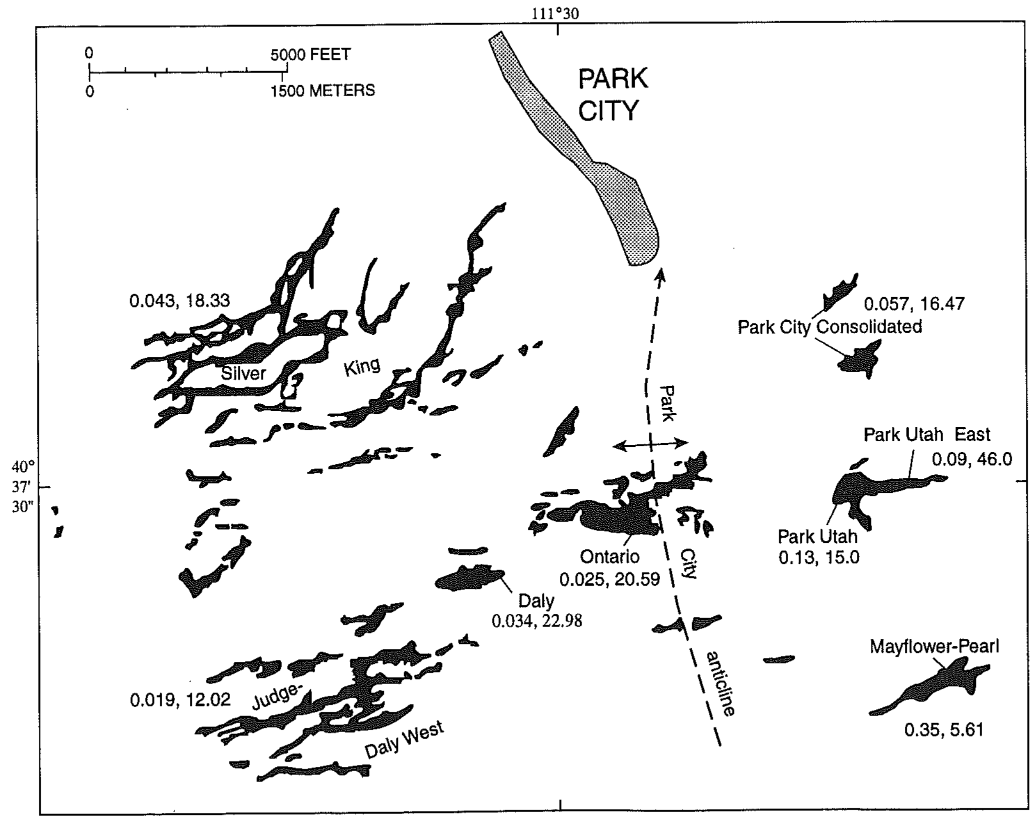


FIG. 7. Map showing surface projection of major ore horizons in the Park City mining district and average gold and silver grades (oz/t). Modified from Bromfield (1989, fig. 6C).

ages of alteration minerals are consistent with field relations, which indicate that many of the deposits are younger than the intrusive rocks, and with the isotopic ages of porphyry stocks in the Park City district which range from 41(?) to 36 Ma (Bromfield et al., 1977; John et al., 1997; Vogel et al., 1997).

Metamorphism and Hydrothermal Alteration

In general, contact metamorphism and hydrothermal alteration are not strongly developed in the Park City mining district, and large areas of bleaching and pyritic alteration are notably absent (Bromfield, 1989). Sedimentary rocks adjacent to the porphyry stocks are only weakly metamorphosed by the intrusions, although on the west side of the district near Jupiter Hill, sedimentary rocks adjacent to the Clayton Peak stock are recrystallized and local skarn is developed. In the Jenney bed in the Judge and Silver King replacement deposits, alteration consists of peripheral bleaching and recrystallization of the carbonate rocks (Erler and Nackowski, 1996). Within 4 m of ore, argillic alteration is present, and within 1 m of ore, sericitic alteration appears. Silicification and dolomite alteration are also locally present in and near ore zones.

In contrast to the sedimentary rocks, propylitic alteration is widespread in many of the porphyry intrusions, notably in the Ontario, Valeo, Flagstaff, and Mayflower stocks (Bromfield, 1989). Williams (1952) describes intermediate argillic and quartz-sericite alteration in the Mayflower mine, and Nash (1973) describes early biotite-K-feldspar-anhydrite alteration associated with Cu-rich quartz veins in the deeper levels of the Mayflower mine along the Mayflower-Pearl vein system. In addition, Bromfield (1989, fig. 4C) describes an irregular, 1-km-wide zone centered around the surface projection of the Mayflower-Pearl fault zone and vein system that contains areas of pyritization, sericitization, silicification, and hydrothermal phlogopite.

District Zoning and Sources of Hydrothermal Fluids

The genesis of most deposits in the Park City mining district has not been studied in detail. Bromfield (1989) summarized existing geologic, isotopic, and fluid inclusion data, and concluded that the replacement and lode deposits are clearly related to mid-Tertiary magmatism, but that the district does not display any simple zonation pattern. However, variations in metal ratios, mineralogy, and hydrothermal alteration, both vertically within deposits and from north to south across the district, suggest that there are district-scale zoning patterns that might be related to a buried porphyry system(s) in the vicinity of the Mayflower mine.

