Geologic history of the Battle Mountain mining district, Nevada, and regional controls on the distribution of mineral systems

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ABSTRACT

The U.S. Geological Survey's recently completed 1:24,000-scale geologic mapping program in the Battle Mountain mining district of north-central Nevada has placed known ore deposits in geologic context and identified regional geologic controls on the distribution of mineral systems.

Paleozoic tectonostratigraphy of the mining district includes rocks of the early to middle Paleozoic Roberts Mountains allochthon that are unconformably overlain by overlap assemblage rocks of the late Paleozoic Antler sequence. Rocks of the Antler sequence are the most favorable host for hydrothermal ore deposits in the mining district. These rocks are structurally overlain by the late Paleozoic Havallah sequence, the base of which is the regionally extensive Golconda thrust. This structural relationship (Havallah sequence over Antler sequence along the Golconda thrust) represents the most important tectonostratigraphic control on the distribution of ore deposits in the mining district.

Mesozoic structural and magmatic events in the mining district include formation of northwest-striking fault zones and emplacement of Late Cretaceous monzogranite stocks with associated low-fluorine porphyry stockwork molybdenum systems. Northwest-striking fault zones are pre-Late Cretaceous in age and manifested by northwest-striking granodiorite porphyry dikes, northwest elongation of larger Late Cretaceous and Tertiary intrusive bodies, aeromagnetic lineaments, and regional alignment of mineralized areas.

Tertiary structural and magmatic events in the mining district included development of north-striking normal fault zones and emplacement of late Eocene to early Oligocene granodioritic stocks and dikes. Tertiary volcanic and volcaniclastic rocks in the mining district include early Oligocene crystal-lithic ash-flow tuff (Caetano Tuff), Oligocene basaltic andesite, Oligocene or Miocene rhyolitic ash-flow tuff (probably part of the regionally extensive Bates Mountain Tuff), and Miocene and Pliocene olivine basalt. Tertiary normal faulting began prior to the late Eocene and has continued, periodically, into the Quaternary. The majority of the mining district's metal endowment discovered to date (1995) formed as skarn, replacement, and distal disseminated deposits of copper, gold, and silver that developed in association with a number of late Eocene to early Oligocene porphyry intrusive centers in the district.

Three northwest-striking and five north-striking fault zones have been delineated in the mining district. Most Tertiary metallization in the mining district occurred in the areas where these zones intersect, suggesting that these structural intersections influenced where magmatic systems, and associated hydrothermal activity, were emplaced in the mining district . Their northwest- and north-striking orientations are believed to have been inherited from Mesozoic and Paleozoic structural fabrics, respectively. Both sets of fault zones developed over a relatively short time span in the Tertiary, from some time prior to 40 Ma to approximately 31 Ma, and may have involved periodic rotation of the regional least principle stress direction during this time interval. The late Miocene Oyarbide fault is a major northeast-striking, post-mineral fault, that has a vertical component of offset of approximately 700 m with its northwestern block down. As many as fifteen recently discovered gold deposits north of, and in the hanging wall of, the Oyarbide fault exhibit characteristics of and are classified as distal disseminated silver-gold deposits whose silver contents were presumably leached during periods of Tertiary oxidation. These distal disseminated deposits distinguish the northern part of the mining district from the southern part which contains seven exposed porphyry copper or stockwork molybdenum systems. Post-mineral displacement along the Oyarbide fault has resulted in levels of exposure such that all deposits in the hanging-wall block of the Oyarbide fault have current levels of exposure that should be close to the tops of their respective porphyry mineral systems.

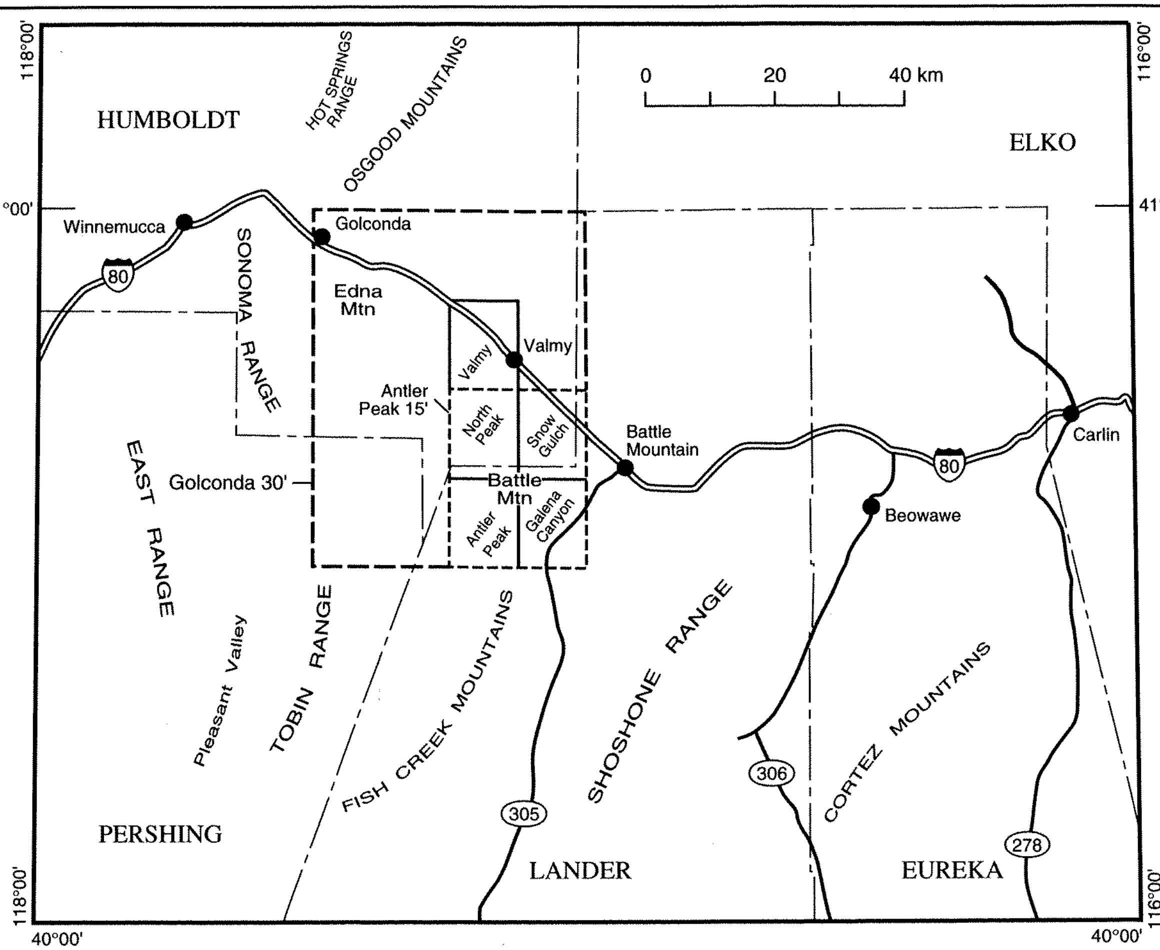
INTRODUCTION

The Battle Mountain mining district has been endowed with large resources of gold, silver, copper, and molybdenum (Table 1). Mining activity in the district spans more than 125 years, and large-scale mining operations have been continuous for the past 30 years. More than 311 tonnes (10 million ounces) of Au, 933 tonnes (30 million ounces) of Ag, and 113,400 tonnes (250 million pounds) of Cu have been produced or are present as mineable reserves in porphyry and porphyry-related deposits throughout the mining district. In addition, a drill defined resource of 0.9 to 1.3 billion tonnes (1.0 to 1.4 billion short tons) of ore averaging 0.06 weight percent Mo, that also contains as much as 3,110 tonnes (100

Table 1—Deposit-type, production status, and metal endowment information for developed ore deposits in the Battle Mountain mining district. See figure 2 for locations of deposits.

Deposit (locality on figure 2)	Deposit Type[1]	Years in Production	Endowment[2] Gold (troy oz)	Endowment[2] Silver (troy oz)	Endowment[2] Copper (pounds)
Copper Canyon Area[3]					
East Copper (19)	Porphyry Cu-Au-Ag	1966-1978	177,702	3,974,803	214,805,711
West Copper (23)	Cu-Au-Ag skarn				
Minnie (20)	Au-Ag-Zn skarn	1978-1981	75,646	180,010	na
Tomboy (20)	Au-Ag-Zn skarn	1978-1982	354,505	866,250	na
Northeast Extension (18)	Porphyry Cu-Au-Ag	1981-1983	196,836	864,670	na
Upper Fortitude (21)	Au-Ag replacement	1982-1984	225,692	2,355,899	na
Lower Fortitude (21)	Au-Ag skarn	1984-1993	2,037,211	8,981,123	na
Iron Canyon (17)	Distal disseminated Ag-Au	1991-	50,799	489,597	na
Midas Pit (25)	Au-Ag skarn	1994-	344,122	2,113,380	na
Phoenix (22)	Au-Ag skarn	No Production (1995)	911,490	4,557,450	na
Reona (24)	—	do.	234,060	1,691,340	na
Sunshine (26)	—	do.	25,669	216,160	na
Copper Basin Area[4]					
Contention/Carissa (14)	Au-Ag skarn (early production on Carissa), Porphyry Cu-Au-Ag, supergene enriched	1927-1954, 1966-1981	40,522	381,385	96,921,701
Sweet Marie (15)	Porphyry Cu-Au-Ag, supergene enriched	1929-1954, 1966-1967	138	6,220	9,298,383
Widow (15)	do.	1927-1945	14	630	29,166,009
Copper Queen (11)	do.	1917-1951	100	3,654	28,722,635
Empire (16)	Distal disseminated Ag-Au	1982, 1991-1994	88,416	289,677	na
Surprise (13)	Au-Ag skarn	1937-1954, 1987-1993	155,554	1,279,053	32,505
Labrador (13)	do.	1987-1993	96,180	276,699	na
Northern Lights (16)	Distal disseminated Ag-Au	1993	19,964	73,587	na
Bailey Day (10)	Au-Ag skarn	1934-1948, 1993	11,981	17,446	54,974
Marigold Mine Area[5]					
Eight South (1)	Distal disseminated Ag-Au	1988-1995	442,000	-	na
Top Zone (2)	do.	1990-	159,565	-	na
East Hill/UNR (3)	do.	1991-	278,598	-	na
Red Rock (4)	do.	1994-	52,219	-	na
Lone Tree[6]	do.	1991-	4,597,269	-	na
Buffalo Valley Gold[7] (28)	Porphyry Cu, distal disseminated Ag-Au	1924-1951, 1986-1991	65,000	-	9,607

[1]As defined in Cox and Singer (1986), Theodore et al. (1991), and Bliss (1992). — = not classified.
[2]Endowment includes production plus proven, probable and possible reserves. na = not applicable, - = unknown. Metric conversion factors are as follows:
1 metric ton = 1000 kilograms = 32,150.7 troy ounces = 2,204.6 pounds.
Endowment data sources:
[3]P.R. Wotruba (written commun. 1994); Doebrich et al. (1996).
[4]Roberts and Arnold (1965); P.R. Wotruba (written commun., 1994); Doebrich et al. (1996).
[5]D.H. McGibbon (written commun., 1994)
[6]Nevada Bureau of Mines and Geology (1995); Green et al. (1996).
[7]Roberts and Arnold (1965); Seedorff et al. (1991).



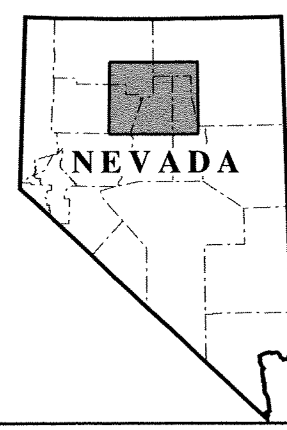


Figure 1—Index map of north-central Nevada showing location of Battle Mountain area and outlines of other quadrangle mentioned in the text. References for geologic maps of 7.5-minute quadrangles are as follows: Antler Peak (Doebrich, 1992, 1995), Galena Canyon (Doebrich, 1994), North Peak (Theodore, 1991a), Snow Gulch (Theodore, 1994), and Valmy (Theodore, 1991b). Antler Peak 15-minute quadrangle (Fig. 2) coincides with the four southernmost 7.5-minute quadrangles shown. Battle Mountain mining district, as used in the text, refers to the area covered by all five 7.5-minute quadrangles shown here.

million ounces) of silver, is present in the Buckingham porphyry stockwork molybdenum deposit.

The earliest systematic geologic studies of the Battle Mountain mining district were conducted by Hague and Emmons (1877) and Hill (1915), who examined many of the small, polymetallic vein and replacement mines then in production. A classic study of the geology and mineral deposits of Battle Mountain was conducted in the 1940s and 1950s by a group of U.S. Geological Survey scientists, most notably Ralph J. Roberts. Results of geologic mapping were initially incorporated in the 1:125,000-scale geologic map of the Golconda 30-minute quadrangle (Ferguson et al., 1952) (Fig. 1). The results of this early work were compiled, synthesized, and interpreted by Roberts (1964) and Roberts and Arnold (1965) in their study of the geology and mineral deposits of the Antler Peak 15-minute quadrangle (Figs. 1, 2). This work provided a foundation for understanding the Paleozoic geologic history of northern Nevada and led to the naming and documentation of the Antler orogeny (Roberts et al., 1958). Theodore et al. (1973) conducted the first geochronologic study of plutonic rocks in the Battle Mountain mining district.

In the 1970s and 1980s much of the published work in the mining district focused on mineral deposits in the Copper

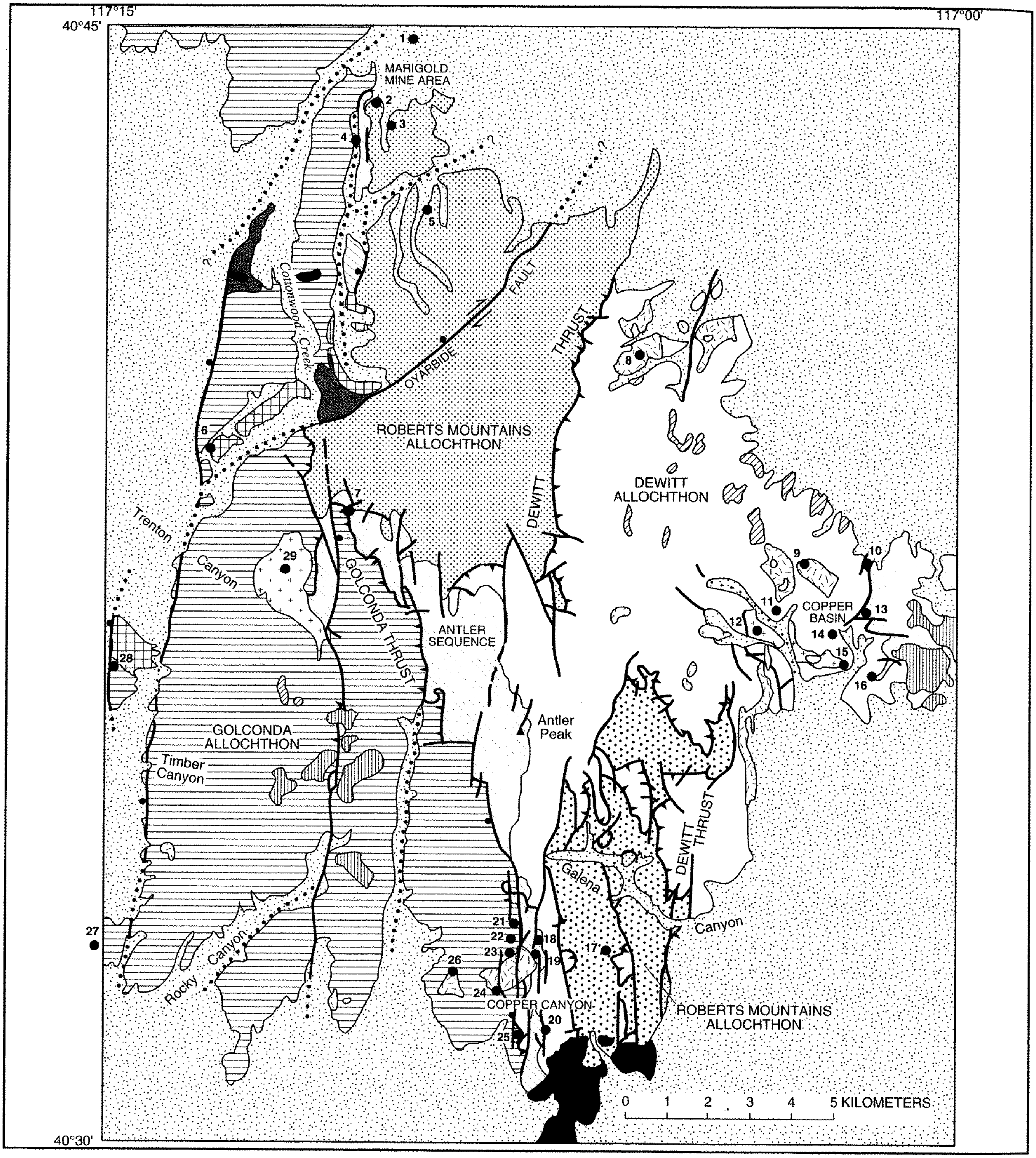


Figure 2—Generalized geology of Antler Peak 15-minute quadrangle (see Fig. 1), modified from Roberts (1964), showing locations of ore deposits and mineral systems in the Battle Mountain mining district. See Table 1 for information on developed ore deposits in the mining district. **1**, Eight South (Marigold Mine); **2**, Top Zone (Marigold Mine); **3**, East Hill/UNR (Marigold Mine); **4**, Red Rock (Marigold Mine); **5**, Valmy-Trout Creek (Santa Fe Pacific Gold's [SFPG] Trenton Canyon project); **6**, North Peak-Section 11(SFPG's Trenton Canyon project); **7**, Trenton Canyon gold (SFPG's Trenton Canyon project); **8**, Elder Creek porphyry copper system; **9**, Paiute Canyon porphyry molybdenum-copper system; **10**, Bailey Day; **11**, Copper Queen; **12**, Buckingham low-fluorine porphyry molybdenum system; **13**, Surprise and Labrador deposits; **14**, Contention and Carissa deposits; **15**, Sweet Marie and Widow deposits; **16**, Empire and Northern Lights deposits; **17**, Iron Canyon; **18**, Northeast Extension; **19**, East Copper; **20**, Tomboy and Minnie deposits; **21**, Fortitude; **22**, Phoenix; **23**, West Copper; **24**, Reona; **25**, Midas Pit; **26**, Sunshine; **27**, Buffalo Valley porphyry molybdenum system; **28**, Buffalo Valley gold deposit; **29**, Trenton Canyon porphyry molybdenum system.

