GEOLOGY AND MINERALIZATION OF THE EOCENE TUSCARORA VOLCANIC FIELD, ELKO COUNTY, NEVADA

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ABSTRACT

The Tuscarora volcanic field is the largest remnant of Eocene magmatism in Nevada. Detailed geologic mapping reveals that at least five major volcanic centers formed in a ~450 km^2 area in the southeastern part of the Tuscarora volcanic field during a remarkably intense period of magmatism between ~39.9 and 39.3 Ma. (**1**) The Pleasant Valley volcanic complex erupted andesitic to dacitic lava flows and minor pyroclastic rocks at ~39.9-39.7 Ma. (**2**) The Mount Blitzen volcanic center, which formed between 39.8 and 39.7 Ma, is a 11x6-km fault-bounded basin filled with dacitic domes, small-volume pyroclastic flows erupted from the domes, and reworked deposits. (**3**) The Big Cottonwood Canyon caldera, a ≥15-km diameter rhyolitic ash-flow caldera, lies just north of and truncates the Mount Blitzen center and erupted at ~39.7 Ma. (**4**) The Mount Neva intrusive episode consists of a granodiorite stock, numerous dacitic intrusions, and abundant, northeast-striking, andesitic to low-silica rhyolitic dikes. The granodiorite and dacites were emplaced along the margins of the Mount Blitzen center, and the dikes intruded throughout the center, between 39.5 and 39.3 Ma. These intrusions probably represent continued activity of the Mount Blitzen center. (**5**) Andesitic to dacitic lava flows, similar to those of the Pleasant Valley complex, erupted east of the Big Cottonwood Canyon caldera at ~39.3 Ma.

Gold-silver deposits at Tuscarora lie along and just outside the southeastern margin of the Mount Blitzen center, are closely associated with volcanism, and constitute the oldest Tertiary volcanic-hosted epithermal mineralization in Nevada. Two deposit types are present: (**a**) base-metal-bearing, high-grade Ag-Au veins (Ag/Au ~310) that lie in the northern and eastern parts of the district, and (**b**) base metal-poor Au-Ag veins and stockworks (Ag/Au ~25) that lie in the southern and western parts of the district. The deposits are hosted by dacites of the Mount Neva intrusive episode and reworked tuffs of the Pleasant Valley complex. ^{40}Ar/^{39}Ar dates on six samples of adularia, four from Au-rich and two from Ag-rich veins, range narrowly from 39.32±0.14 (2σ) to 39.14±0.13 Ma, with all but one ≥39.24 Ma. The location and timing of mineralization are consistent with hydrothermal circulation having been driven by intrusions of the Mount Neva episode. Both the near surface volcanic rocks and deeper Paleozoic rocks are prospective for additional deposits.

INTRODUCTION

Geologic mapping of the Tuscarora volcanic field is part of a broader project to understand Eocene magmatism and tectonism in northeastern Nevada (fig. 1). The Tuscarora volcanic field is interesting in itself; it represents some of the oldest Tertiary magmatism in Nevada, is the largest Eocene volcanic field in Nevada, and has significant mineral potential. Epithermal gold-silver deposits at Tuscarora are clearly associated with igneous activity and structure of the Tuscarora volcanic field. Our geologic mapping is also intended to help address potential environmental concerns if large-scale mining becomes warranted in the area. Another particularly important goal is to understand the relation between Eocene magmatism and tectonism and Carlin-type gold deposits in the region (fig. 1; Henry and Boden, 1997). The Tuscarora volcanic field lies just north of major gold deposits of the Carlin trend and west of deposits in the Independence Mountains (fig. 1). The age and origin of these deposits remain controversial (e.g., Sillitoe and Bonham, 1990; Arehart and others, 1993; Kuehn and Rose, 1995; Thorman and others, 1995; Ilchik and Barton, 1997), but evidence is growing that many deposits in the Carlin trend, Independence Mountains, and adjacent areas formed in the Eocene (Hofstra, 1995; Emsbo and others, 1996; Leonardson and Rahn, 1996; Phinisey and others, 1996; Rota, 1996; Groff and others, 1997).