Wilson (1959) and Grant (1966) noted subtle mineralogical and metal zoning across the district: ruby silver minerals and argentite in the northeast part of the district, Ag-Pb-Zn ore bodies in a band across the center of the district, and Cu- and Au-rich ores in the southeast part of the district. This may indicate a temperature gradient decreasing from south to north. There is also a suggestion of vertical zoning within ore bodies as summarized by Bromfield (1989). In the Ontario vein, Zn and Zn/Pb ratios tend to increase downward. Pb and Zn are more abundant in the upper levels of the Mayflower mine, and Cu and Au increase downward, notably in the Pearl vein (Quinlan and Simos, 1968; Nash, 1975). Nash (1973) notes the presence of high-temperature, high-salinity fluid inclusions in deep early veins in the Mayflower mine associated with biotite-K-feldspar alteration. These veins are similar to early veins in porphyry copper systems. In contrast, ore stage fluids in the Mayflower mine were cooler and much more dilute. Bromfield (1989) notes that the only zone of strong hydrothermal alteration exposed in the district overlies the Mayflower-Pearl fault zone. All of these patterns are consistent with a heat source near the Mayflower mine.

In contrast, Aiken (1982) and Erler and Nackowski (1996) suggest that the Clayton Peak stock was the source of heat and fluids for many of the deposits in the district. Aiken (1982) reported geochemical anomalies for Cu, Mo, Pb, and Zn in soils over the eastern part of the Clayton Peak stock and adjacent sedimentary rocks. The Cu and Mo anomalies are closed over the stock, whereas the Pb and Zn anomalies overlie sedimentary rocks east of the stock and are open to the east. The Pb and Zn anomalies overlie western extensions of the Ontario-Daly and Crescent faults which were feeders for many of the deposits in the district. Aiken (1982) suggests that the Clayton Peak stock was the source of mineralizing fluids for many of Ag-Pb-Zn deposits and for smaller Cu deposits in the Jupiter Ridge-Scott Hill area (Fig. 6). However, John (1992) has pointed out that chalcopyrite veins are common in the eastern part of the Alta stock, which intrudes the Clayton Peak stock, indicating that the Cu mineralization is younger and probably unrelated to the Clayton Peak stock. Thus, existing data are suggestive that the fissure and replacement deposits in the Park City mining district may be related to a buried porphyry system near the Mayflower mine.

Fissure Deposits

Three principal zones of fissure (lode) deposits were present along ENE-striking fault zones in the district: Ontario-Daly, Hawkeye-McHenry (Park Utah), and Mayflower-Pearl (Figs. 6 and 7). Many of the lodes cropped out and the Mayflower-Pearl Lode was followed down-dip 1,000 m from the surface. The Pennsylvanian Weber Quartzite was the host rock for many of the deposits, notably the Ontario-Daly and Hawkeye-McHenry Lodes. The Ontario and Mayflower stocks were the primary hosts for lode deposits in the Mayflower-Pearl fault zone (Fig. 8).

Ontario and Daly Lodes–Ontario and Daly Mines. Discovered in 1872, the Ontario vein was the first major discovery that marked the beginning of mining in the district. For many years, the Ontario mine, which exploited the

Ontario vein, was the chief silver-producing mine in the United States (Barnes and Simos, 1968). The Ontario vein is on the west side of the Park City anticline and generally follows the Ontario fault, which strikes N60°E and has an average dip of about 60°N (Fig. 6; Bromfield, 1968). High-grade Ag ore was followed downdip 400 m from the surface and along strike for 1,540 m to the west, where it crossed over a SW-striking spur of the Daly fault to become the Daly Lode, which was mined for 770 m farther west along strike. To the east, the vein was terminated against a set of NE-striking transverse faults named the No. 9 fault. In 1916, exploration began east of the Park City anticline along the Hawkeye-McHenry fault, which resulted in the discovery of the Park Utah ore bodies in 1920 (see below).

The upper parts of the Ontario and Daly Lodes were in the Pennsylvanian Weber Quartzite. The Ontario Lode ranged from 0.6 to 6 m in width, typically being 1.3 to 1.6 m wide (Ashburner and Jenney, 1881). The ore zone within the lode typically was 0.5 to 0.6 m wide. At the 1300 level, the zone of fissuring entered underlying limestones of the Mississippian Doughnut Formation and became much narrower and less distinct, and contained much less mineralized rock. This marked the base of the high-grade ore shoots of the Ontario Lode. The upper levels of the lode were argentiferous Pb ores with some Zn and local Cu. At increasing depth, zinc and pyrite became more abundant. Primary ores consisted of argentiferous galena, tetrahedrite, minor sphalerite, and pyrite in a quartz ± calcite gangue. Upper levels of the lode were oxidized and contained abundant cerrusite, anglesite, and Fe oxides.

At the west end of the Daly Lode, ore feathered out along the Daly fault, which remained barren for about 300 m until the Daly West Lode was encountered (Figs. 6 and 7). Ore in the Daly West shoot was mined for about 770 m west on the Daly West property and another 600 m west on the Daly Judge property. These lodes were mined only to average depths of 200 m and the ores mined were generally lower grade and less continuous than the ores mined farther east.

Production from the Ontario and Daly Lodes can be split into three periods (Barnes and Simos, 1968). Early production, from 1872 to 1902, consisted of rich bonanza-type ores from both properties, and much of the ore was oxidized. During this period, the Ontario mine produced 655,126 tons of ore which averaged 58.2 oz/t Ag, 0.03 oz/t Au, and 1 to 3 percent Pb. The ore was mined