EXPLANATION

- Unconsolidated deposits (Quaternary)
- Basaltic rocks (Pliocene to Oligocene)—Oligocene rocks present near Cottonwood Creek and Pliocene rocks present east-southeast of Copper Canyon
- Calc-alkaline rhyolite tuff (Miocene and (or) Oligocene)—Equivalent in age to Bates Mountain Tuff (Stewart and McKee, 1977; McKee, 1994)
- Gravel deposits (Oligocene)—Locally interbedded with basaltic rocks near Cottonwood Creek
- Pyroclastic rocks (Oligocene)
- Porphyritic monzogranite and granodiorite porphyry (Oligocene or Eocene)
- Monzogranite (Tertiary?)
- Monzogranite and monzogranite porphyry (Late Cretaceous)
- Antler sequence (Permian and Pennsylvanian)

GOLCONDA ALLOCHTHON

- Havallah sequence of Silberling and Roberts (1962) (Permian, Pennsylvanian, and Mississippian)

ROBERTS MOUNTAINS ALLOCHTHON

- Scott Canyon Formation (Devonian)—As mapped, includes some rocks of Valmy Formation
- Valmy Formation (Middle and Early Ordovician)

DEWITT ALLOCHTHON

- Harmony Formation (Late Cambrian)

- Contact
- High-angle fault—Dashed where approximately located; dotted where concealed or inferred; ball on downthrown side
- Thrust fault—Dashed where approximately located; dotted where concealed or inferred. Sawteeth on upper plate
- Location of ore deposit or mineral system

Figure 2—Explanation.

Canyon area (Theodore and Nash, 1973; Theodore and Blake, 1975; 1978; Theodore et al., 1986; Wotruba et al., 1988; Myers and Meinert, 1991; Myers, 1994), at the Buffalo Valley molybdenum prospect (Thomas, 1985), in the Copper Basin area (Schmidt et al., 1988; Theodore and Hammarstrom, 1991; Theodore and Jones, 1992; Theodore et al., 1992), at the Buffalo Valley Mine (Seedorff et al., 1991), and at the Marigold Mine (Graney and McGibbon, 1991). Renewed interest in the structure and stratigraphy of the Roberts Mountains allochthon (Madrid, 1987) and the Golconda allochthon (Miller et al., 1982; Brueckner and Snyder, 1985; Murchey, 1990) drew geologists back to the mining district in the 1980s and led to a reinterpretation of the structure and stratigraphy of the Golconda allochthon and a recognition of its tectonostratigraphic complexity .

The U.S. Geological Survey completed a 1:24,000-scale geologic mapping program in the Battle Mountain mining district in 1994. Begun in 1990, the program has produced geologic maps of the Antler Peak (Doebrich, 1992, 1995), Galena Canyon (Doebrich, 1994), North Peak (Theodore, 1991a), Snow Gulch (Theodore, 1994) and Valmy (Theodore, 1991b) 7.5-minute quadrangles (Fig. 1). Primary objectives of the program were to place known ore deposits in geologic context and to identify regional geologic controls on distribution of ore deposits. The usage of "Battle Mountain mining district" or "mining district" throughout this paper refers to that area covered by the five 7.5-minute quadrangles listed above (Fig. 1). Figure 2 shows the generalized geology for the four southernmost quadrangles which comprise the Antler Peak 15-minute quadrangle.

This paper is an outgrowth of the 1:24,000-scale district-wide geologic mapping and recent work conducted at specific mine sites and properties. The paper is intended to be a review of current understanding of the geology and ore deposits of the Battle Mountain mining district and addresses important geologic concepts and relationships that are critical to understanding both local and regional controls on the distribution of mineral systems in the mining district.

The usage of the term "distal disseminated silver-gold deposit" throughout the text refers to the descriptive mineral deposit model of Cox (1992). The published grade and tonnage model for this deposit type (Cox and Singer, 1992), however, indicates a much higher silver:gold ratio than what is found in these types of the deposits in the Battle Mountain mining district. Because all of these deposits in the mining district are oxidized, it is believed that silver has been leached to produce deposits with much greater amounts of gold than silver. Thus, usage of the term "distal disseminated silver-gold deposit" in the text should not infer that silver is present in greater quantities than gold.

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PALEOZOIC TECTONOSTRATIGRAPHY

Paleozoic tectonostratigraphy of the Battle Mountain mining district (Fig. 3) consists of the Roberts Mountains allochthon, which contains Late Cambrian Harmony Formation, Ordovician Valmy Formation, and Devonian Scott Canyon Formation, emplaced during the Antler orogeny, (Fig. 4), unconformably overlain by the overlap assemblage (Antler sequence of Roberts, 1964) containing the Middle Pennsylvanian Battle Formation, Pennsylvanian and Permian Antler Peak Limestone, and Permian Edna Mountain Formation. These rocks are structurally overlain by the Mississippian, Pennsylvanian, and Permian Havallah sequence of the Golconda allochthon, the base of which is the regionally extensive Late Permian to Early Triassic Golconda thrust, which was active during the Sonoma orogeny (Fig. 4) (Silberling and Roberts, 1962; Roberts and Thomasson, 1964; Stewart et al., 1977; Stewart et al., 1986; Murchey 1990; Tomlinson, 1990). Intraformational tectonostratigraphy has been greatly refined with new mapping and new microfossil age determinations, particularly for the Valmy Formation, Scott Canyon Formation, and Havallah sequence.

Rocks of the Roberts Mountains Allochthon and the Antler Orogeny

The Late Cambrian Harmony Formation crops out over a large area in the eastern part of the mining district (Fig. 2) and structurally overlies the Ordovician Valmy Formation and Devonian Scott Canyon Formation along the Dewitt thrust (Figs. 2, 3). The Dewitt thrust is considered a major imbricate thrust or splay of the Roberts Mountains thrust, such that rocks of the Harmony Formation comprise an allochthon within an allochthon, known locally as the Dewitt allochthon (Fig.2). The Harmony Formation consists of feldspathic and micaceous sandstone (locally calcareous) with lesser amounts of calcareous shale and limestone. The formation is considered Late Cambrian in age on the basis of trilobites found in the Hot Springs Range, 5 to 10 km west-northwest of the Osgood Mountains (Fig. 1) (Roberts et al., 1958; Hotz and Willden, 1964). Recent identification of Late Devonian conodonts in limestone apparently belonging to the Harmony Formation from the Hot Springs Range (A.E. Jones, written commun., 1995) is enigmatic. Reworking of the Ordovician Valmy Formation during the Devonian, however, has been documented in the Shoshone Mountains (C.T. Wrucke, oral commun., 1995), and may have also locally affected the Harmony Formation. Moreover, the regionally distinctive Harmony Formation is recognized as olistolithic blocks enclosed within the Devonian Scott Canyon Formation (Doebrich, 1994) and as clasts in the Devonian rocks of the Slaven Chert in the Shoshone Mountains, 20 km to the southeast (Fig. 1) (Madrid, 1987). This requires that the Harmony Formation be older than Late Devonian in age. Calcareous units of the Harmony Formation are converted to biotite hornfels in the Copper Canyon and Copper Basin areas where they are near intrusions and to garnet-pyroxene skarn at many deposits in the Copper Basin area and in exposures west of the Labrador pit (Fig. 2) (Theodore et al., 1992). In the Copper Basin area, the Harmony Formation was host for supergene-enriched porphyry copper ore at the Contention, Carissa, Copper Queen, Sweet Marie, and Widow deposits, and to gold-silver skarn and distal disseminated silver-gold deposits at the Labrador, Surprise, Northern Lights, and Empire deposits (Fig. 2, Table 1) (Schmidt et al., 1988). The Harmony Formation also is host for half of the 1 billion tonnes of mineralized rock at the Buckingham stockwork molybdenum deposit (Theodore et al., 1992). At the East copper deposit in the Copper Canyon area (Fig. 2), rocks of the Harmony Formation were host for porphyry copper ore associated with potassic alteration assemblages along the east side of the granodiorite of Copper Canyon (Theodore and Blake, 1975).

Early and Middle Ordovician rocks of the Valmy Formation underlie a large area in the northern part of the mining district (Fig. 2) and is found as small fault-bounded slivers structurally intercalated with Late Devonian Scott Canyon Formation in the Galena Canyon area (Fig. 2) (McCollum et al., 1987; Doebrich, 1994). The Valmy Formation consists of four units: (1) largely quartzarenite at the base; (2) succeeded upwards by mostly chert and quartzarenite; (3) overlain by additional quartzarenite, submarine basalt, cherty argillite, and shale; and, finally, (4) shaly argillite, chert, minor basalt, and quartzarenite at the top. Rocks of the Valmy Formation in the Battle Mountain mining district are provisionally considered to be Early and Middle Ordovician in age based on extensive collections of graptolites described by Roberts (1964). Rocks of the Valmy Formation in the Sonoma Range (Gilluly, 1967), Shoshone Mountains (Gilluly and Gates, 1965; Madrid, 1987) and Independence

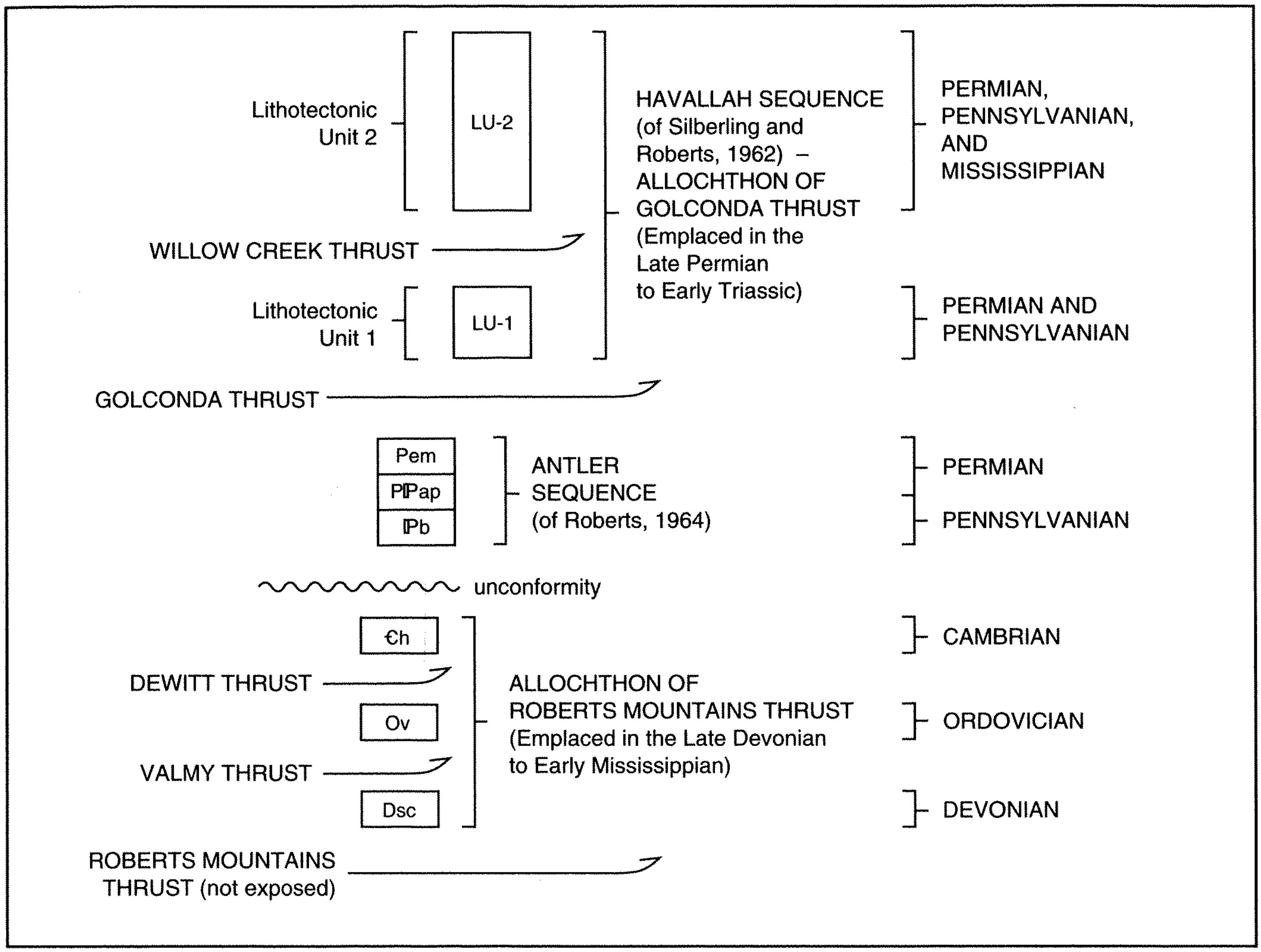


Figure 3—Paleozoic tectonostratigraphy of the Battle Mountain mining district. Dsc, Scott Canyon Formation; Ov, Valmy Formation; Ꞓh, Harmony Formation; IPb, Battle Formation; PIPap, Antler Peak Limestone; Pem, Edna Mountain Formation; LU-1, lithotectonic unit 1 of Murchey (1990) of Havallah sequence; LU–2, lithotectonic unit 2 of Murchey (1990) of Havallah sequence. Valmy thrust is that of Madrid (1987).

Range (Churkin and Kay, 1967; Watkins and Browne, 1989) are assigned to the Early, Middle, and Late Ordovician. Rocks of the Valmy Formation, particularly quartzarenite units, are host for distal disseminated silver-gold ore bodies at the Top Zone deposit at the Marigold Mine and at the Valmy-Trout Creek and Trenton Canyon gold deposits of Santa Fe Pacific Gold's Trenton Canyon project (Fig. 2) (Graney and McGibbon, 1991; Doebrich et al., 1996).

The Devonian Scott Canyon Formation is exposed in the southeast part of the mining district, both north and south of Galena Canyon (Fig. 2), and is structurally overlain by the Late Cambrian Harmony Formation along the Dewitt thrust. The formation consists of structurally intercalated units of chert and argillite, metabasalt, and olistostrome (Doebrich, 1994). Olistostrome, which when exposed consistently crops out directly below the Dewitt thrust, consists of olistoliths of Early Cambrian archaeocyathid- and trilobite-bearing limestone (McCollum et al., 1987; Debrenne et al., 1990), arkose of Late Cambrian Harmony Formation, Ordovician limestone (L.B. McCollum, written commun., 1993), and Ordovician(?) chert in a tuffaceous greenstone matrix. The olistostrome most likely formed from volcanogenic debris flows, which derived their component material from a highland or advancing front of an allochthon containing early Paleozoic rocks, that were then deposited in a Devonian basin. Limestone olistoliths were first described by Roberts (1964) as carbonate lenses or bioherms, requiring that the Scott Canyon Formation be assigned an Early Cambrian age based on the contained archaeocyathids and trilobites. Recent examinations of radiolarians in chert mapped as the Scott Canyon Formation indicate both Devonian and Ordovician ages for chert (Jones et al., 1978; Theodore et al., 1992; Murchey,