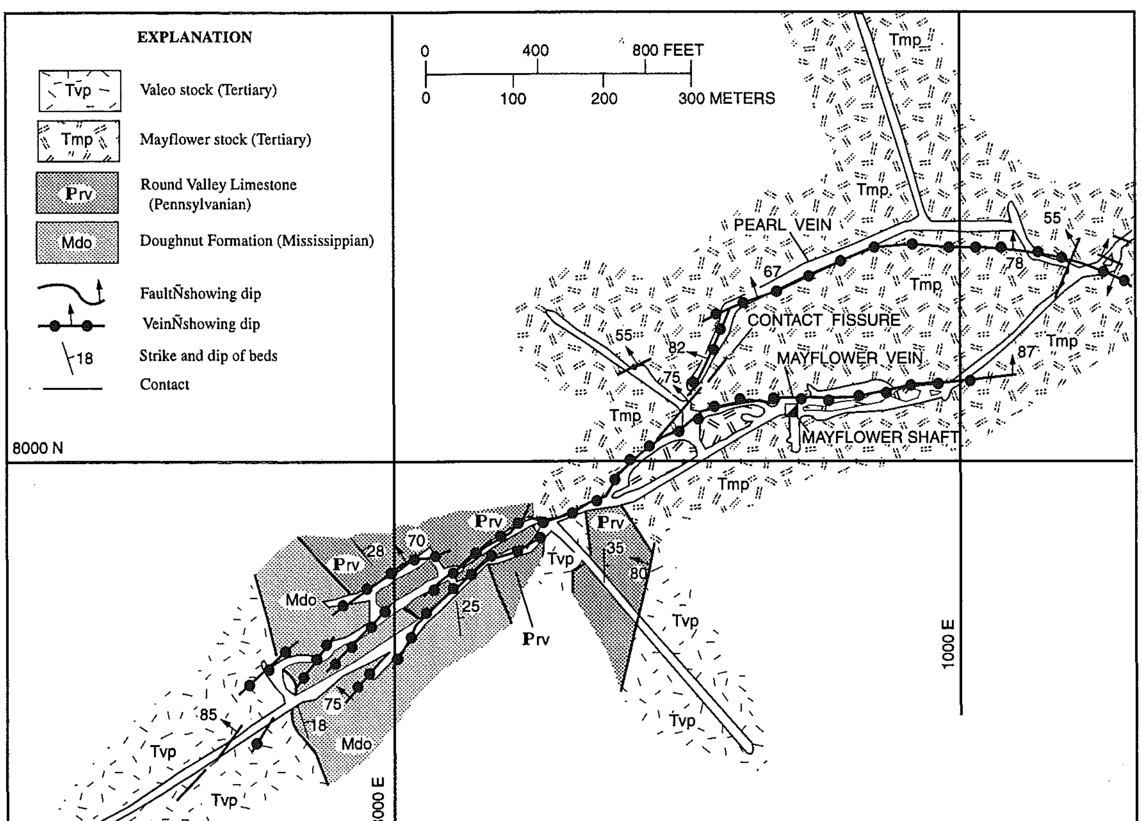


FIG. 8. Generalized geologic map of the 800 level of the Mayflower mine. Redrawn from Barnes and Simos (1968).

for Ag, and Au and Pb values were often not reported. During the early years of the Daly mine, from 1886 to 1902, production totaled 278,068 tons of ore that averaged about the same grade. From 1902 to 1924, production from the Ontario mine was 169,111 tons that averaged 0.026 oz/t Au, 24.8 oz/t Ag, and 2 percent Pb, while production from the Daly mine was 20,103 tons with an estimated grade of 0.03 oz/t Au, 15.0 oz/t Ag, 7.5 percent Pb, and 8.5 percent Zn. From 1924 to 1942, production from the Ontario mine was from the so-called Dunyon vein on the east side of the No. 9 fault along the Hawkeye fault zone. Production during this period was approximately 126,000 tons that averaged 0.027 oz/t Au, 29.8 oz/t Ag, 2.9 percent Pb, and 3.3 percent Zn.

Hawkeye-McHenry Lodes—Park Utah Deposit. The Park Utah orebodies were discovered in 1920 along the Hawkeye-McHenry fault zone about 925 to 1,200 m east of the east end of the Ontario vein (Figs. 6 and 7). The Hawkeye-McHenry fault may be an eastward continuation of the Ontario-Daly fault zone. The deposits were discovered by driving a tunnel south from the Ontario drain tunnel to intersect the McHenry fault zone at the 1950 level and then mined upwards to the 450 level where the vein lensed out. Two ore shoots were discovered: the West and East ore zones. The ore shoots were lenticular-shaped fissure zones that varied from 1 to 25 m wide, were as much as 275 m long, and dipped 40° to 50°N. They formed in cymoid loop structures along the Hawkeye-McHenry fault, an ENE-striking fault that has 250 to 375 m of normal displacement. Ore was hosted primarily in the Weber Quartzite, and below the 1850 level, where the vein was entirely in underlying limestone units, it split into several narrow veins and became uneconomic.

In the West orebody, ore in the upper zone from the surface to the 800 level consisted of galena and minor sphalerite. The ore was Ag rich, probably due to supergene enrichment. Ore in the intermediate zone from the 800 to the 1800 level consisted of quartz, galena, sphalerite, and Ag-rich tetrahedrite. Total production from the West ore body was 1,117,778 tons averaging 0.13 oz/t Au, 15.0 oz/t Ag, 4.6 percent Pb, 6.2 percent Zn, and 0.2 percent Cu (Barnes and Simos, 1968).

The East ore body extended upward to the 1100 level and was oxidized between the 1100 and 1400 levels. In the oxidized zone, the vein consisted of rusty quartz and minor secondary copper minerals. Silver was the principal metal recovered. In the sulfide zone below the 1400 level, the vein consisted of quartz, tetrahedrite-tennantite, and argentite with minor galena and sphalerite. The East ore body produced 110,000 tons of ore averaging 0.09 oz/t Au, 46.0 oz/t Ag, 1.2 percent Pb, and 0.2 percent Cu.

Mayflower Lode–Mayflower Mine. The Mayflower Lode is southeast of other lodes in the district and on a separate fault system, the Mayflower-Pearl fault zone (Figs. 6 and 7). It also has several other distinctions from other lode deposits, including a much higher Au content (average 0.35 oz/t), a higher Cu content (0.7%), the largest production from fissure veins in the district, and the only deposit hosted mostly by igneous rocks (Table 2). Ore was mined from the Mayflower mine, which produced about 2.6 million tons of ore containing about 900,000 oz Au, 14.6 million oz Ag, 263 million lbs Pb, 280 million lbs Zn, and 38 million lbs Cu from 1936 to 1972 (Bromfield, 1989). Descriptions of the Mayflower mine include Barnes and Simos (1968), Quinlan and Simos (1968), Nash (1973, 1975), Villas and Norton (1977), and Bromfield (1989).

Productive veins in the Mayflower mine were in the complex Mayflower-Pearl fault zone, a 60-m-wide zone composed of parallel, en echelon, interlacing, and braided veins. The NE- to ENE-striking Mayflower fault transects both Paleozoic sedimentary and Tertiary igneous rocks, but displacement is only about 30 m down to the north (Bromfield, 1989). The veins formed in a bend in the fault where it passed from sedimentary to igneous rocks and changed strike from N60°E to a more easterly trend (Fig. 8). Three main veins were productive: the Mayflower, Pearl, and No. 3 veins. The Mayflower vein was mined from the surface to the 2005 level but was most productive between the 600 level and the 1755 level. It has a strike of N60°E to N80°E and dips 60° to 70°N. The Pearl vein strikes N80°E and dips 80° to 90° N. It was most productive from the 1020 to the 3000 level. The No. 3 vein, which connected the Mayflower and Pearl veins, was productive between the 1380 and 1880 levels, below which it joined the Pearl vein. It was subparallel to the Mayflower and Pearl veins and formed a cymoid curve between them. The Mayflower vein generally was in the footwall of the Mayflower fault, whereas the Pearl vein was in the hanging wall of the ore zone (Fig. 8).

Ore from the Mayflower vein mostly was sphalerite and galena, with minor chalcopyrite and native gold in a gangue of quartz, calcite, and pyrite. The Pearl and No. 3 veins had lower Pb and Zn and higher Ag contents, more abundant chalcopyrite, and were mined primarily for their Au values. Anhydrite and hematite were abundant in the Pearl and No. 3 veins. Gold was consistently associated with chalcopyrite. In addition to the ore veins, Nash (1973) described early deep veins outside of the ore zone comprised of quartz, K-feldspar, biotite, anhydrite, and pyrite, with local magnetite, amphibole, and chalcopyrite. Fluid inclusions in these veins had much higher salinities (as much as 44 wt % NaCl) and higher homogenization temperatures (315° to 430°C) than ore stage fluids (0 to 11 wt % NaCl equivalent and 220° to 300°C homogenization temperatures).

Replacement Deposits

Replacement deposits were the main source of production after exhaustion of near-surface, high-grade Ag "bonanza" ores of the Ontario and Daly Lodes. Most of the replacement deposits were in limestone horizons in the Permian Park City and Triassic Thaynes Formations, although more recent discoveries in the Ontario mine were in the Mississippian Humbug Formation. About 75 percent of the ore was produced from limestone beds in the Park City Formation, and most of this production was from the Jenney bed. Major replacement deposits included the Silver King, Daly West, Judge, and Ontario mines (Table 2).

Silver King Mine. The Silver King mine was one of the great bonanza deposits in the district, producing more than 200,000 oz Au, 86 million oz Ag, 1.3 billion lbs Pb, and 330 million lbs Zn from about 4.7 million tons of ore (Barnes and Simos, 1968; Bromfield, 1989). The orebody was a replacement deposit in the Jenney bed in the lower part of the Permian Park City Formation and consisted of long, narrow, meandering mantos of high-grade Pb-Ag ore. The deposit was on the northwest flank of the Park City anticline and extended 3,075 m west to the trough of the adjacent syncline. The Jenney bed was mined downdip for 615 m with little change in grade. The ore zones were arcuate in plan view due to the change in strike of the Park City Formation (Fig. 7). The Park City Formation was cut by several small thrust faults that generally parallel the beds and acted as ground preparation for orebearing solutions. These faults locally repeated the Jenney bed, resulting in the formation of ore both above and below the fault plane (Barnes and Simos, 1968). Orebearing solutions were channeled in fissures that did not penetrate the overlying shaly limestones in the Park City Formation, which acted as a cap forcing the fluids along the Jenney bed (Barnes and Simos, 1968). Hypogene mineralogy of the ores was galena, tetrahedrite, sphalerite, and pyrite in a gangue of quartz and calcite. Oxidized parts of the deposit contained anglesite, cerrusite, bindheimite, and malachite.

Judge and Daly West Mines. Ore in the Judge and Daly West mine area was produced from replacement bodies at four horizons in the Park City Formation that were locally called "vein zones" (Figs. 6 and 9; Barnes and Simos, 1968). The vein zones are minor east-striking faults that allowed access of mineralizing fluids into favorable horizons. Ore was produced primarily from the intersection of the vein zones with the Jenney bed and with the 920 horizon near the top of the Park City Formation (Fig. 9). Ore occurred on the west side of the Park City anticline where the Park City Formation is warped into a gentle syncline (Fig. 9). The largest production was from the Middle vein zone, which was characterized by a series of small faults and fissures associated with steeply dipping porphyry dikes. In the Middle vein zone, ore was produced from the Jenney bed along a strike length of more than 1,540 m, a width as much as 45 m, and a thickness of 8 to more than 30 m (Barnes and Simos, 1968). The upper 920 horizon ore body was about 1,700 m long but narrower than the Jenney ore body (Fig. 9). Total production from the four main vein zones in the Daly West and Judge mines is estimated to have been about 3,478,000 tons ore that averaged about 0.026 oz/t Au, 25.3 oz/t Ag, 14.1 percent Pb, and 12.1 percent Zn (Barnes and Simos, 1968). About 2.6 million tons of ore was produced from the Middle vein zone (Barnes and Simos, 1968). Ore from the Judge and Daly West mines was primarily argentiferous galena, with some tetrahedrite and sphalerite, and was oxidized near the surface.