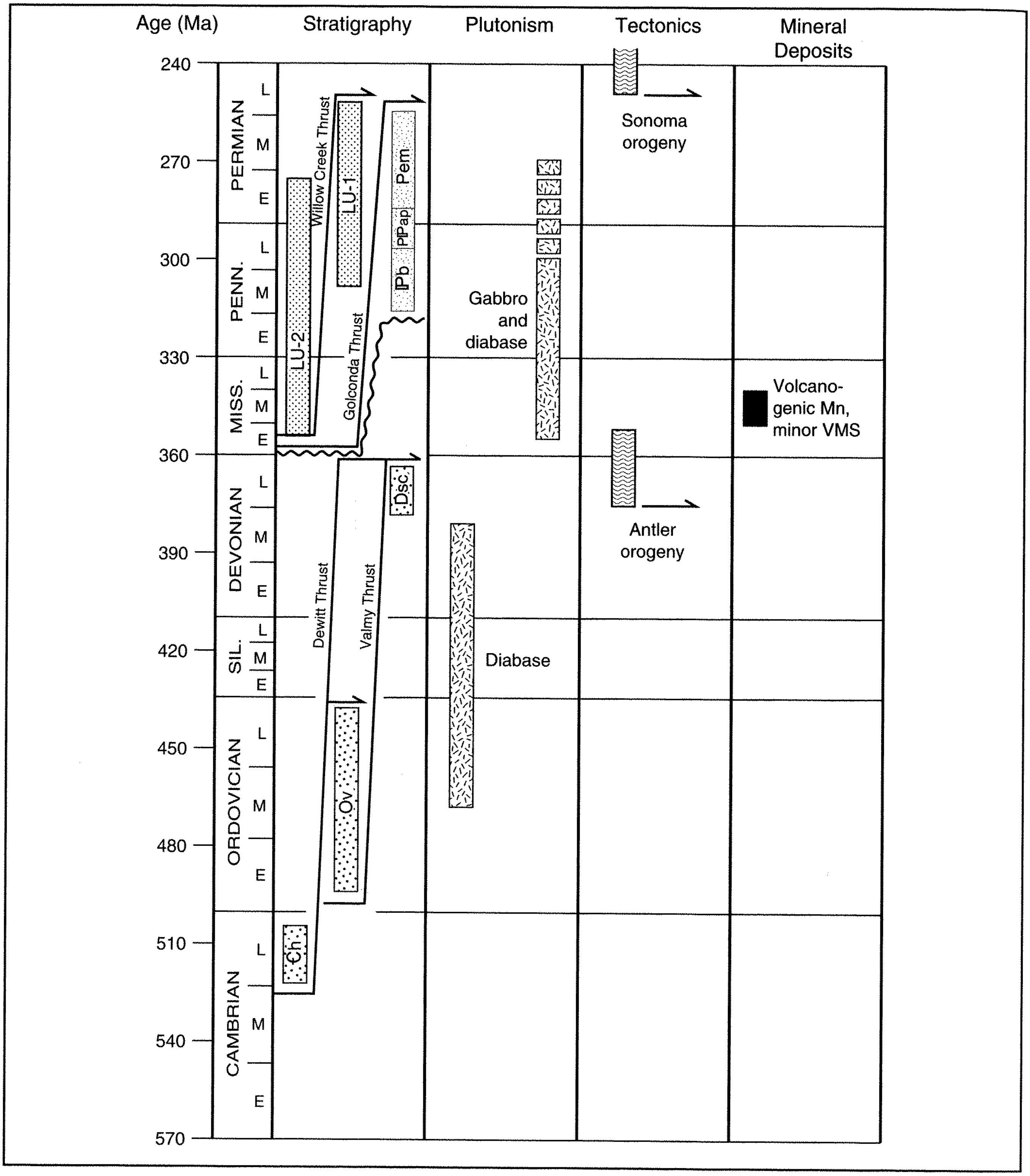


Figure 4—Chart summarizing Paleozoic geologic history of the Battle Mountain mining district, illustrating temporal relationships between deposition of strata, plutonism, tectonic events, and development of mineral deposits. Valmy thrust is that of Madrid (1987). Wavy line in stratigraphy column represents unconformity between rocks of Antler sequence (ℙb, PℙAp, Pem) and rocks of Roberts Mountains allochthon (Ꞓh, Ov, Dsc). Arrows in tectonic column indicate general direction of allochthon emplacement (eastward) during orogenies. **Ꞓh**, Harmony Formation; **Ov**, Valmy Formation; **Dsc**, Scott Canyon Formation; **ℙb**, Battle Formation; **PℙAp**, Antler Peak Limestone; **Pem**, Edna Mountain Formation; **LU–1**, lithotectonic unit 1 of Murchey (1990) of the Havallah sequence; **LU–2**, lithotectonic unit 2 of Murchey (1990) of the Havallah sequence; **VMS**, volcanogenic massive sulfide.

written commun., 1994). Chert that yielded Ordovician radiolarians was collected adjacent to olistostrome and may be from a large olistolith within the olistostrome unit. It is also possible that tectonically imbricated and downfaulted blocks of the Ordovician Valmy Formation are now structurally intercalated with the Devonian Scott Canyon Formation (McCollum et al., 1987). The Scott Canyon Formation is host for distal disseminated silver-gold ore at the Iron Canyon Mine (Fig. 2) (Doebrich, 1994; Doebrich et al., 1996) where ore is closely associated with an Oligocene granodiorite porphyry dike.

Rocks of the Roberts Mountains allochthon were transported eastward, on the Roberts Mountains thrust, during the Late Devonian to Early Mississippian Antler orogeny (Roberts, 1964; Speed and Sleep, 1982) (Fig. 4). Some studies have concluded, however, that in northeastern Nevada the Antler orogeny produced uplift and erosion and not thrusting (Ketner et al., 1993), and that thrusting may have occurred during the Mesozoic (Ketner and Smith, 1982). The Roberts Mountains thrust is not exposed at Battle Mountain, and deep drilling indicates that it probably underlies the mining district at depths greater than 1,300 m (Theodore and Roberts, 1971). A Paleozoic structural fabric, primarily consisting of fold axes, was imparted on rocks of the Roberts Mountains allochthon during the Antler orogeny and generally strikes N. 10° W. to N. 20° E. (Evans and Theodore, 1978, Theodore, 1991a, 1994; Doebrich, 1994).

Rocks of the Antler Sequence

The Pennsylvanian and Permian Antler sequence of Roberts (1964), also referred to as the overlap assemblage, is exposed at several localities in the mining district (Fig. 2) and constitutes the only Paleozoic autochthonous rocks in the district. The sequence consists of the Middle Pennsylvanian Battle Formation, Pennsylvanian and Permian Antler Peak Limestone, and Permian Edna Mountain Formation (Fig. 3). Thicknesses of formations are extremely variable district wide, such that individual formations may be absent from local stratigraphic sections. Rocks of the Antler sequence lie unconformably on rocks of the Roberts Mountains allochthon (Fig. 3), documenting the Antler orogeny as defined by Roberts (1964) (see also Doebrich et al., 1996). Rocks of the Antler sequence are the most favorable host for hydrothermal mineral deposits in the Battle Mountain mining district.

The Middle Pennsylvanian Battle Formation is at the base of the Antler sequence and locally lies unconformably on the Late Cambrian Harmony Formation and Ordovician Valmy Formation. Most of the Battle Formation consists of immature thick-bedded conglomerate and sandstone, and lesser amounts of siltstone, shale, and limestone. Siliciclastic units are variably calcareous and clastic components were derived from rocks of the Roberts Mountains allochthon during erosion of the Antler highland. In the Copper Canyon area, the Battle Formation was the primary host for porphyry copper ore in the East copper deposit (Theodore and Blake, 1975), for gold-silver skarn ore in the Tomboy-Minnie deposits (Theodore et al., 1990), and for gold-silver replacement ore in the Upper Fortitude deposit (Wotruba et al., 1988; Doebrich et al., 1996), and is the primary host for gold-silver skarn ore currently being mined from the Midas pit (Fig. 2, Table 1) (Doebrich et al., 1996). In the Copper Basin area, the Battle Formation hosts gold-silver skarn ore at the Labrador and Surprise deposits (Schmidt et al., 1988; Doebrich et al., 1996) and hosts distal disseminated silver-gold ore at the Lone Tree deposit (Bloomstein et al., 1993), and at the East Hill and Red Rock deposits at the Marigold Mine (Fig. 2, Table 1) (Graney and McGibbon, 1991).

The Pennsylvanian and Permian Antler Peak Limestone is the middle formation of the Antler sequence. It consists mostly of medium- to thick-bedded fossiliferous limestone, locally containing quartz sand, with lesser amounts of shale and pebbly conglomerate. In the Copper Canyon area, the Antler Peak Limestone was the primary host for gold-silver skarn ore in the Lower Fortitude ore zone (Wotruba et al., 1988; Myers, 1994; Doebrich et al., 1996) which yielded most of the ore (1.9 million ounces Au) from the Fortitude Mine, and is the primary host for gold-silver skarn ore in the Phoenix deposit, a southern extension of the Fortitude deposit (Fig. 2, Table 1) (Doebrich et al., 1996).

The Permian Edna Mountain Formation is uppermost unit of the Antler sequence and commonly is directly below the trace of the Golconda thrust (Figs. 2, 3, 4). Its lower contact with the Antler Peak Limestone is depositional and unconformable (Murchey et al., 1995). The formation consists of calcareous siltstone, sandstone, pebble conglomerate, and limestone. Conglomerate and sandstone are texturally more mature than those in the Battle Formation. Near its base, the Edna Mountain Formation contains a regionally extensive unit of debris flow conglomerates with intercalated siltstone (Murchey et al., 1995), which is the primary host for distal disseminated silver-gold ore at the 8 South, 8 North, and 5 North deposits at the Marigold Mine (Fig. 2, Table 1) (Graney and McGibbon, 1991; Doebrich et al., 1996). Siltstone and sandstone of the Edna Mountain hosts distal disseminated silver-gold ore at the Lone Tree deposit (Bloomstein et al., 1993). In the Copper Canyon area, the Edna Mountain Formation hosted minor amounts of gold-silver skarn ore in the Lower Fortitude ore body, and hosts gold-silver skarn ore in the Phoenix deposit (Fig. 2, Table 1) (Doebrich et al., 1996).

Rocks of the Golconda Allochthon and the Sonoma Orogeny

The Havallah sequence, which constitutes the upper plate of the Golconda thrust, is a Mississippian, Pennsylvanian, and Permian allochthonous tectonostratigraphic assemblage of chert, argillite, shale, siltstone, sandstone, conglomerate, limestone, and metavolcanic rocks exposed over a large area throughout the western part of the mining district (Fig. 2). The base of the Havallah sequence is the regionally extensive Golconda thrust (Figs. 2, 3, 4), which places the Havallah sequence structurally over the Antler sequence. This structural relationship (the Havallah sequence over the Antler

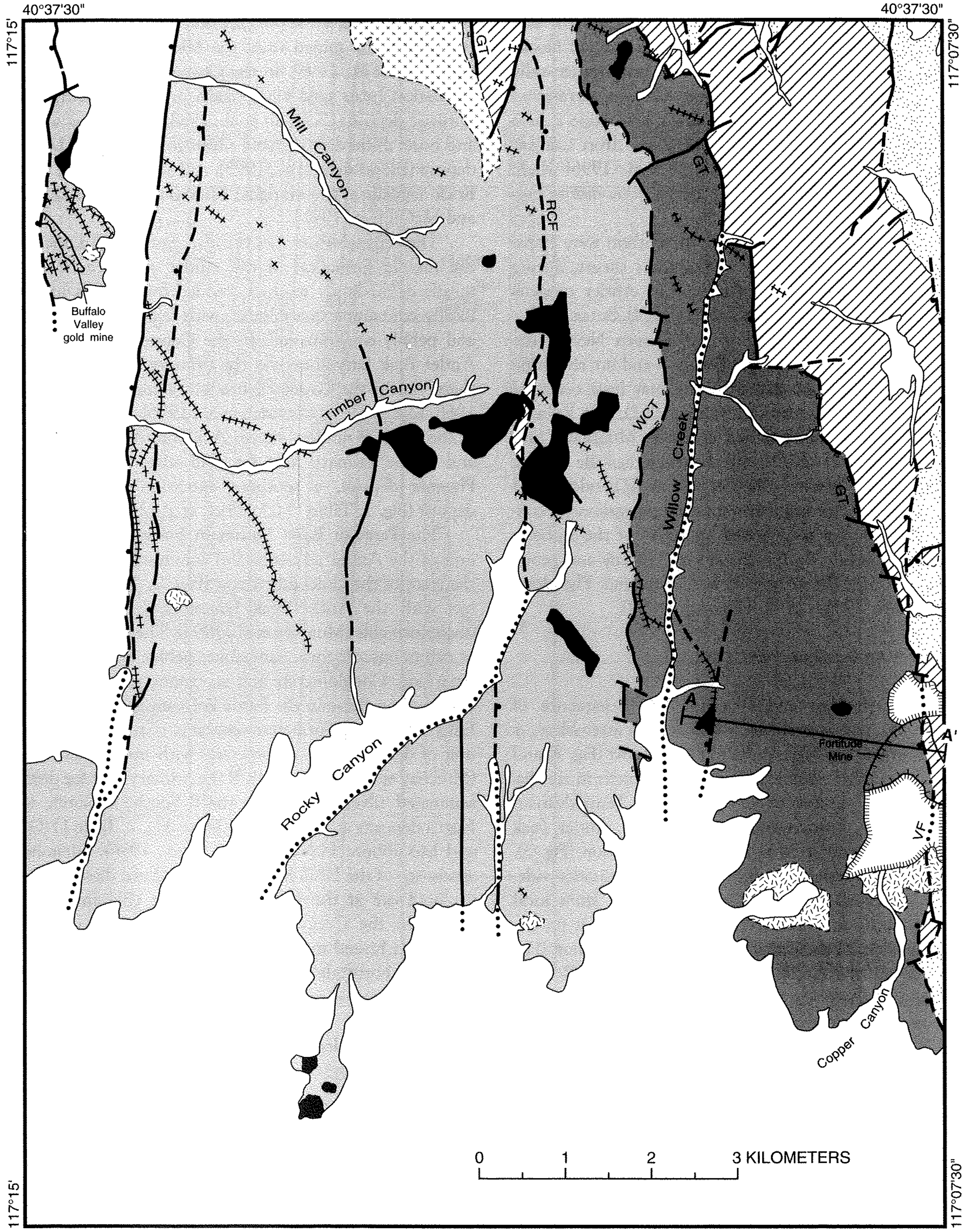


Figure 5—Generalized geologic map of the Antler Peak 7.5-minute quadrangle (modified from Doebrich, 1992, 1995). Cross section A-A′ is shown in Figure 11. GT, Golconda thrust; WCT, Willow Creek thrust; RCF, Rocky Canyon fault; VF, Virgin fault.

EXPLANATION

Quaternary alluvium

Tertiary volcanic rocks

Tertiary intrusive rocks

Cretaceous intrusive rocks

Paleozoic volcanic and sedimentary rocks

Golconda allochthon
Havallah sequence of Silberling and Roberts (1962)

Basinal sequence and turbidite (Permian, Pennsylvanian, and Mississippian)
Lithotectonic unit 2 of Murchey (1990)

Slope sequence (Permian and Pennsylvanian)
Lithotectonic unit 1 of Murchey (1990)

Overlap assemblage (Permian and Pennsylvanian)
Antler sequence of Roberts (1964)

Roberts Mountains allochthon (Ordovician and Cambrian)

Contact dashed where approximately located

Normal fault ball on downdropped block

Thrust fault sawteeth on upper plate

Dike

Perimeter of open-pit mine

Mine dump

Figure 5—Explanation.

sequence along the Golconda thrust) represents the most important tectonostratigraphic control on the distribution of ore deposits in the Battle Mountain mining district. The Willow Creek thrust is identified as a major imbricate thrust that divides the Havallah sequence and Golconda allochthon into two lithotectonic units, LU-1 and LU-2 (Murchey, 1990) (Figs. 3, 4, 5).

Lithotectonic unit 1 (LU-1) is structurally the lowest part of the Havallah sequence and forms the footwall of the Willow Creek thrust and hanging wall of the Golconda thrust (Figs. 3, 4, 5). LU-1 consists of Pennsylvanian and Permian slope deposits of argillite, cherty shale, and sponge-spicule chert (Murchey, 1990; Doebrich, 1995), and largely corresponds to the Pennsylvanian(?) Pumpernickel Formation as described by Roberts (1964).

Lithotectonic unit 2 (LU-2) is structurally higher than LU-1, forms the hanging wall of the Willow Creek thrust (Figs. 3, 4, 5), and largely corresponds to the Pennsylvanian and Permian Havallah Formation as described by Roberts (1964). LU-2 consists of Mississippian basin deposits of radiolarian chert and shale, and Pennsylvanian and Permian turbidite deposits of calcareous siltstone, sandstone, pebble conglomerate, and pebbly to micritic limestone (Murchey, 1990; Doebrich, 1995). The calcareous units of LU-2 are the sole host for porphyry-copper-related gold ore at the Buffalo Valley gold deposit (Fig. 2, Table 1) (Seedorff et al., 1991; Doebrich, 1995), and also hosts distal disseminated silver-gold ore at the Lone Tree deposit (Bloomstein et al., 1993). LU-2 also contains two chemically distinct suites of volcanic rock: (1) Mississippian basalt and basaltic andesite, and (2) Pennsylvanian and (or) Permian basaltic trachyandesite and trachyandesite. The former have trace element geochemical affinities with plume-type or enriched mid-ocean ridge basalt (MORB) whereas the latter have affinities with within-plate alkali basalt and within-plate tholeiites (Doebrich, 1995; T.G. Theodore, unpub. data). The presence of volcanogenic massive sulfide and manganese deposits in association with Mississippian pillow basalt and radiolarian chert of LU-2 in the mining district (Doebrich, 1995) indicates that the Mississippian was a time of active seafloor fumarolic activity in a plume-type MORB environment (Fig. 4). These associations are more indicative of an oceanic or marginal rift basin setting than a back-arc basin setting.

The time of emplacement of the Golconda allochthon is a subject of debate (Gabrielse et al., 1983). Emplacement must have occurred after the early Late Permian, as deformed rocks of this age comprise the youngest units of both the Havallah and Antler sequences. The contrast in structural disruption between rocks of the Havallah sequence and the underlying Antler sequence, however, is striking. Rocks of the latter sequence are virtually undeformed, suggesting that most folding, thrusting, and crustal shortening in the Golconda allochthon occurred prior to its emplacement. Structural fabric within the Havallah sequence, as a result of this deformation, is largely north-striking (N. 20° W. to N. 20° E.) with east vergence, though the fabric varies considerably. Deformation of the Havallah sequence took place during the Sonoma orogeny, occurring between early Late Permian and late Early Triassic time, as undeformed late Early Triassic volcanic rocks of the Koipato Group overlie deformed rocks of the Havallah sequence in the Tobin Range. Emplacement of the allochthon either occurred during the Sonoma orogeny or was unrelated to the orogeny and occurred in the Jurassic or Cretaceous (Ketner, 1984). The minimum age of allochthon emplacement in the mining district is constrained by truncation of the Golconda thrust by the Late Cretaceous monzogranite of Trenton Canyon (Fig. 5).

MESOZOIC TECTONICS AND MAGMATISM

Mesozoic structural and magmatic events in the Battle Mountain mining district included formation of a northwest-striking structural fabric, including faults and broad open folds, and emplacement of Late Cretaceous granodioritic to monzogranitic stocks at Trenton Canyon, Buckingham, and probably at the Buffalo Valley molybdenum prospect just to the west of the southwest corner of the mining district (Figs. 2, 6). Low-fluorine porphyry molybdenum systems developed with the Late Cretaceous stocks in the mining district.

Northwest-Striking Structural Zones

Northwest-striking structural zones are manifested by granodiorite porphyry dikes and larger elongated intrusive bodies, aeromagnetic lineaments, and regional alignment of mineralized areas. They generally are subtle features that trend N. 30° to 40° W., which become evident only after regional mapping and compilation, and are not as obvious as the north-striking fault zones described below. Three such northwest-striking zones have been delineated in the Battle Mountain mining district (Fig. 7). From northeast to southwest these zones are referred to as NW1, NW2, and NW3.

Zone NW1 is defined by the northwest orientation of the northern range front of Battle Mountain, the elongation and alignment of several major mineral systems, and a broad regional aeromagnetic gradient. Mineral systems along NW1, from southeast to northwest, include the northwest-elongated Paiute Canyon porphyry molybdenum-copper system (Fig. 2) (Ivosevic and Theodore, this volume), and gold-silver skarn and distal disseminated silver-gold deposits of the Copper Basin area, (Empire, Surprise, Labrador, Northern Lights and Bailey Day deposits) (Fig. 2), the weakly mineralized Elder Creek porphyry copper system (Theodore, this volume) (Fig. 2), distal disseminated silver-gold deposits of the Marigold Mine area (Fig. 2), and distal disseminated silver-gold deposits at the Lone Tree Mine. On a regional scale NW-1 coincides with a broad aeromagnetic gradient that extends from Edna Mountain on its northwest end through the northern Shoshone Mountains on its southeast end where it merges with the steep aeromagnetic gradient of the northern Nevada rift (see Hildenbrand and Kucks, 1988; Kirchoff-Stein, 1988). Further to the northwest, NW-1 and the corresponding aeromagnetic gradient aligns with the northwest-striking valley that separates the Santa Rosa Range from the Bloody Run Hill (see Stewart and Carlson, 1978), which may define a large northwest-striking structural zone that pre-dated Cenozoic magmatism in this area of north-central Nevada.

Zone NW2 is defined by the general NW-SE elongation of the monzogranite of Trenton Canyon and its alignment with the granodiorite of Copper Canyon and porphyry copper-related deposits associated with it (Figs. 2, 7). Several N. 30° W.-striking granodiorite porphyry dikes are present in the zone between the stocks at Trenton Canyon and Copper Canyon (Fig. 5) (Doebrich, 1995). Between zones NW2 and NW3 is a N. 30° W.-striking synclinal hingeline in rocks of LU-2 of the Havallah sequence that parallels the orientation of these structural zones (Doebrich, 1995).

Zone NW3 is characterized by a series of northwest-striking granodiorite porphyry and basaltic dikes, small granodiorite porphyry stocks and related altered and mineralized zones, and by a prominent linear positive aeromagnetic anomaly (Fig. 8). The Buffalo Valley gold deposit and associated northwest-striking dike swarm is found at the northwest end of this zone (Figs. 5, 7, 8). Continuing to the southeast from the Buffalo Valley gold deposit is a large granodiorite porphyry dike, and two small granodiorite porphyry stocks (Figs. 2, 5, 8). A northwest-striking aeromagnetic lineament is well defined and subparallels the large continuous granodiorite porphyry dike (Fig. 8). A recently identified basaltic dike (E. Struhsacker, written commun., 1994) is centered on the southeast end of the aeromagnetic lineament (Fig. 8). Note that the two granodiorite porphyry stocks and related alteration aureoles are along opposite margins of the lineament and associated with magnetic lows. The magnetic lows are indicative of magnetite-destructive alteration zones and may correspond to zones of pyritic alteration.

The Northwest-striking structural zones in the Battle Mountain mining district are apparently pre-Late Cretaceous in age based on the orientation and age of the monzogranite of Trenton Canyon. The northwest zones may coincide with shattered hingelines of large-scale folds associated with a regional Jurassic compressional event (Fig. 6) (Madrid, 1987; Madrid and Roberts, 1991). However, the district-scale antiformal hingeline that these authors and Roberts (1964) show through the mining district (based on bedding orientations of rocks of the Pennsylvanian and Permian Antler sequence) has a more northerly strike than the northwest-striking zones that our mapping has delineated (approximately N. 20° W. versus approximately N. 30° to 40° W.). The N. 20° W. hingeline probably is of a different age than the N. 30° to 40° W. fabric, and is either older and related to the emplacement of the Golconda allochthon or younger and related to extension along the N. 20° W.° striking northern Nevada rift.

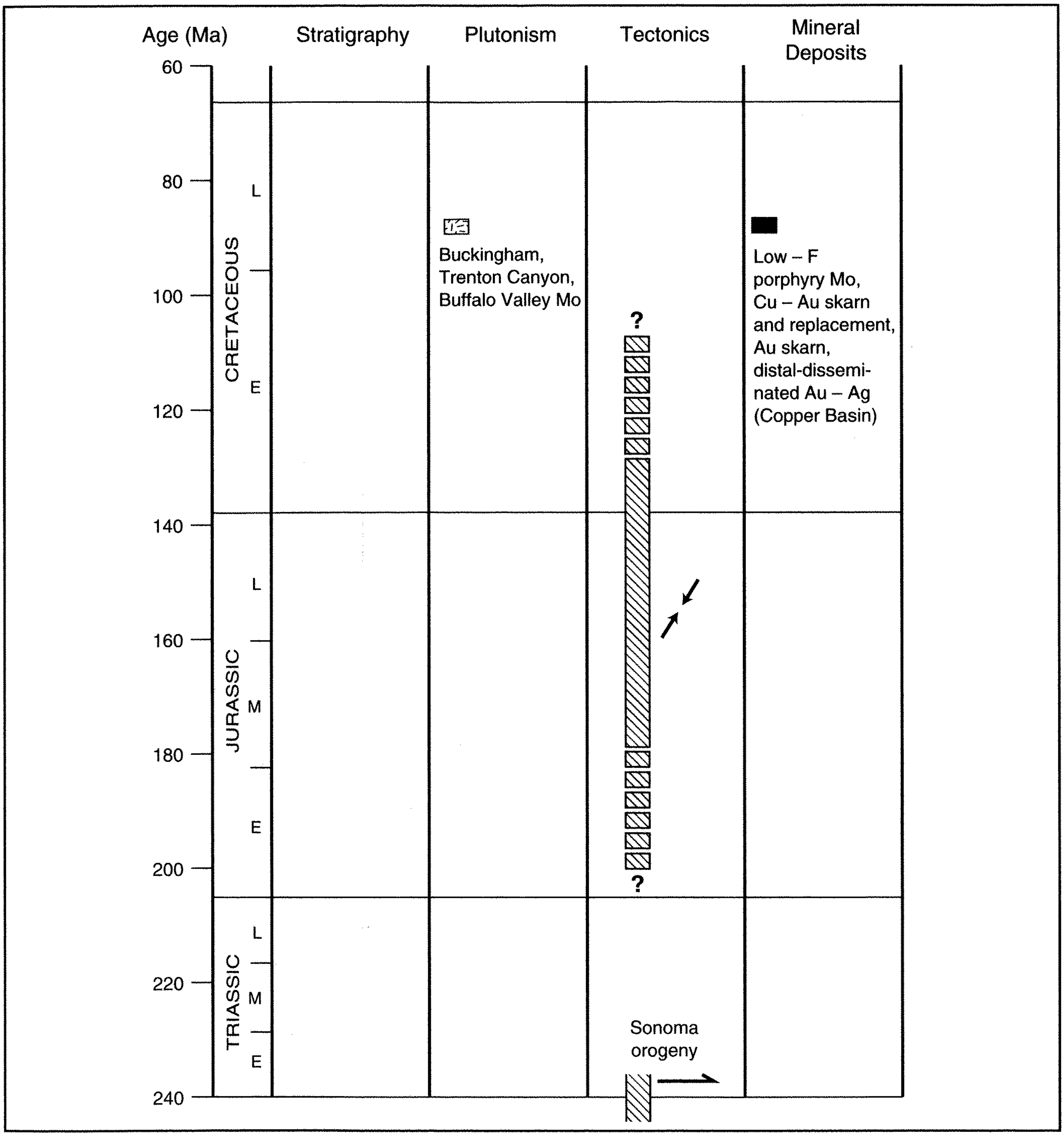


Figure 6–Chart summarizing Mesozoic geologic history of the Battle Mountain mining district, illustrating temporal relationships between plutonism, tectonic events, and development of mineral deposits. Arrows in tectonics column indicate general principle compressional directions.

Late Cretaceous Intrusions

Mesozoic magmatism in the Battle Mountain mining district consisted of emplacement of two, and possibly three, Late Cretaceous granodioritic to monzogranitic intrusive complexes that generated low-fluorine porphyry molybdenum mineralizing systems of varying intensity (Fig. 6). These include the Buckingham system in the Copper Basin area, the monzogranite of Trenton Canyon, and a weak mineral system at the Buffalo Valley molybdenum prospect just outside and extending into the southwest corner of the mining district (Figs. 2, 8).

The Buckingham stockwork molybdenum system (Fig. 2) is classified as a low-fluorine (or quartz monzonite) molybdenum system by Theodore and Menzie (1984). It contains one of the largest identified resources of molybdenum in the

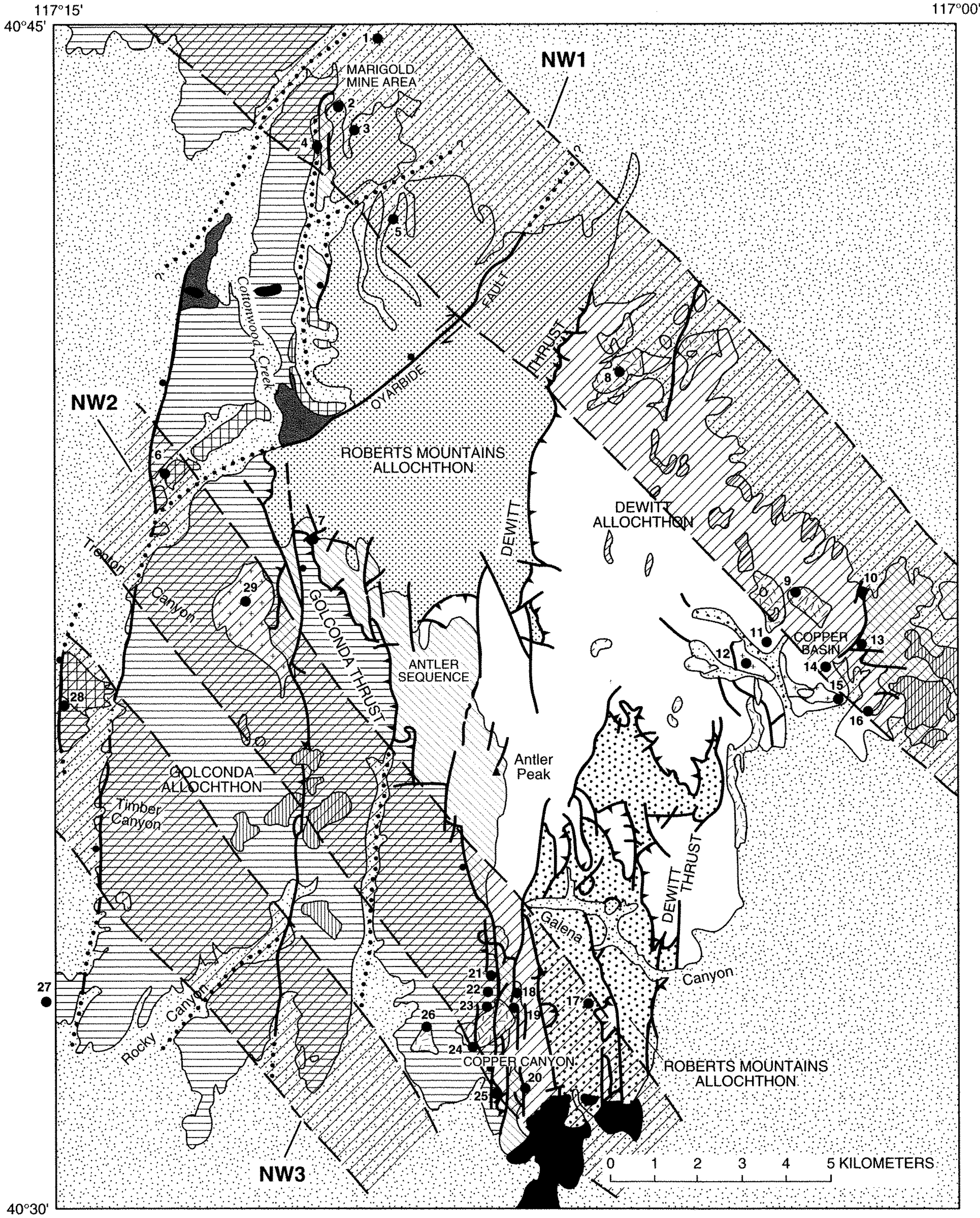
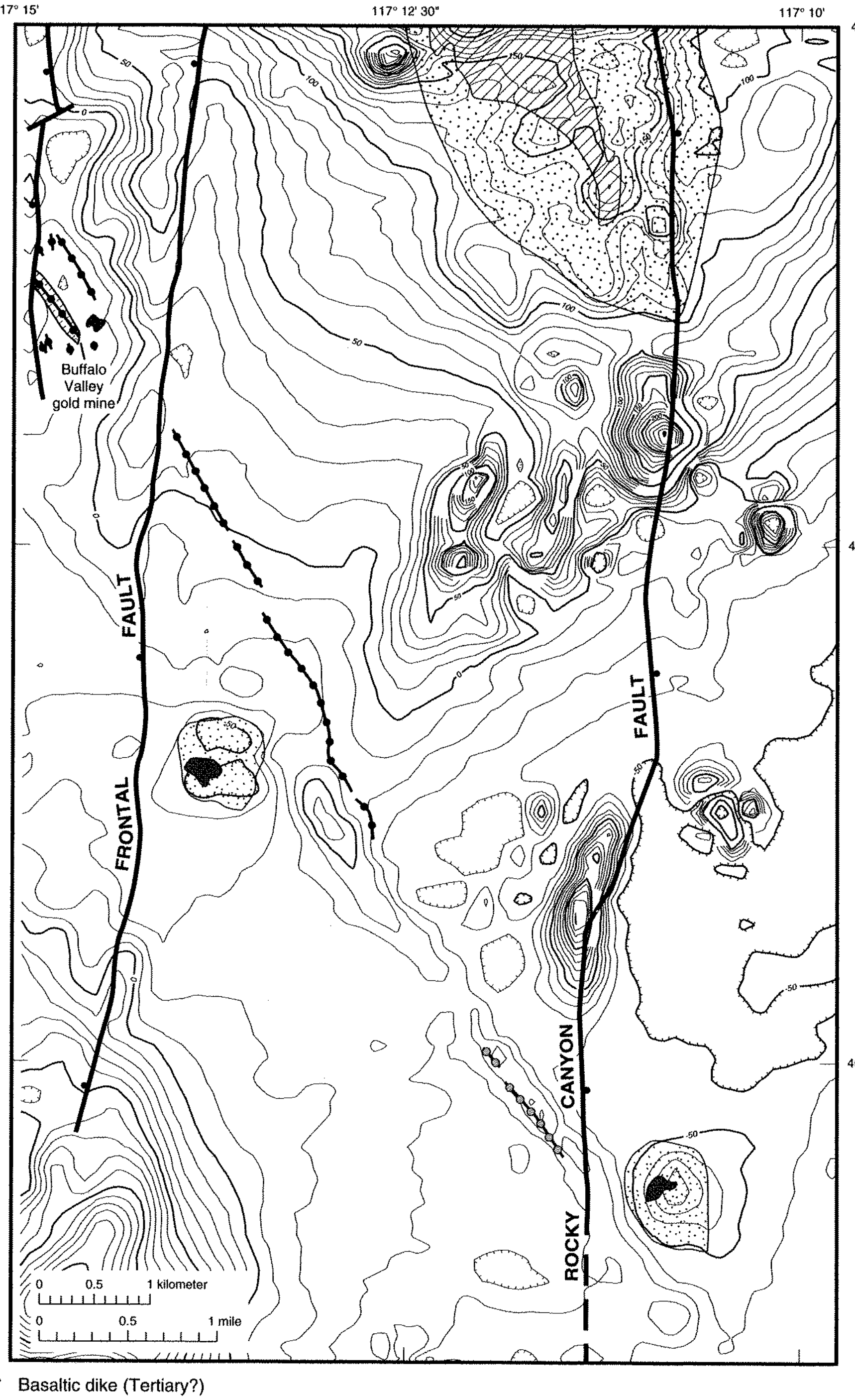


Figure 7—Northwest-striking fault zones in the Battle Mountain mining district. These zones are characterized by northwest-striking elongated plutons and granodiorite porphyry dikes, aeromagnetic lineaments, and regional alignment of mineralized areas. From north to south, these northwest-striking fault zones are referred to in the text as NW1, NW2 and NW3. Geology modified from Roberts (1964) and is the same as in Figure 2.