Ontario Mine. Replacement deposits in the Ontario mine were mined from the Mississippian Humbug Formation beneath the Weber Quartzite, which hosted most of the lode deposits (Barnes and Simos; 1968; Erickson, 1968; Garmoe and Erickson, 1968). Two orebodies were discovered near the crest and on the northwest and northeast flanks of the Park City anticline (Northwest and Northeast Flank ore bodies, respectively). The orebodies lay in a small fault block of the Humbug Formation that was bounded by east-striking faults, the Hawkeye-McHenry fault on the south and the Silver (Jefferson) fault about 300 m farther north.

Ore in the Northwest Flank orebody formed as irregular bedding replacements in the Humbug Formation along small, steep, ENE-trending mineralized fissures that are interpreted to be tension fractures between the bounding faults (Fig. 10; Barnes and Simos, 1968). Ore minerals were deposited along bedding planes, but ore zones cut across bedding along fissures. Replacement occurred in horizons throughout the formation and formed a series of bedded replacements separated by barren horizons. Replacement horizons terminated against the Hawkeye fault which had considerable post-mineral displacement (Fig. 10).

The upper part of Northeast Flank orebody was a replacement body of a single bed in the upper part of the Humbug Formation. It extended down dip about 250 m and averaged 45 m in strike length and 2 to 6 m thick. This replacement horizon abruptly ended but other replacement horizons were discovered in lower parts of the formation. Overall, ore was followed down dip for about 550 m. Both orebodies were composed of galena- and sphalerite-rich ores that showed an increase in sphalerite with depth. Total production from replacement deposits in the Ontario mine was more than 1.8 million tons that averaged about 5.8 oz/t Ag, 6.4 percent Pb, 8.6 percent Zn, and 0.14 percent Cu.

Deposits East of the Park City Mining District

On the east side of the Park City mining district, several types of deposits are present in the southwestern part of the composite Park Premier stock (Figs. 6 and 11). The oldest deposits are low-grade porphyry Cu-Au, Cu-bearing skarn, and polymetallic vein occurrences at the Park Premier mine and in nearby prospects that are now mostly covered by water filling the Jordanelle Reservoir (Fig. 11). Porphyry and skarn alteration are crosscut by structurally-controlled advanced argillic alteration and by low-grade Au-Ag mineralization at the Park Konold mine and the Queen tunnel (Figs. 11 and 12; John, 1989b).

Near the Park Premier mine, the Park Premier stock consists of five intrusive phases: the main phase, intrusions 1 and 2, and the porphyries of Bone Hollow and

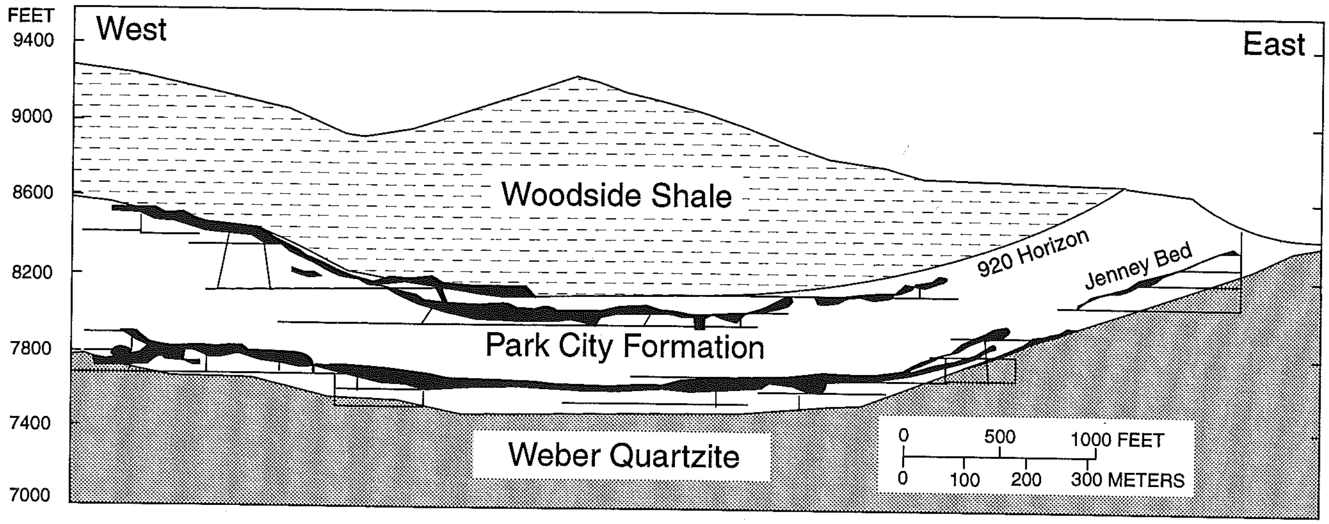


FIG. 9. Longitudinal section of the Middle Vein stopes, Judge and Daly-West mines, showing strong bedding control on replacement ores. Redrawn from Barnes and Simos (1968).