- Basaltic dike (Tertiary?)
- Granodiorite porphyry, locally showing alteration aureole (Oligocene or Eocene)
- Monzogranite of Trenton Canyon showing alteration aureole (Cretaceous)
- Alteration aureole surrounding specific intrusions
- Normal fault, ball on downdropped block
- Magnetic contours, showing adjusted and corrected total intensity magnetic field of the Earth in gammas (1 gamma = 1 nanotesla) relative to an arbitrary datum. Hachured to indicate closed areas of lower magnetic intensity. Contour intervals are 10 and 50 gammas.

Figure 8–Aeromagnetic map of the southwest part of the Battle Mountain mining district. Area of Figure corresponds to approximately the western half of the Antler Peak 7.5-minute quadrangle (Fig. 5). Superimposed on aeromagnetic map are selected faults and intrusive bodies. Note prominent northwest-striking positive lineament in southern half of area which is paralleled by granodiorite porphyry and basaltic dikes on the surface. Broad positive aeromagnetic responses in southwest corner and northeast corner of Figure are related to Buffalo Valley and Trenton Canyon porphyry molybdenum systems, respectively. See Doebrich (1995) for a more thorough discussion of the relation between aeromagnetics and geology in the Antler Peak 7.5-minute quadrangle.

United States, estimated at more than 1 billion tonnes of mineralized rock averaging approximately 0.06 weight percent molybdenite (MoS_2) and containing 100 million ounces of silver, and smaller amounts of tungsten, copper, and gold. Molybdenum mineralization is related to emplacement of an 86-Ma composite porphyry system that intruded and metamorphosed the surrounding Late Cambrian Harmony Formation to biotite hornfels (Theodore et al., 1992). Seven intrusive phases were emplaced as two stocks aligned in an east-west direction. The main Buckingham molybdenum deposit formed in association with five of the igneous phases in the two stocks. All five phases developed umbrella-shaped shells of molybdenite mineralization that drape over the stocks and locally overlap to produce grades of approximately 0.10 to 0.20 weight percent MoS_2. Approximately half of the Buckingham deposit is hosted by metamorphosed and intensely veined rocks of the Late Cambrian Harmony Formation and half by intrusive rocks (Theodore et al., 1992).

Porphyry copper deposits, in the copper zone which surrounds the central molybdenum zone, underwent supergene enrichment to create the Contention, Carissa, Copper Queen, Widow, and Sweet Marie copper deposits. Gold-silver skarn ore at the Surprise Mine and distal disseminated silver-gold ore associated with silica-pyrite alteration at the Empire Mine (approximately 1.5 million tonnes averaging 1.8 g Au/t) and at the Northern Lights Mine (approximately 390,000 tonnes averaging 1.6 g Au /t) may be associated genetically with the Buckingham system. There appears to be metal zoning from proximal copper-rich ores in the Contention Pit to the distal gold-silver-copper ores in the Surprise Mine. There is some suggestion, however, that there may have been a subsequent low-temperature epithermal overprint in some of the ores in the Empire Mine (McKee et al., 1993).

The monzogranite of Trenton Canyon, the largest exposed intrusive body in the Battle Mountain mining district, crops out as a northwest-striking elongated stock in the west-central part of the mining district (Fig. 2). The stock intrudes chert and calcareous siltstone and sandstone of LU-2 of the Havallah sequence above the Golconda thrust, as well as a fault-bounded conglomerate lens of the Battle Formation below the Golconda thrust. Primary biotite from the stock yielded K-Ar ages of about 90 Ma (Theodore et al., 1973; age recalculated using constants of Steiger and Jäger, 1977). The stock ranges in composition from granodiorite to monzogranite, is medium-grained, and largely equigranular, though generally more porphyritic in areas of stockwork veining. Formation of a large contact-metamorphic aureole (Fig. 8) was associated with emplacement of the stock. In the aureole, siliciclastic rocks have been recrystallized and calcareous rocks have been silicified and converted to a calc-silicate hornfels and, locally, to skarn. Large areas of the intrusion are hydrothermally altered (sericitized and argillized) and contain stockwork quartz veining. These altered zones are associated with a deep porphyry molybdenum-copper system of the quartz monzonite (Westra and Keith, 1981) or low-fluorine molybdenum type (Theodore and Menzie, 1984). Airborne magnetics over the area of emplacement shows broad closures of magnetic contours centered on the stock, covering an area much larger than the area of exposure and alteration (Fig. 8) (Doebrich, 1995). This may indicate the presence of a considerable amount of concealed Cretaceous igneous rock, altered wallrock, or both, underlying an area of as much as 25 km^2.

A subeconomic quartz monzonite porphyry molybdenum system is present at the Buffalo Valley prospect, immediately southwest of the mining district (Fig. 2) (Thomas, 1985). Based on the Late Cretaceous age of other monzogranitic porphyry systems in the Battle Mountain mining district and in the northern Fish Creek Mountains to the south (Miller and Silberman, 1977), the age of the Buffalo Valley molybdenum system is presumed to be Cretaceous. At the Buffalo Valley prospect, quartz monzonite has intruded chert, calcareous siltstone and sandstone, and limestone of LU-2 of the Havallah sequence. Wallrocks have been converted to biotite and calc-silicate hornfels and locally skarn. Stockwork quartz veining is associated with K-feldspar, sericitic, and propylitic alteration of intrusive rock and as much as 0.06 weight percent MoS_2 are reported (Thomas, 1985). As with the Buckingham and Trenton Canyon systems, airborne magnetics over the area of the Buffalo Valley prospect displays a broad positive response (Fig. 8) that probably corresponds to the subsurface extent of igneous rock or altered wallrock, or both.

CENOZOIC TECTONICS AND MAGMATISM

Tectonics and magmatism during the Cenozoic in the Battle Mountain mining district was vastly different from that in the Paleozoic and Mesozoic. The tectonic regime changed from one of largely compression to one of extension. Plutons became generally more intermediate in composition and were emplaced at higher levels, giving rise to a number of porphyry copper and molybdenum-copper systems with associated deposits of base-and precious metals. These types of deposits are especially concentrated in a 50-km-long north-striking zone that extends from the Lone Tree/Stonehouse deposits on the north to the Cove/McCoy deposits on the south. Cenozoic structural and magmatic events in the Battle Mountain mining district included development of north-striking normal fault zones, emplacement of late Eocene to early Oligocene granodioritic stocks and dikes throughout the region, and eruption of volcanic and volcaniclastic rock, ranging in age from early Oligocene to Pliocene (Figs. 2, 9). Periodic change in extension directions during the Cenozoic resulted in several generations of normal fault sets with variable orientations.

North-Striking Normal Fault Zones

North-striking (roughly N. 20° W. to N. 20° E.) normal faults in the Battle Mountain mining district are abundant and many predate late Eocene to early Oligocene dikes and stocks emplaced within them (Fig. 9). The preponderance of north-striking Tertiary normal faults and dikes probably results partly from these structures having inherited

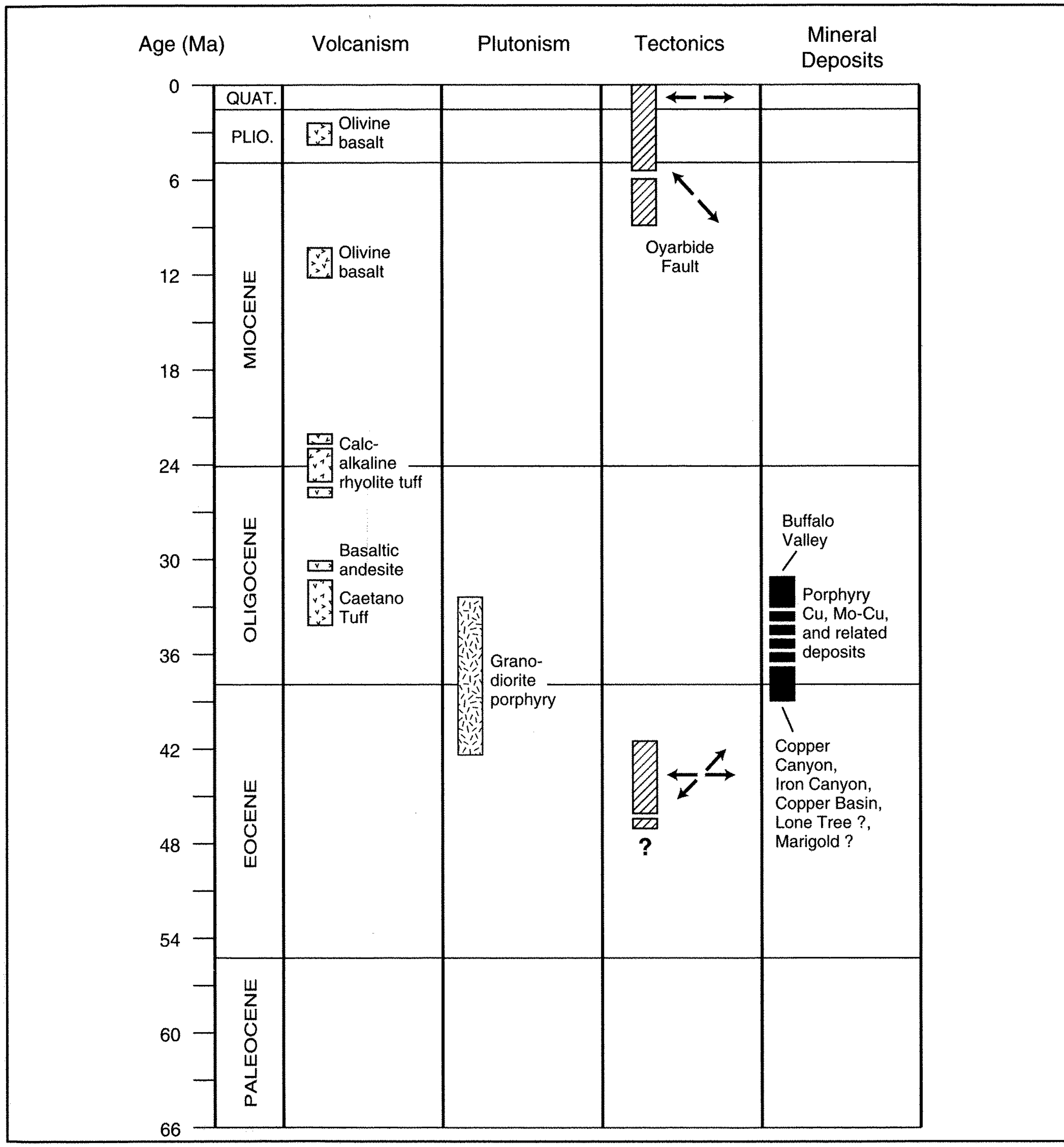


Figure 9—Chart summarizing Tertiary geologic history of the Battle Mountain mining district, illustrating temporal relationships between volcanism, plutonism, tectonic events, and development of mineral deposits. Arrows in tectonics column generally indicate least principle stress directions.

their orientations from the strong north-south structural grain throughout the early Paleozoic Roberts Mountains and late Paleozoic Golconda allochthons (Evans and Theodore, 1978; Theodore, 1991a, 1991b; Doebrich, 1994, 1995; T.G. Theodore, unpub. data, 1995). Though initiated in pre-late Eocene time, there is ample evidence that north-striking normal-fault displacement in the Battle Mountain mining district has continued periodically throughout the Cenozoic. Most zones, as a whole, change from a north-south to slightly west of north orientation along their southern parts to a north-northeast orientation along their northern parts (Fig. 10). Five normal-fault zones have been delineated in the mining district (Fig. 10). From west to east these zones are referred to as N1, N2, N3, N4, and N5.

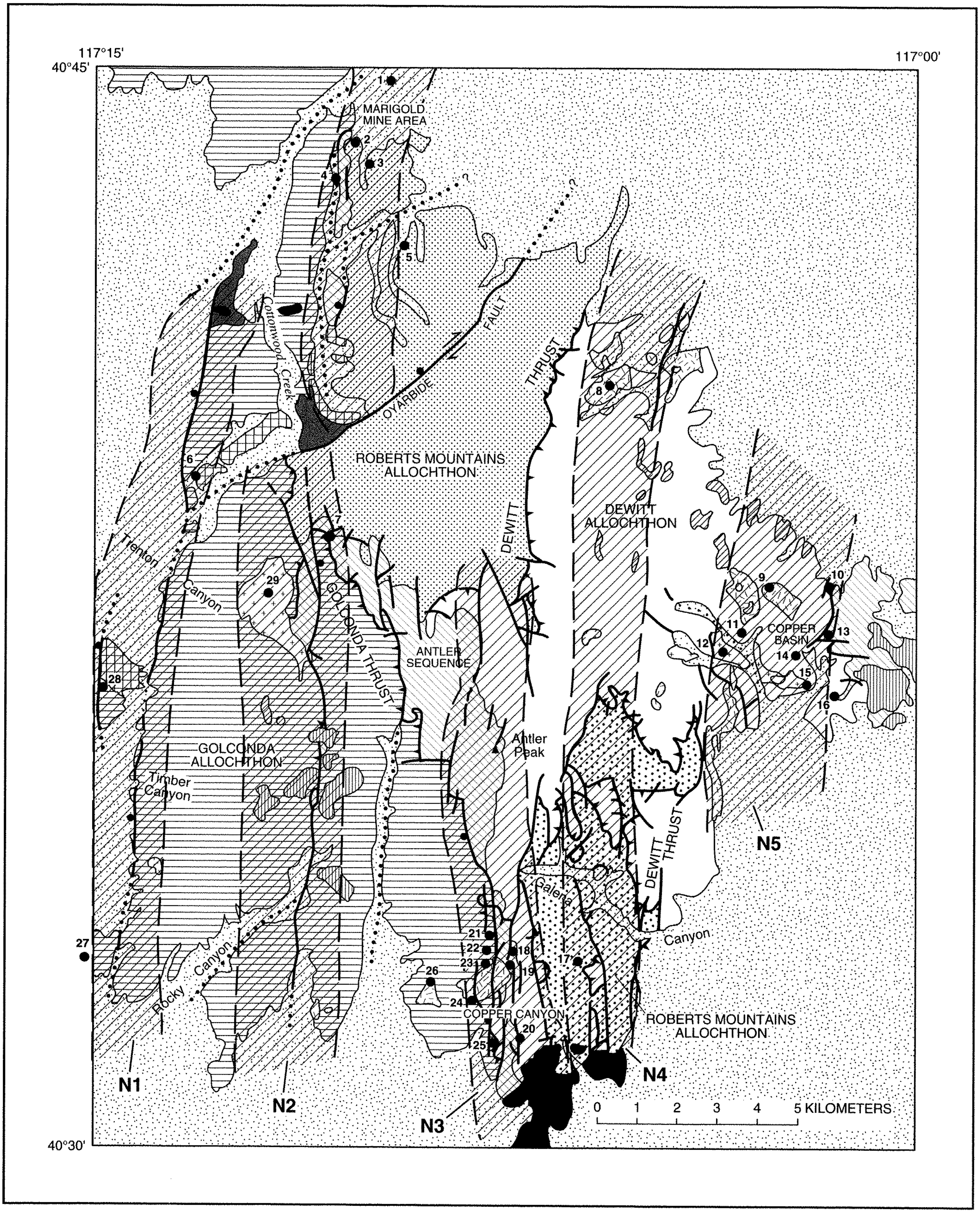


Figure 10—North-striking fault zones in the Battle Mountain mining district. These zones are characterized largely by closely spaced north-striking normal faults, granodiorite porphyry dikes, and locally by positive aeromagnetic lineaments. From west to east, these north-striking fault zones are referred to in the text as N1 to N5. Geology modified from Roberts (1964) and is the same as in Figure 2.

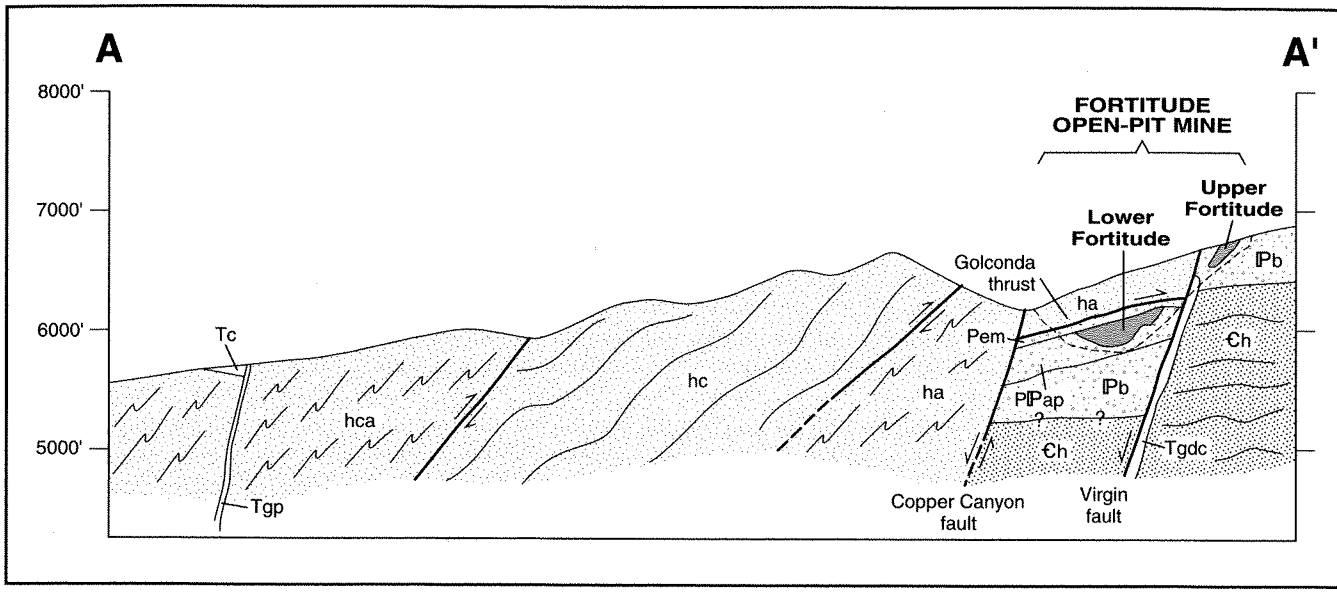


Figure 11—East-west cross section A-A′ (see Figure 5 for line of section) through the Fortitude Mine and area to the west, showing north-striking normal faults and granodiorite porphyry dikes (Tgp, Tgdc). Different stipple patterns differentiate: (1) Roberts Mountains allochthon (Late Cambrian Harmony Formation, Ꞓh), (2) Antler sequence of Roberts (1964) (IPb, PIPap, Pem), and (3) chert and argillite subunits (hc, hca, ha) of lithotectonic unit 1 of Murchey (1990) of the Mississippian, Pennsylvanian, and Permian Havallah sequence. Note downdropped early Oligocene Caetano Tuff (Tc) in hanging wall of westernmost normal fault which is intruded by a granodiorite porphyry dike.

Zone N1 coincides with the prominent frontal faults along the western margin of the mining district (Fig. 10). This zone contains the Buffalo Valley gold mine fault block (Figs. 5, 10) which is bounded on the west and east by west-dipping normal faults (Seedorff et al., 1991; Doebrich, 1995). The west-bounding fault has relatively shallow dips (40° W to 50° W) compared to most normal faults in the quadrangle. Quaternary displacement on this structure is indicated by a fault scarp in alluvium north of the Buffalo Valley Mine (Figs. 5, 10). Normal faults subparallel to the main range-front fault are present as much as 1 km to the east of the range-front. Some of these have been intruded by granodiorite porphyry dikes (Fig. 5; also see Doebrich, 1995). Though undated, these dikes are petrologically similar to late Eocene or early Oligocene granodiorite porphyry dikes elsewhere in the Battle Mountain mining district and are assumed to be of the same age. This would suggest that the north-striking faults intruded by these dikes formed in pre-late Eocene time, though they have locally been reactivated during subsequent extensional events in middle to late Tertiary and Quaternary time.

Zone N2 coincides with the Rocky Canyon fault as defined by Doebrich (1995). The Rocky Canyon fault (Figs. 5, 8, 10) is one of a series of north-striking normal faults present in this zone, which appear to be steeply east-dipping, and which transect the western part of the Battle Mountain mining district, through the Antler Peak and North Peak 7.5-minute quadrangles (Doebrich, 1995; Theodore, 1991a). Uplifted, discontinuous, fault-bounded slivers of the Pennsylvanian and Permian Antler sequence (Battle Formation, Antler Peak Limestone, and Edna Mountain Formation) are in the footwall of the fault from near the headwaters of Rocky Canyon and northward (Fig. 5; also see Doebrich, 1995). A large fault-bounded wedge of the Battle Formation also is present in the footwall of an east-dipping normal fault immediately east of the monzogranite of Trenton Canyon (Figs. 5, 10). The Rocky Canyon fault locally is onlapped by outflow facies rock of the 34-Ma Caetano Tuff (Fig. 5) (Doebrich, 1995) indicating that the fault developed prior to about 34 Ma and has not had appreciable displacement since then. Zone N2 has been displaced by the late Miocene Oyarbide fault such that the northern end of the zone coincides with the Marigold Mine area (Fig. 10). At the Marigold Mine, east- and west-dipping, north-striking normal faults transect the area and display pre- and post-mineral displacement (Graney and McGibbon, 1991; Doebrich et al., 1996).

Zone N3 (Fig. 10) coincides with the Virgin fault and other west-dipping normal faults in the Copper Canyon area and northward (Figs. 5, 10; see also Theodore and Blake, 1975; Doebrich, 1994, 1995). Locally these faults have breccia zones, as wide as 75 m, displaying evidence of repeated displacements, perhaps over a relatively long time (Theodore and Blake, 1975). In the Copper Canyon area, a pre-late Eocene age for initial displacement on the Virgin fault is documented from the 38-Ma age determination on the granodiorite of

Copper Canyon, a dike of which emanates northward along the fault in the vicinity of the Fortitude Mine (Fig. 11) (Theodore et al., 1973). The upper and lower ore zones at the Fortitude Mine (Fig. 11) formed in place during, or shortly after, emplacement of the dike along the Virgin fault and do not represent a single ore zone that was subsequently displaced by the Virgin fault. The stratigraphic throw on the Virgin fault is estimated to be about 300 m (Wotruba et al., 1986). Other west-dipping normal faults in, and adjacent to, zone N3 show evidence of later displacement than the Virgin fault. The Copper Canyon fault (Fig. 11) is a post-mineral normal fault that displaces the granodiorite of Copper Canyon (Wotruba et al., 1988). To the west of Copper Canyon is a north-striking normal fault that may be a splay or southern extension of a normal fault that underlies the Willow Creek drainage (Fig. 5). This fault is expressed on the surface by an altered granodiorite porphyry dike that has intruded it (Fig. 5). Exposures of the early Oligocene Caetano Tuff crop out in the hanging wall of the fault (Fig. 11). Erosional remnants of the Caetano Tuff, and the late Eocene erosional surface upon which it was deposited, are exposed on ridge tops on opposite sides of Willow Creek (Fig. 5; see also Doebrich, 1995) and indicate about 300 m of normal displacement on this fault since about 34 Ma.

Zone N4 is a 1- to 2-kilometer-wide zone of closely spaced north-striking normal faults and granodiorite porphyry dikes and stocks that extends from the Philadelphia Canyon area on the south to the Elder Creek area on the north (Figs. 10, 12). Normal faults are both steeply west and east dipping in this zone. The Iron Canyon gold deposit (Fig. 2, Table 1) (Doebrich et al., 1996) is located near the south end of this zone (Fig. 12) and consists of oxide and sulfide ore associated with a 39-Ma granodiorite porphyry dike that intrudes chert and argillite of the Scott Canyon Formation (Doebrich, 1994). Zone N4 coincides with a north-striking positive aeromagnetic lineament (Battle Mountain Exploration Co., unpub. data, 1995), that is most prominent along the southern half of the zone. Reduced expression of this lineament to the north may result from the effects of the intrusive complexes at Buckingham and Elder Creek, both of which have prominent positive aeromagnetic responses, particularly around the margins of the stocks. It is not clear from the surface geology what may be responsible for this aeromagnetic lineament. Pyrrhotite-bearing rock or magnetite-bearing mafic intrusive rock at depth along this zone could be responsible for the aeromagnetic response.

Zone N5 transects the Copper Basin area and is the easternmost of the north-striking normal-fault zones in the Battle Mountain mining district (Fig. 10). This zone is characterized by large N. 10° W.- to N. 10° E.-striking dike-like bodies and small plugs of Oligocene granodiorite porphyry (also referred to as latite porphyry by Loucks and Johnson, 1992) that extend from the mouth of Little Cottonwood Canyon, north-northeast to the range front (Fig. 10). Primary hornblende from granodiorite porphyry from this zone yielded a 35.4±1.1-Ma age by potassium-argon method (McKee, 1992). The zone also contains north- and north-northeast-striking normal faults (e.g., the Copper King fault) that juxtapose the Pennsylvanian and Permian Antler sequence with the Late Cambrian Harmony Formation (Theodore et al., 1992).

Tertiary Intrusive Rocks and Mineral Deposits

All dated Tertiary intrusive rocks in the Battle Mountain mining district are late Eocene to early Oligocene in age (41 to 31 Ma) and mostly monzogranitic to granodioritic in composition (Fig. 9) (Theodore et al., 1973; McKee, 1992; Garside et al., 1993; Doebrich, 1995; E.H. McKee, unpub. data, 1995). Although Tertiary intrusive rocks are scattered throughout the mining district as small stocks and dikes, the main exposed Tertiary intrusive centers are in the Copper Canyon, Copper Basin, Elder Creek and Buffalo Valley gold mine areas (Fig. 2). Associated with each of these intrusive centers are porphyry-style (Cu-Au and (or) Mo-Cu) alteration assemblages, mineralized zones, and related base- and precious-metal deposits.

The Copper Canyon area has historically been the most productive area in the Battle Mountain mining district, having produced about 97,520 tonnes (215 million pounds) of Cu, 78 tonnes (2.5 million oz) Au, and 467 tonnes (15 million oz) Ag since 1967 (Doebrich et al., 1996). All deposits in the Copper Canyon area are related to the 38-Ma granodiorite of Copper Canyon and the hydrothermal system that evolved with its emplacement, and most ores are hosted in calcareous rocks of the Antler sequence. Concentric metal zonation surrounding the stock was first documented by Roberts and Arnold (1965). Porphyry copper and copper-gold skarn deposits are present proximal to the intrusive center, gold-silver skarn and replacement deposits are present in a zone outward from these, and lead-zinc-silver skarn, replacement and vein deposits are present in a distal zone. Copper and copper-gold deposits include the upper levels of the old Copper Canyon Mine (Roberts and Arnold, 1965), the West Copper deposit (Theodore and Blake, 1978), and the East Copper deposit (Fig. 2, Table 1) (Theodore and Blake, 1975). Gold-silver deposits include the upper and lower ore zones of the Fortitude deposit (Wotruba et al., 1988; Myers, 1994; Doebrich et al., 1996), the Tomboy-Minnie deposits (Theodore et al., 1990), the Midas Pit, and the Phoenix deposit (Fig. 2, Table 1) (Doebrich et al., 1996). Lead-zinc-silver deposits include the mines and prospects in the Galena Canyon area and a deposit in the lower levels of the old Copper Canyon mine (Roberts and Arnold, 1965). Lead-zinc skarn and replacement ore was also present in the more distal parts of the Fortitude and Tomboy-Minnie gold-silver skarn deposits. The Reona and the Sunshine gold deposits, west of Copper Canyon (Fig. 2), are different from all other deposits at Copper Canyon. These deposits consist of quartz-pyrite stockwork veins and are partially hosted by the granodiorite of Copper Canyon and (or) sheared and altered contact zones between the stock and chert of the Havallah sequence (Doebrich et al., 1996).

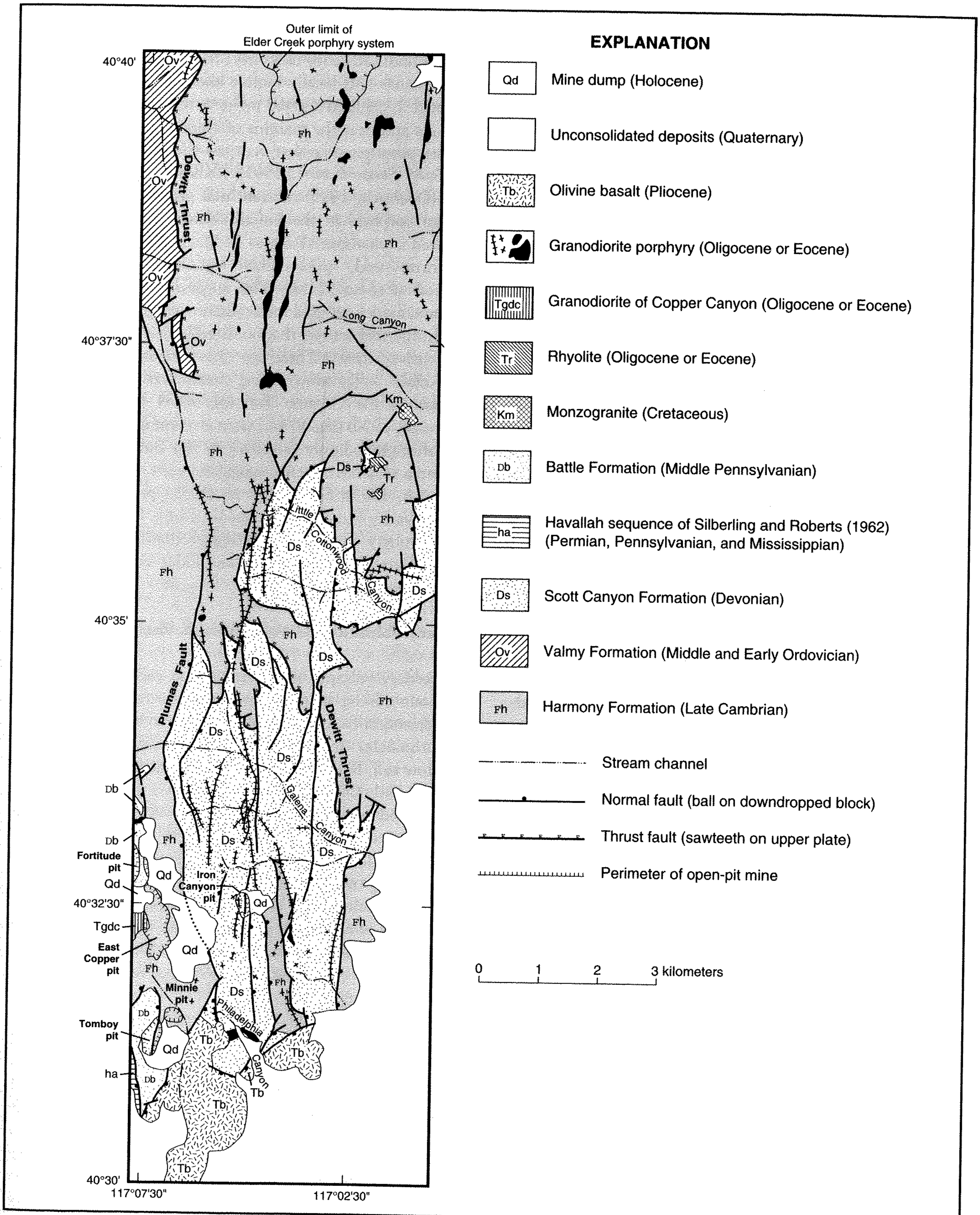


Figure 12—Generalized geologic map of an area in the eastern part of the Battle Mountain mining district, from the Philadelphia Canyon area on the south to the area of the Elder Creek porphyry system on the north, and largely coinciding with normal fault zone N4 of Figure 10. Note the concentration of closely spaced north-striking normal faults and granodiorite porphyry dikes and stocks along this zone. Geology modified from Doebrich (1994) and Theodore (1994).

The Copper Basin area has produced considerable amounts of copper, gold, and silver from supergene-enriched porphyry copper, skarn, replacement, and distal disseminated deposits, all of which are hosted in calcareous rocks of the Late Cambrian Harmony Formation and (or) Middle Pennsylvanian Battle Formation. The proximity of the Late Cretaceous Buckingham stockwork molybdenum system (Theodore et al., 1992), the early Oligocene Paiute Canyon Mo-Cu porphyry system (Ivosevic and Theodore, this volume), and other Tertiary dikes and stocks in the area (Fig. 2), makes it difficult to establish, with certainty, a direct relationship between deposits and mineral systems from which they were derived. Gold skarn ore at the Surprise Mine and distal disseminated silver-gold ore associated with silica-pyrite alteration at the Empire Mine may be related genetically with the Late Cretaceous Buckingham stockwork molybdenum system. There is some suggestion, however, that there was a subsequent low-temperature epithermal overprint in some of the ores in the Empire Mine (McKee et al., 1993). Gold-silver skarn at the Labrador Mine apparently is associated with late Eocene or early Oligocene porphyritic leucogranite of the Paiute Canyon porphyry Mo-Cu system (Fig. 2) (Ivosevic and Theodore, this volume). The Paiute Canyon system consists of four 38- to 39-Ma intrusive bodies (McKee, 1992), aligned along a N. 40° to 45° W. trend, and emplaced into the Harmony Formation (Fig. 2). A broad thermal metamorphic aureole contains biotite and calc-silicate hornfels and disseminated epigenetic pyrite. Propylitic and potassic alteration assemblages, quartz stockwork veining, and intrusive breccia bodies are localized in and marginal to intrusive stocks. Metal zonation in the porphyry system consists of a low-grade molybdenum-copper zone near the intrusive center of the system, surrounded by a gold-silver zone, and then a more distal lead-zinc zone (Ivosevic and Theodore, this volume).

The Elder Creek area (Fig. 2) contains a 5-km-wide porphyry copper system that is genetically related to a cluster of approximately 37-Ma porphyritic monzogranite intrusions that are potassically altered and emplaced into the Harmony Formation (see Theodore, this volume). Polymetallic veins and mineralized faults in the area have been exploited for their copper, lead, silver, and gold, during the late 1800s and early 1900s (Roberts and Arnold, 1965). A broad area of pyritic alteration surrounds the system, and a zone of quartz stockwork veining generally coincides with the areas of porphyritic monzogranite and potassic alteration (Theodore, 1994). Silver:gold weight ratios from samples in the Elder Creek porphyry copper system appear to vary systematically across the system, showing a dramatic increase in the silver:gold ratio toward the margin of the system (Theodore, this volume).