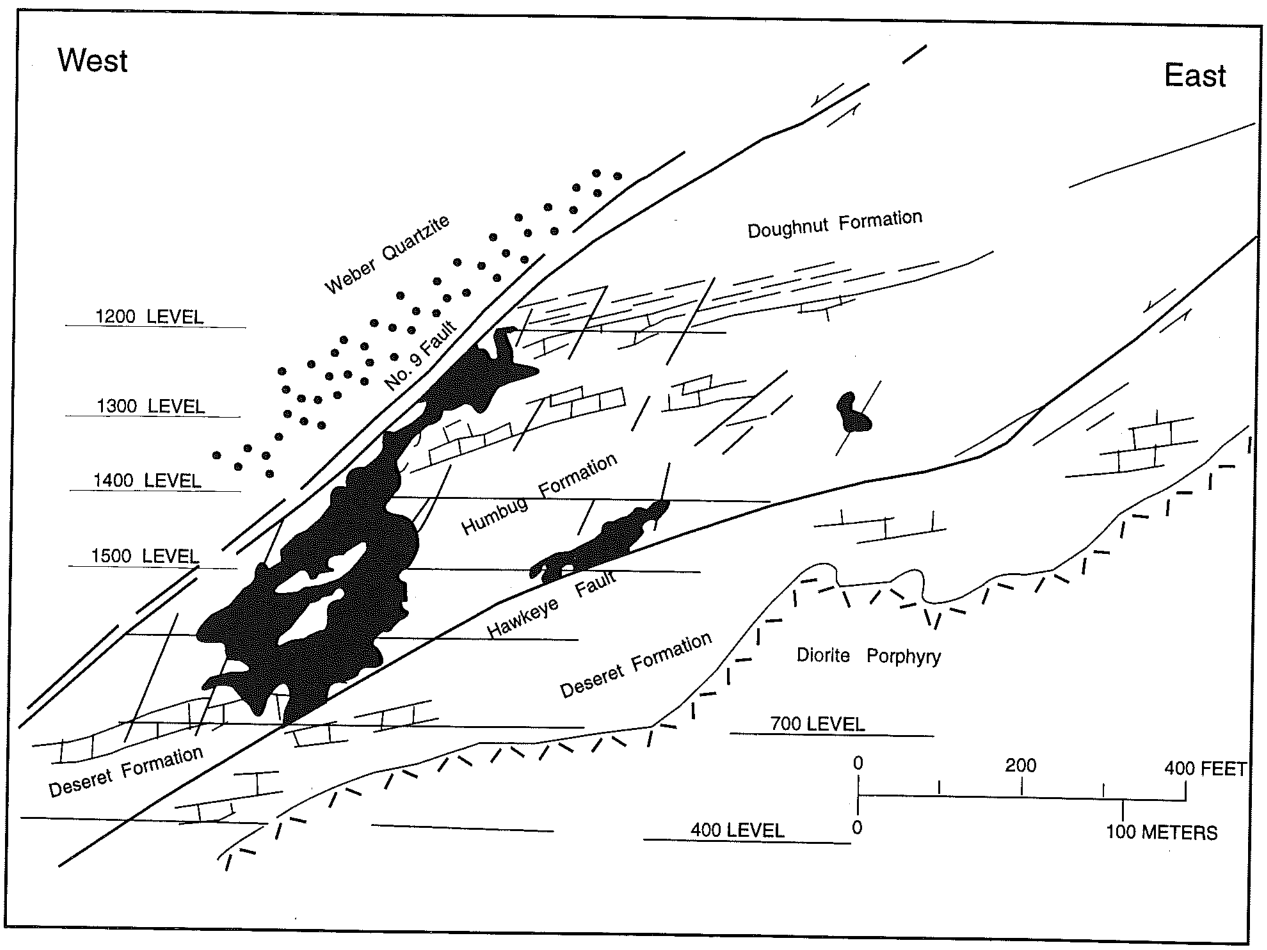
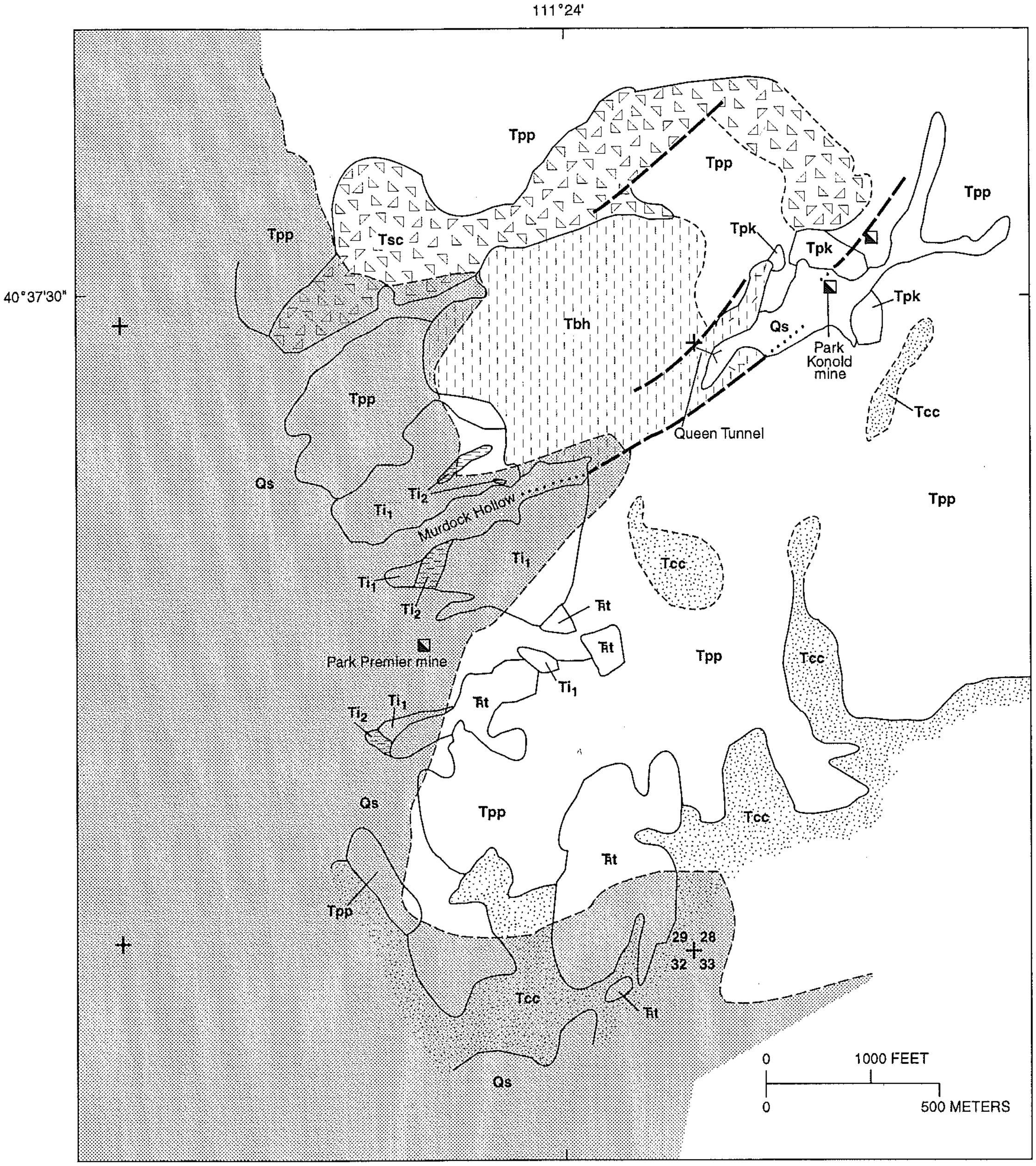