The Buffalo Valley gold mine area is in a normal-fault-bounded block on the western margin of the Battle Mountain mining district (Figs. 2, 5). The area contains a swarm of northwest-striking granodioritic porphyry dikes and small plugs that intrude rocks of the Havallah sequence. Altered and mineralized zones are restricted to more reactive calcareous rocks of the Havallah sequence that make up the southern part of the block (Doebrich, 1995). The deposit is in an aureole of contact-metamorphosed and locally metasomatized rocks. Non-calcareous rocks have been altered to biotite hornfels and calcareous units have been converted to calc-silicate hornfels and locally marble and skarn. Gold was concentrated in oxidized sheeted pyrite veinlets in steeply dipping fractures and near the margins of a potassically altered granodiorite porphyry dike that occupies the long axis of the pit (Fig. 5, 8) (Seedorff et al., 1991). Radiometric age determinations (Doebrich, 1995) indicate that granodiorite and granodiorite porphyry in the Buffalo Valley gold mine area was emplaced from about 37 Ma to 34 Ma, whereas hydrothermal alteration, and, presumably associated mineralization occurred at about 32 Ma. This suggests that potassic alteration and associated gold mineralization represent a late phase of hydrothermal activity that occurred long after initial phases of intrusive activity. These age determinations indicate that the Buffalo Valley mineralizing system was coeval with the eruption of the Caetano Tuff (31 to 34 Ma; McKee and Silberman, 1970) (Fig. 9) and trace element geochemistry suggests that granodiorite porphyry in the Buffalo Valley gold mine area may have been comagmatic with the Caetano Tuff (Doebrich, 1995). Seedorff et al. (1991) proposed that the Buffalo Valley Mine area represents a high level of exposure of a porphyry copper system, higher than that exposed at Copper Canyon, Copper Basin, and Elder Creek.

Tertiary Volcanic And Volcaniclastic Rocks

Tertiary volcanic and volcaniclastic rocks in the Battle Mountain mining district were erupted during at least five separate episodes, from the early Oligocene to the Pliocene (Fig. 9). Lithologies include lithic- and crystal-rich rhyolitic ash-flow tuff, basaltic andesite, and olivine basalt.

The Early Oligocene Caetano Tuff is a rhyolitic ash-flow tuff exposed as a ridge-capping and cliff-forming unit in the southwest and extreme eastern parts of the mining district (Fig. 2). In all places, the Caetano Tuff lies with angular unconformity on Paleozoic rocks. Its dips are generally shallow and it locally forms broad bowl-shaped features. Biotite from the Caetano Tuff at Elephant Head in the eastern part of the Battle Mountain mining district yielded a K-Ar age of 35 Ma (McKee and Silberman, 1970; age recalculated using constant of Steiger and Jäger, 1977). Lower parts of the Caetano Tuff consist of nonwelded to slightly welded lithic tuff containing clasts of Paleozoic rock fragments and pumice fragments. More commonly, exposures consist of densely welded crystal tuff with vitreous quartz phenocrysts, flattened pumice fragments and some lithic clasts. The erosion surface upon which deposition of the Caetano Tuff occurred is extremely important from a metallogenic standpoint because it provides a datum below which exploration efforts may be focused in the search for targets near the late Eocene and early Oligocene paleosurface.

Oligocene olivine-augite basaltic andesite is found as thin flows at two localities in the North Peak quadrangle in the northwest part of the mining district (Fig. 2) (Theodore, 1991a). At one locality, basaltic andesite lies unconformably on rocks of the Havallah sequence, whereas at the other locality, basaltic andesite is interbedded with Tertiary gravel (Fig. 2). Two samples of basaltic andesite yielded whole-rock potassium-argon ages of about 31.3±0.8 and 31.4±1.0 Ma (E.H. McKee, unpub. data, 1995).

Oligocene or Miocene calc-alkaline rhyolite tuff is exposed in the Buffalo Valley Mine area, in the Trout Creek area of the North Peak quadrangle, and in the north highwall of the 8 South pit at the Marigold Mine, and has been encountered at depth within Tertiary sedimentary deposits in an area about 1.5 km west of the Lone Tree Mine (Theodore, 1991a; Bloomstein et al., 1993; Doebrich, 1995; Doebrich et al., 1996). In the Trout Creek area, rhyolite tuff lies unconformably on rocks of the Valmy Formation and of the Havallah sequence (Theodore, 1991a). At the 8 South Pit, rhyolite tuff is partly in contact with mineralized rocks of the Edna Mountain Formation and partly interbedded with Tertiary gravel (Doebrich et al., 1996). At the Buffalo Valley Mine area and in the area west of the Lone Tree Mine, rhyolite tuff overlies and is interbedded with Tertiary gravel. At the Buffalo Valley Mine area, rhyolite tuff is draped over Tertiary paleotopography (Doebrich, 1995). West of the Lone Tree Mine, rhyolite tuff is covered by 70 to 85 m of Tertiary gravel and Quaternary sediments (Bloomstein et al., 1993). Potassium-argon age determinations on this rhyolite tuff yielded ages of 25.5 ± 0.8 Ma (whole-rock, Trout Creek area) and 22.9 ± 0.7 Ma (biotite, 8 South pit) (Doebrich et al., 1996). On the basis of age and chemistry, the Oligocene or Miocene calc-alkaline rhyolite tuff in the Battle Mountain mining district is correlated with the Bates Mountain Tuff (McKee, 1968; Stewart and McKee, 1968; Stewart and McKee, 1977; McKee, 1995). If this correlation is correct, these occurrences in the Battle Mountain mining district represent the northernmost known extent of the Bates Mountain Tuff.

Miocene olivine basalt crops out in the area of Treaty Hill, north of the Humboldt River, along the northern margin of the Valmy quadrangle (Theodore, 1991b), at the extreme northern end of the Battle Mountain mining district. At Treaty Hill, olivine basalt unconformably overlies rocks of the Ordovician Valmy Formation and rocks of the Permian Edna Mountain Formation. A whole-rock potassium-argon age of 12.0±0.4 Ma (E.H. McKee, unpub. data, 1995) for the olivine basalt at Treaty Hill is as much as 1 m.y. younger than the youngest age reported to date for basaltic lavas close to and presumably related to the northern Nevada rift (Struhsacker, 1980; Zoback et al., 1994). Two approximately 12-Ma basaltic rock samples from the Sheep Creek Range, several kilometers east of the rift, are reported by Stewart and McKee (1977).

The youngest dated volcanic rock unit in the Battle Mountain mining district is Pliocene olivine basalt that crops out along the southern margin of the district. Southeast of Copper Canyon (Fig. 2), Pliocene olivine basalt unconformably overlies rocks of the Harmony Formation and Scott Canyon Formation, whereas south of Rocky Canyon (Fig. 5) isolated outcrops of basalt unconformably overlie rocks of the Havallah sequence. This basalt unit yielded whole-rock potassium-argon ages of 2.8 Ma (south of Rocky Canyon; Doebrich, 1995) and 3.3 Ma (southeast of Copper Canyon; McKee, 1992).

Northeast-Striking Normal Faults

A change in the regional least principal stress direction to an orientation of about S. 50° to 65° E., in the late Miocene, was responsible for development of the Oyarbide fault (Fig. 2) and other northeast-striking post-mineral normal faults in the Battle Mountain mining district (Fig. 9). The Oyarbide fault parallels many other faults in the region related to development of the prominent Midas geomorphic trough which cuts and postdates the approximately 14-Ma northern Nevada rift north of the Battle Mountain mining district. Additional post-rift faults having roughly the same strike as the Midas trough (approximately N. 65° E.) are widespread throughout a 240-km-long segment of the rift that extends from the Midas trough on the north to the Cortez fault, along the northwest flank of Cortez Mountains, on the south (Zoback et al., 1994, Fig. 3). The Battle Mountain mining district is located approximately in the center of this segment of the crust showing southeast-northwest extension sometime after development of the 17- to 14-Ma rift.

The Oyarbide fault, located in the northwest part of the mining district (Fig. 2) (Theodore, 1991a) is the most prominent of the late Miocene northeast-striking, post-mineral normal faults in the district. The fault has a vertical component of offset of approximately 700 m with its northwestern block down, producing a very prominent geomorphic expression, with lower elevation and much more subdued topography in the downdropped block. The Oyarbide fault also displays some right-lateral component of displacement.

Quaternary Normal Faults

The regional least principal stress direction must have returned to an east to N. 80° W. orientation in the mining district during the Quaternary to account for north- to N. 10° E. -striking range-front faults primarily along the west side of the mining district (Fig. 2). Fault scarps displacing Tertiary gravel and Quaternary fanglomerate deposits locally can be traced for more than 2 kilometers (Theodore, 1991a; Doebrich, 1995).

LOCALIZATION OF MINERAL SYSTEMS AND LEVELS OF EXPOSURE

Structural Intersections

Three northwest-striking and five north-striking fault zones have been delineated in the Battle Mountain mining district and described above (Figs. 7, 10). Most major loci of Tertiary metallization in the mining district are present in the broad areas where these zones intersect (Fig. 13), suggesting that these structural intersections influenced the positioning of magmatic systems and associated hydrothermal activity. Both sets of fault zones were active and developed over a relatively short time span in the Tertiary from some time prior to 40 Ma to approximately 31 Ma. Their northwest- and north-striking orientations are believed to have been inherited from Mesozoic and Paleozoic structural fabric, respectively, as described above.

Table 2 summarizes important known mineral systems and deposits as well as important ore-controlling and anomalous features in each of the intersection zones shown on Figure 13. In addition to their presence within areas of regional structural intersection, the most important areas of the mining district with respect to Tertiary metal endowment (Copper Canyon, Lone Tree/Stonehouse, and Marigold Mine areas) (Table 1) have several other common denominators. These are: (1) the presence of pre-late Eocene north-striking normal faults, (2) the presence (or suspected presence, see below) of late Eocene or early Oligocene magmatic-hydrothermal systems, (3) the presence of rocks of the Antler sequence as a receptive host, and (4) the presence of the Golconda thrust and the important tectonostratigraphic control that it has played in ponding and channeling ascending hydrothermal fluids.

The Role of Extension Direction

The presence of structural intersections, as described above, was a necessary but not sufficient condition for emplacement of magmatic and related hydrothermal systems. To maximize their influence on positioning of magmatic centers in the Battle Mountain mining district, these structural intersections must have experienced least principle stress conditions in directions perpendicular to the north- and northwest-striking structural zones during the late Eocene to early Oligocene magmatic event.

Significant east-west extension and its accompanying initial breakup of the crust during the Tertiary in this part of the Great Basin apparently began at some time prior to 40 Ma based on geologic relations in the Battle Mountain mining district (Fig. 9). If the least principal stress had been oriented roughly east-west at approximately 40 Ma, then emplacement of magmas of about this age along northwest-striking zones would have to be envisioned as being entirely controlled by the pre-Late Cretaceous zones of weakness that are possibly associated with shattered hingelines of Jurassic age (Madrid, 1987; Madrid and Roberts, 1991). In other words, the northwest-striking zones could be envisioned as having been reactivated tectonically and magmatically during the time when the bulk of the extension in the mining district was being accommodated by normal offsets along the north-south striking zones. A necessary corollary of this hypothesis would be that there also should be present some components of lateral offsets along the northwest-striking zones. Lack of piercing points makes this difficult if not impossible to prove.

Orientation of regional stress to accommodate synmineral faulting and igneous activity simultaneously along both these structural trends may have involved a regional least principal stress regime that fluctuated between an east direction and a N. 50° to 60° E. direction approximately between 40 Ma and 31 Ma (Fig. 9). Evidence that both north- and northwest-striking faults were under least principle stress conditions simultaneously is displayed by single continuous granodiorite porphyry dikes that have both north and northwest orientations. Examples of this are shown on Figure 5, with one locality between Willow Creek and the Fortitude Mine and another near the range front, southeast of the Buffalo Valley gold mine. It can also be argued that, rather than fluctuation of least principle stress directions, a constant least principal stress oriented roughly N. 70° to 75° E., would allow for simultaneous faulting along both structural trends. However, potential components of lateral offset along both north- and northwest-striking high-angle faults in the mining district would be maximized under these conditions, and data to verify such lateral offsets are extremely difficult to obtain, again, because of the absence of piercing points.

There is ample evidence that during this period between about 40 and 31 Ma, faulting and magmatism were nearly continuous. There are many places in the mining district where north-striking dikes, mostly Oligocene granodiorite porphyry, and faults cut late Eocene and early Oligocene intrusions that crop out in northwesterly striking zones and that are an integral component of the northwest-elongated plutons. One of these places is in the Bluff area of Copper Basin, where late Eocene and early Oligocene porphyritic monzogranite is cut by north-south striking Oligocene granodiorite dikes (Theodore et al., 1992; Theodore, 1994; Ivosevic and Theodore, this volume).

The Oyarbide Fault and Levels of Exposure

As discussed above, the late Miocene Oyarbide fault (Fig. 2) is a major northeast-striking, post-mineral fault (Midas trough-like fault) in the northwest part of the mining district that has a vertical component of offset of approximately 700 m with its northwestern block down. As many as fifteen gold deposits recently have been discovered in the downdropped block. These include the deposits at the Marigold and Lone Tree Mines. None of the deposits show clear-cut spatial ties to felsic or intermediate intrusions, yet many exhibit characteristics of distal disseminated silver-gold deposits (Cox, 1992), presumably related to a porphyry-copper environment. The relative abundance of gold, i.e., high gold:silver ratios, in these deposits, when compared to most distal disseminated silver-gold deposits (Cox and Singer, 1992), is believed to be a result of leaching of silver from these deposits during oxidation in the Tertiary. The distal disseminated deposits, north of the Oyarbide fault and including high-sulfidation and low-sulfidation alteration assemblages, distinguish the northern part of the mining district from the southern part of the district which contains seven porphyry

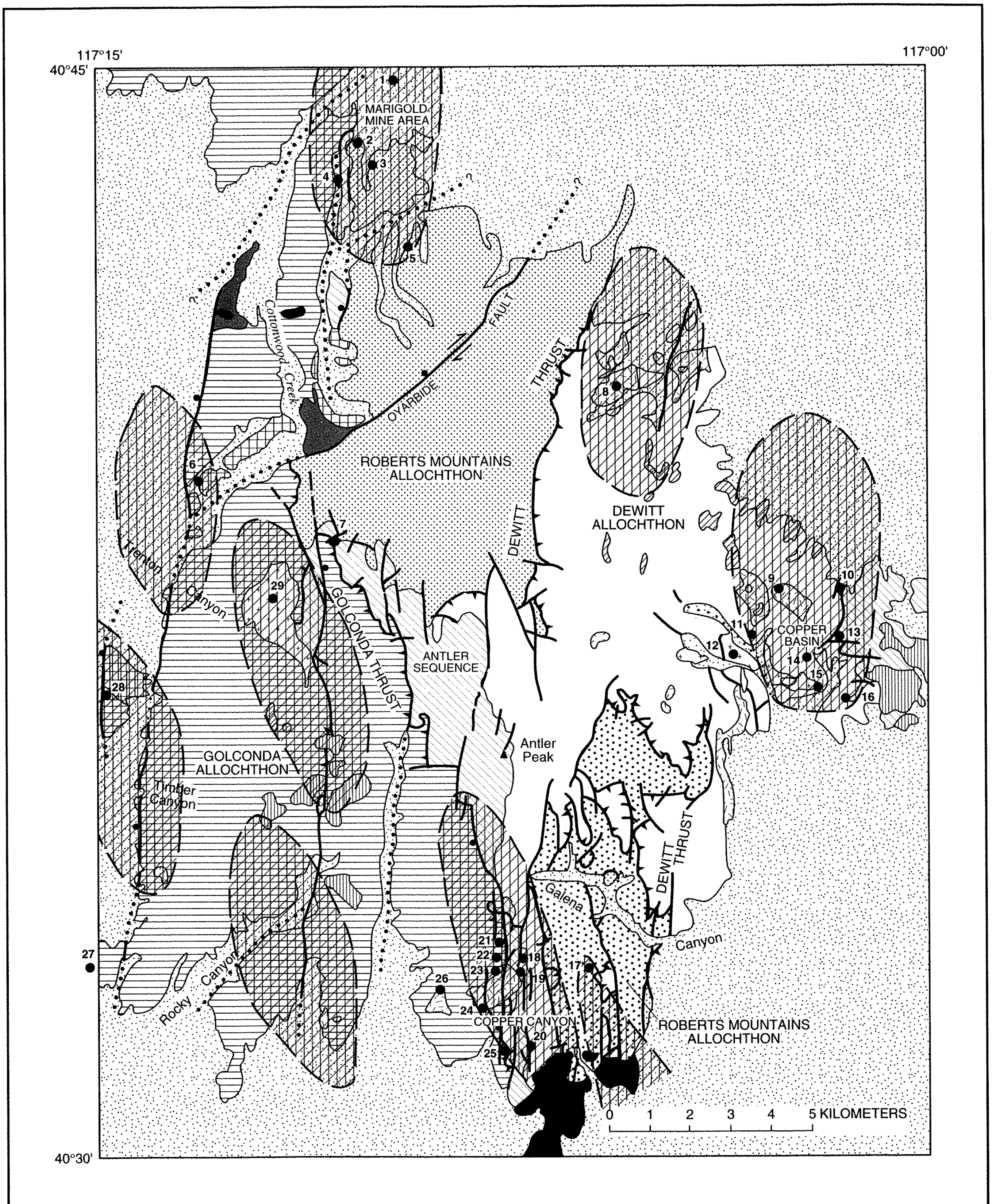


Figure 13–Broad areas of intersection of northwest- and north-striking fault zones in the Battle Mountain mining district as depicted in Figures 7 and 10, respectively. These areas coincide with major loci of Tertiary metallization in the mining district. See Table 1 for a summary of known mineral systems and ore deposits as well as important ore-controlling and anomalous features in these areas. Geology modified from Roberts (1964) and is the same as in Figure 2.