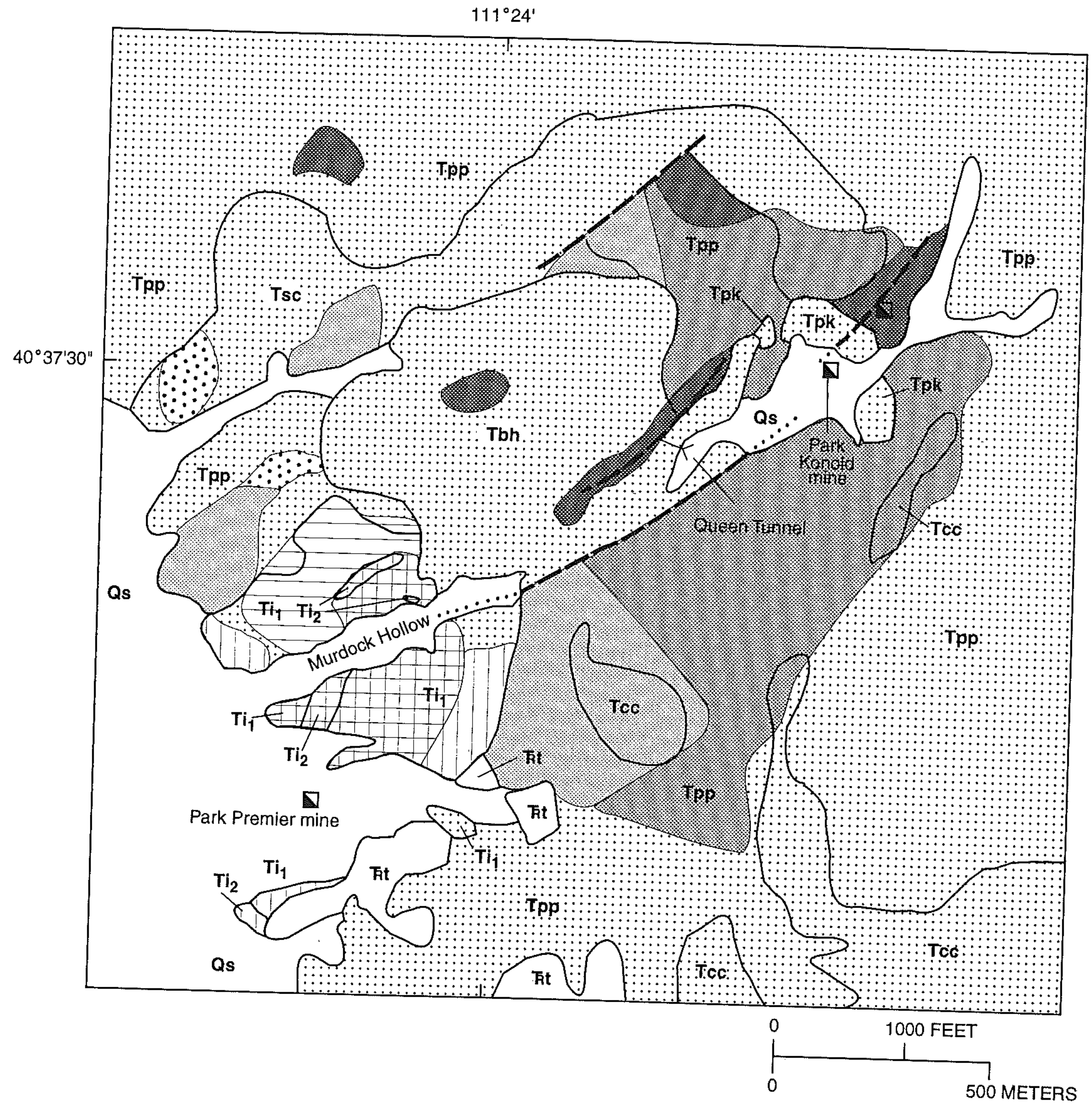
FIG. 10. Cross section of replacement deposits in the Northwest Flank ore bodies in the Ontario mine. Redrawn from Barnes and Simos (1968, fig. 11).



EXPLANATION

Qs Surficial deposits (Quarternary)
Park Premier stock (Tertiary)—
divided into:
Tbh Porphyry of Bone Hollow
Tpk Porphyry of Park Konold mine
Ti2 Intrusion 2
Ti1 Intrusion 1
Tpp Main phase
Tsc Breccia of Silver Creek (Tertiary)
Tcc Breccia of Coyote Canyon (Tertiary)
Ћt Thaynes Formation (Triassic)
----- Contact; dashed where uncertain
· · — — Inferred fault; dotted where concealed

FIG. 11. Generalized geologic map of the southwestern part of the Park Premier stock. Modified from John (1989b).



EXPLANATION

Qs Surficial deposits (Quaternary)
Park Premier stock (Tertiary)—
divided into:
Tbh Porphyry of Bone Hollow
Tpk Porphyry of Park Konold mine
Ti_2 Intrusion 2
Ti_1 Intrusion 1
Tpp Main phase
Tsc Breccia of Silver Creek (Tertiary)
Tcc Breccia of Coyote Canyon (Tertiary)
Ŧt Thaynes Formation (Triassic)
——— Contact; dashed where uncertain
·—— Inferred fault; dotted where concealed

Hydrothermal alteration types:

- Advanced argillic
- Quartz+sericite
- Quartz+albite+sericite
- Hydrothermal biotite
- Hydrothermal actinolite+magnetite
- Weak to strong propylitic
- Intermediate argillic/propylitic alteration

FIG. 12. Map showing generalized distribution of hydrothermal alteration in the southwestern part of the Park Premier stock.

Park Konold mine (John, 1989b; Fig. 11). The main phase of the stock is 35 to 34 Ma (Bromfield et al., 1977; John et al., 1997). Porphyry-style stockwork quartz veins, disseminated hydrothermal biotite, magnetite-actinolite alteration, and low-grade Cu-Mo-Au mineralized rock are centered on two granodiorite porphyry stocks (intrusions 1 and 2) that intrude the main phase of the Park Premier stock (Figs. 11 and 12). A broad zone of hydrolytic alteration elongated to the northeast surrounds the granodiorite intrusions (Fig. 12; John, 1989b). Hydrolytic alteration consists of an inner zone of quartz+albite+sericite alteration grading outward into quartz+sericite alteration and then into propylitic alteration (John, 1989b). All assemblages contain minor pyrite. The hydrolytic alteration is inferred to have been formed by magmatic gases released during crystallization of the granodiorite porphyries (John, 1989b). Hydrothermal biotite from an area of pervasive biotitization in the granodiorite porphyries yielded an $^{40}Ar/^{39}Ar$ age of 33.53 ± 0.09 Ma (John et al., 1997). The zone of stockwork quartz veins, hydrothermal biotite, and magnetite-actinolite alteration generally averages ≤0.2 percent Cu, ≤0.01 percent Mo, and 0.1 to 0.6 ppm Au (John, 1989b).

Early porphyry-related alteration is crosscut by the porphyry of Bone Hollow, which has K-Ar ages of 31.6 ± 0.39 Ma (biotite) and 32.38 ± 0.24 Ma (hornblende) (John et al., 1997). Both the porphyry of Bone Hollow and earlier alteration are cut by NE-striking fault zones that are locally marked by silicification, advanced argillic alteration assemblages containing alunite, pyrophyllite, kaolinite, and diaspore, and local zones of Au-Ag mineralization at the Queen Tunnel and Park Konold mine (Fig. 12). The faults project westward approximately to the Mayflower-Pearl fault zone (Fig. 6). Coarse-grained hypogene alunite from one of these zones yielded an $^{40}Ar/^{39}Ar$ age of 31.42 ± 0.10 Ma (John et al., 1997). This alteration and mineralization are interpreted as manifestations of high-sulfidation Au deposits.

Relatively little is known about the mining history of the Park Premier area. Production, if any, was small. The area around the Park Premier mine was explored by the Anaconda Company from at least the 1950s to the early 1980s. Exploration initially focused on porphyry copper potential in the granodiorite porphyries, and later attention was given to the potential for deep Cu skarn mineralization. The exploration history in the Park Konold mine area is unknown. The Park Premier mine is now covered by water, and the Queen tunnel and the Park Konold mine are along the reservoir shoreline inside Jordanelle State Park.

Summary and Conclusions

The combination of numerous distinct intrusions and widely varying depths of erosion from east to west across the central Wasatch Mountains result in a spectacular range of intrusion-related mineral deposits. Major types of intrusion-related deposits include Ag-Pb-Zn ± Cu ± Au vein and replacement, porphyry Cu-Au, Cu-bearing skarn, quartz monzonite-type (low F) porphyry Mo, and high sulfidation (quartz-alunite) Au. Most production came from world-class Ag-Pb-Zn vein and replacement deposits in the Park City mining district. Most deposits in the central Wasatch Mountains appear to be genetically related to the mid-Tertiary Wasatch igneous belt, a series of high-K calc-alkaline stocks and cogenetic volcanic rocks that formed about 41(?) to 30 Ma. The intrusive rocks were emplaced mostly along the westward extension of the west-trending Uinta arch during a period of NNW-SSE-directed extension, and much of the mineralization in the Park City mining district was structurally controlled by ENE-striking normal faults.

The central Wasatch Mountains were tilted about 15° down to the east subsequent to formation of the mineral deposits, thereby exposing a continuum of mid-Tertiary paleodepths ranging from about 11 km on the west to <1 km on the east. Most deposits formed at paleodepths of ≤5 km, and the most productive deposits in the Park City district formed at depths of 1 to 2 km. Most deposits appear to have formed in a relatively restricted time period from about 36 to 31.5 Ma, and are related mostly to the latter part of igneous activity in the Park City mining district (Ontario stock?), the composite Park Premier stock, and the Alta stock. The notable exception to this simple picture is the subeconomic White Pine Fork porphyry Mo deposit in the Little Cottonwood stock which formed both later (about 26 to 23.5 Ma) and at greater depths (approximately 6 km) than other deposits.

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