Table 2—Summary of known mineral systems and ore deposits as well as important ore-controlling and anomalous features in areas defined by the intersection of northwest- (rows, NW...) and north- (columns, N...) striking structural zones (Figs. 7, 10, 13) in the Battle Mountain mining district.

	N1	N2	N3	N4	N5
NW1	(This intersection not shown on (Figure 13) Lone Tree/Stonehouse gold deposits ? North-striking, west-dipping normal faults; Golconda thrust Antler sequence; calcareous rocks of LU-2 of Havallah sequence	Marigold Mine area (8 South, Top, East Hill/UNR, and Red Rock ore zones) North-striking, west-dipping normal faults; Golconda thrust Antler sequence; quartz arenite of Valmy Formation	No apparent intersection	Elder Creek porphyry copper system Porphyritic monzogranite (37 Ma)	Paiute Canyon porphyry Mo-Cu system Northwest alignment of intrusive bodies (leucogranite and monzogranite; 38-39 Ma) Calcareous rocks of Harmony Formation; Antler sequence
NW2	Section 11 gold prospect North-striking, west-dipping normal fault Calcareous rocks of LU-2 of Havallah sequence	Trenton Canyon gold deposit (just north of this area along Rocky Canyon fault zone) North-striking, east-dipping normal faults; Golconda thrust Valmy Formation; Battle Formation; calcareous rocks of LU-2 of Havallah sequence	Copper Canyon porphyry copper system Granodiorite porphyry (38 Ma) North-striking, west-dipping normal faults; Golconda thrust Antler sequence	Iron Canyon gold deposit Granodiorite porphyry dike (38 Ma) This intersection extends under alluvium in the southeast part of the mining district	Possible intersection south of district but not exposed
NW3	Buffalo Valley gold deposit (32 Ma) Northwest-striking granodiorite porphyry dikes (33-36 Ma) Calcareous rocks of LU-2 of Havallah sequence	Modoc Mine Granodiorite porphyry plugs and dikes (39 Ma) Calcareous rocks of LU-2 of Havallah sequence Positive aeromagnetic anomaly north of Modoc Mine (Fig. 8)	Possible intersection south of district but not exposed	Possible intersection south of district but not exposed	Possible intersection south of district but not exposed

copper or stockwork molybdenum systems (Copper Canyon, Paiute Canyon, Buckingham, Trenton Canyon (Mo–Cu), Buffalo Valley Mine (Cu–Au), Buffalo Valley prospect (Mo), and Elder Creek) (Fig. 14). One exception is the Trenton Canyon gold deposit of Santa Fe Pacific Gold's Trenton Canyon project (Fig. 14). Though it is south of the Oyarbide fault it is still probably related to an unexposed Tertiary porphyry copper-type mineral system based on a whole rock potassium argon age of 34.9 ± 1.0 Ma (E.H. McKee, unpub. data, 1995) from a sericitized and mineralized dike that partially bounds the deposit.

Sulfur and oxygen isotopic compositions of hydrothermal vein barite, that unequivocally is related to the gold mineralizing event, are tightly constrained and suggest a significant magmatic component in fluids associated with generation of the distal disseminated deposits in the Battle Mountain mining district (Howe et al., 1995). Barite from the 8 South, 8 North, and 5 North deposits at the Marigold Mine, and from the Valmy–Trout Creek deposit of Santa Fe Pacific Gold's Trenton Canyon project, is isotopically uniform, with most $\delta^{34}S$ values between 9 and 12 per mil and most $\delta^{18}O$ values between 7 and 12 per mil. In contrast, barite from the Top and East Hill zones at Marigold and from the Stonehouse deposit (the southern extension of the Lone Tree deposit), is isotopically lighter with $\delta^{34}S$ values between -0.7 to 1.3 per mil and $\delta^{18}O$ values between -1.4 to 3.1 per mil (Howe et al., 1995). These data and calculated $\delta^{18}O$ values of water in equilibrium with hydrothermal barite suggests that sulfur in barite in these deposits was derived from more than one magmatic or deep crustal source (Howe et al., 1995). Comparison of sulfur isotopic values of hydrothermal vein barite from the northern Battle Mountain mining district with vein barite from sediment-hosted gold deposits along the Carlin trend shows that hydrothermal barite from the two areas are distinctly different (Fig. 15). Sulfur in vein barite from gold deposits along the Carlin trend is isotopically much heavier and nearly identical to bedded barite found in the Paleozoic rocks of north-central Nevada (Fig. 15). This suggests that there was a much greater magmatic component in fluids associated with the distal disseminated silver–gold deposits of the northern Battle Mountain mining district than with gold deposits of the Carlin trend.

The distal disseminated silver–gold deposits north of the Oyarbide fault have many notable differences when compared to many deposits elsewhere previously categorized as distal disseminated silver–gold deposits (Cox, 1992; Cox and Singer, 1992). Among the differences are apparently high gold:silver ratios, absence of significant base metals, and a minor-element suite (Au, As, Ba, and Hg) suggestive of Carlin-type systems. These deposits, nonetheless, apparently have a genetic link to the late Eocene to early Oligocene magmatic environment. All deposits north of and in the hanging wall the Oyarbide fault have current levels of exposure that should be close to the tops of their respective mineralized systems, unlike the porphyry copper and porphyry molybdenum–copper systems in the footwall of the Oyarbide fault which have been unroofed.

SUMMARY AND CONCLUSIONS

The extraordinary metal endowment in the Battle Mountain mining district and the nature in which the district's ore deposits are regionally distributed is the result of a series of geotectonic and magmatic events that span the geologic time scale from the middle Paleozoic to the Neogene.

The Late Devonian to Early Mississippian Antler orogeny (Fig. 4) brought Cambrian to Devonian allochthonous rocks into the mining district. These rocks composed the Antler highlands which were eroded to form calcareous overlap assemblage deposits of the Antler sequence, the most important host for ore deposits in the Battle Mountain mining district. The Late Permian to Early Triassic Sonoma orogeny (Fig. 4) placed relatively non-reactive allochthonous rocks of the Havallah sequence structurally over calcareous rocks of the Antler sequence, along the regionally extensive Golconda thrust. This structural relationship later became the most important tectonostratigraphic control on the distribution of ore deposits in the mining district; ascending hydrothermal fluids were ponded below the Golconda thrust and the non-reactive rocks of the Havallah sequence and constrained to reactive rocks of the Antler sequence.

Compressional tectonism continued during the Mesozoic (Fig. 6). The resulting structural fabric was northwest-striking, in contrast to the strong north-striking fabric produced during Paleozoic tectonism. Individual northwest-striking structural zones in the mining district (Fig. 7) are believed to coincide with shattered hinge zones of broad regional Jurassic folds. Late Cretaceous granodioritic to monzogranitic plutonism in the mining district resulted in development of at least two and possibly three low-fluorine porphyry molybdenum stockwork deposits (Fig. 7).

Tectonism during the Cenozoic in the Battle Mountain mining district was vastly different from that in the Paleozoic and Mesozoic. The tectonic regime changed from one of largely compression to one of extension. North-striking normal faults began forming throughout the mining district sometime before the late Eocene, and were concentrated in distinct north-striking fault zones (Fig. 10). A major late Eocene to early Oligocene magmatic event (Fig. 9) affected the entire mining district and resulted in emplacement of numerous granodioritic to monzogranitic stocks, plugs, and dikes. Several late Eocene to early Oligocene intrusive centers developed porphyry copper or molybdenum-copper mineral systems that were responsible for the vast majority of precious-metal and base-metal endowment in the Battle Mountain mining district (Fig. 2, Table 1). Regional distribution of late Eocene to early Oligocene intrusive centers and associated hydrothermal activity was influenced by intersections of northwest- and north-striking fault zones (Fig. 13). Variably oriented least principle stress conditions contributed to emplacement of late Eocene to early Oligocene intrusive bodies into these structural intersections and may have involved periodic change (from east-west to N. 50° to 60° E.) of the regional least principle stress direction during a relatively short time interval (40 to 31 Ma).

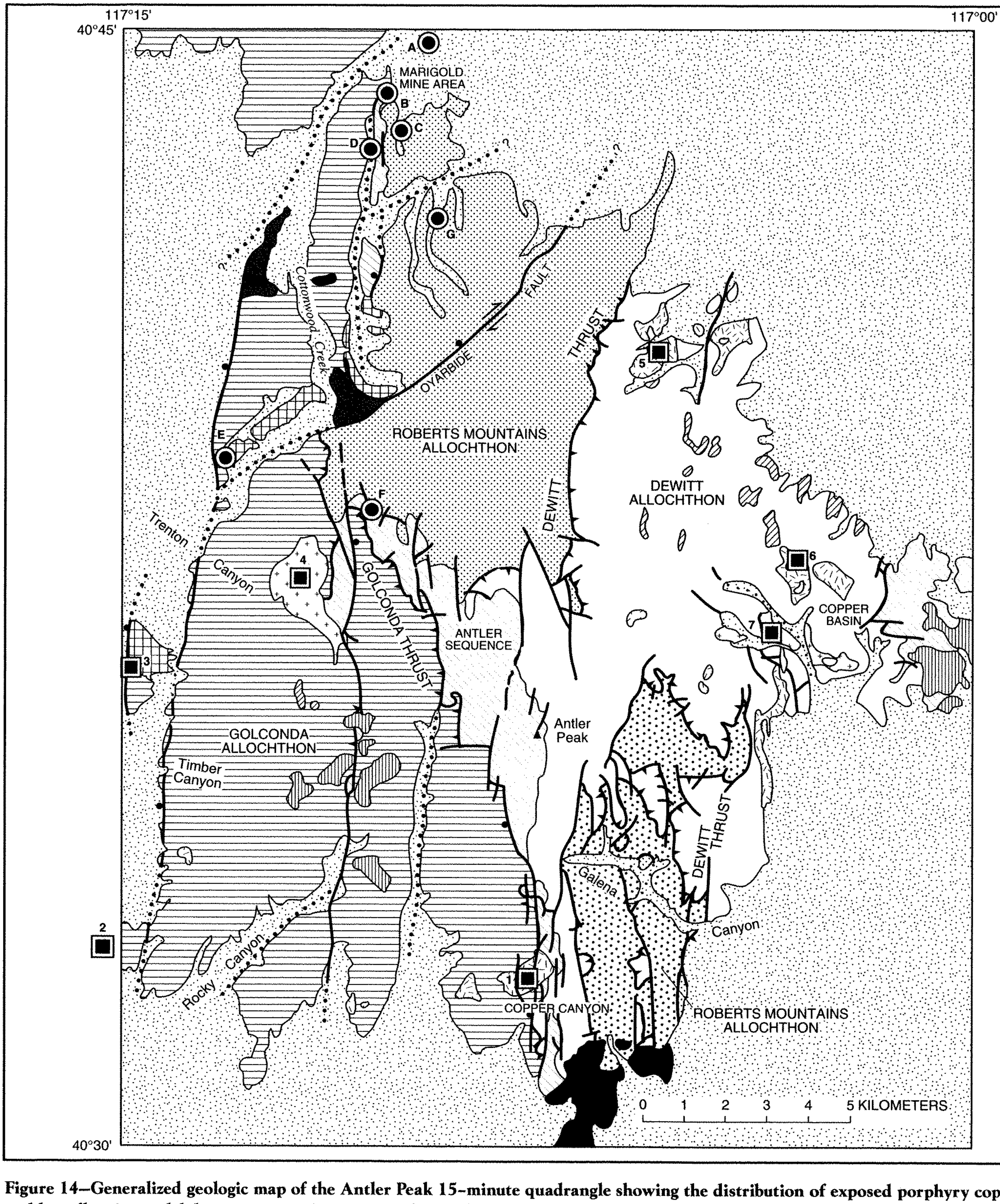
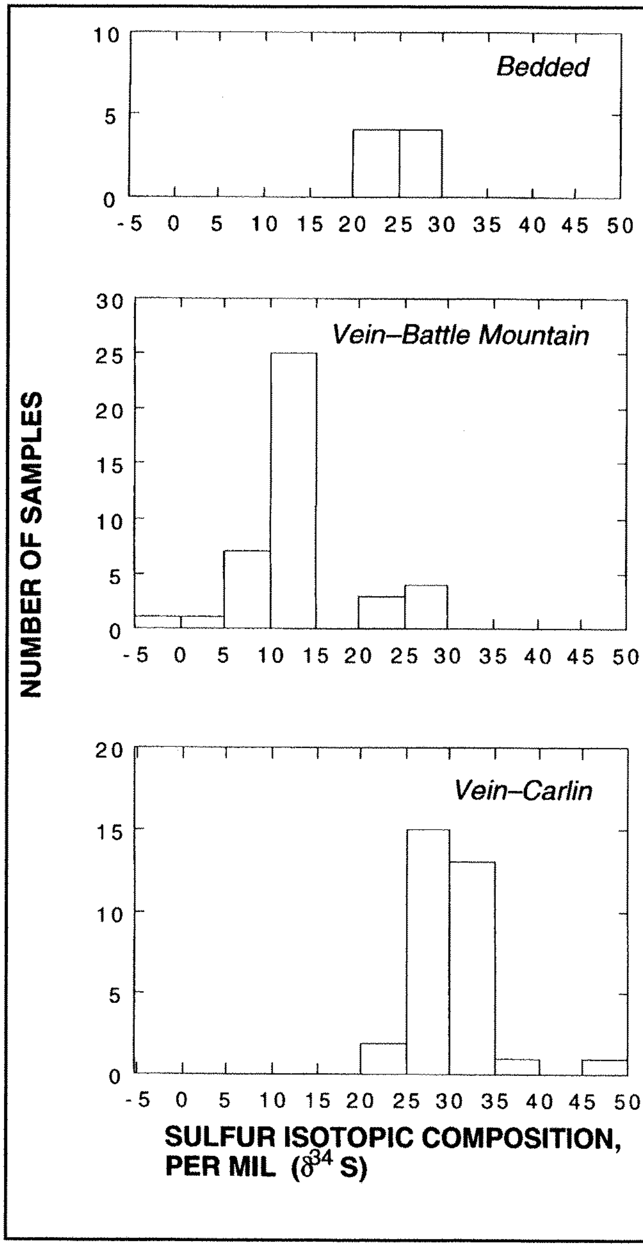


Figure 14—Generalized geologic map of the Antler Peak 15-minute quadrangle showing the distribution of exposed porphyry copper and low-fluorine molybdenum systems (squares) in the southern part of the Battle Mountain mining district and distal-disseminated silver-gold deposits (circles) in the northern part of the mining district. Distal-disseminated silver-gold deposits are located (with one exception) in the hanging wall block of the late Miocene Oyarbide fault. 1, Copper Canyon porphyry copper system; 2, Buffalo Valley stockwork molybdenum system; 3, Buffalo Valley gold deposit; 4, Trenton Canyon porphyry molybdenum-copper system; 5, Elder Creek porphyry copper system; 6, Paiute Canyon porphyry molybdenum-copper system; 7, Buckingham porphyry molybdenum system; A, 8 South deposit, Marigold Mine; B, Top Zone deposit, Marigold Mine; C, East Hill/UNR deposits, Marigold Mine; D, Red Rock deposit, Marigold Mine; E, North Peak-Section 11 deposit (Santa Fe Pacific Gold's [SFPG] Trenton Canyon project); F, Trenton Canyon gold deposit (SFPG's Trenton Canyon project); G, Valmy-Trout Creek deposit (SFPG's Trenton Canyon project). Geology modified from Roberts (1964) and is the same as in Figure 2.

Figure 15—Comparison of sulfur isotopic compositions of hydrothermal vein barite from distal-disseminated silver-gold deposits in the northern Battle Mountain mining district with similar hydrothermal barite from sediment-hosted gold deposits along the Carlin trend, and with bedded barite from localities in north-central Nevada (S.S. Howe, unpub. data, 1995). $\delta^{34}S$ values are relative to Cañon Diablo troilite.



Eventual change of the regional least principal stress direction to an orientation of about S. 50° to 65° E., in the late Miocene, resulted in development of the Oyarbide fault (Fig. 14) and other northeast-striking post-mineral normal faults in the Battle Mountain mining district (Fig. 9). The Oyarbide fault is a major northeast-striking, post-mineral fault in the northwest part of the mining district that has a vertical component of offset of approximately 700 m with its northwestern block down. As many as fifteen gold deposits, including deposits at the Lone Tree and Marigold Mines, recently have been discovered in the downdropped block, northwest of the Oyarbide fault. Although there are no clear-cut spatial ties to felsic or intermediate intrusions, sulfur and oxygen isotopic compositions of genetically related hydrothermal barite suggests that mineralizing fluids contained a magmatic component. Therefore, these deposits are classified as distal disseminated silver-gold deposits. The distal disseminated silver-gold deposits distinguish the northern part of the Battle Mountain mining district from the southern part of the mining district which contains seven porphyry copper and low-fluorine molybdenum systems (Fig. 14). Post-mineral displacement along the Oyarbide fault has resulted in levels of exposure, within the hanging-wall block, that should be close to the tops of more extensive magmatic-hydrothermal mineral systems.

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