This work briefly summarizes results of detailed mapping of the Mount Blitzen (Henry and Boden, 1998) and Tuscarora quadrangles and the southern two thirds of the Toe Jam Mountain quadrangle (area covered in fig. 2). This mapping documents at least five voluminous volcanic-intrusive centers in the southern part of the Tuscarora volcanic field (figs. 1 and 2). ^{40}Ar/^{39}Ar dates show that the five centers developed between approximately 39.9 and 39.3 Ma during a brief,

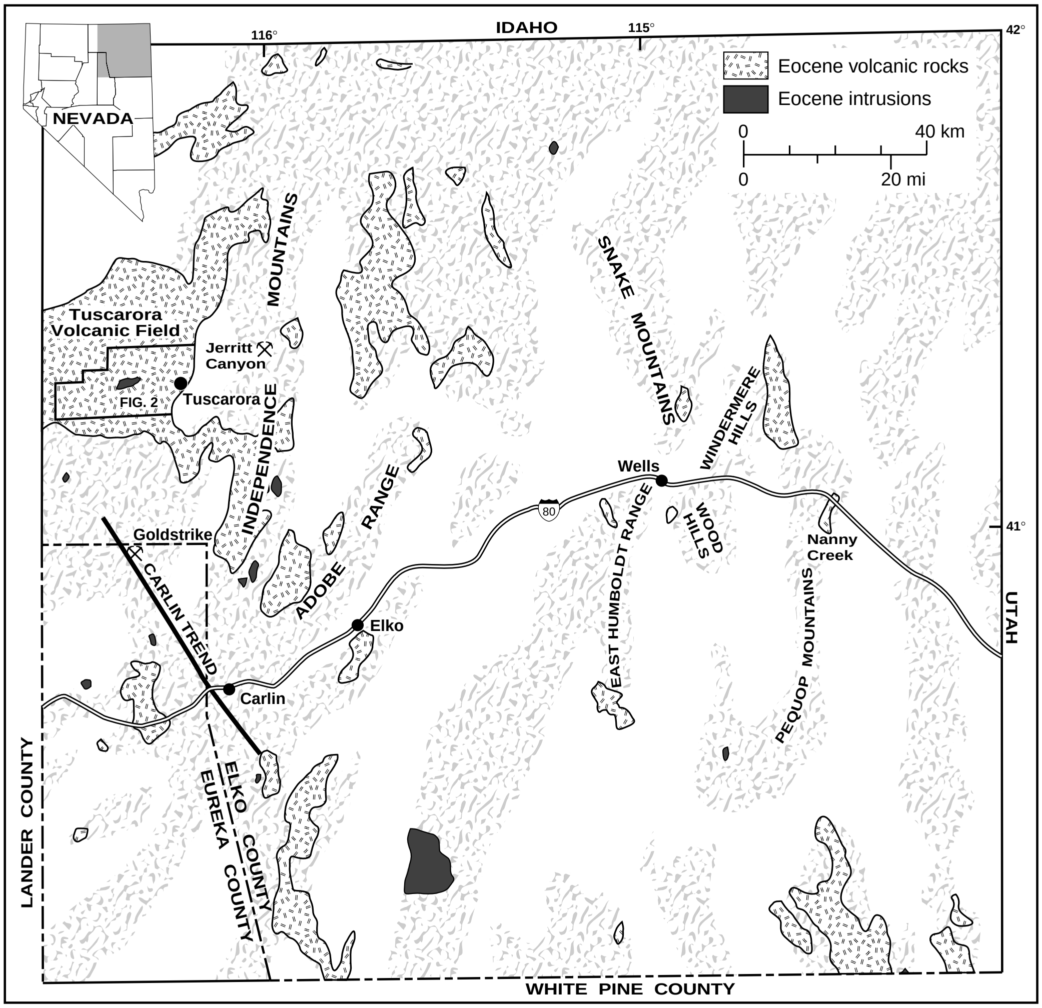

Figure 1. Location map showing generalized distribution of Eocene volcanic and intrusive rocks in northeastern Nevada, especially the Tuscarora volcanic field. Note that Eocene magmatism was particularly intense around the Carlin trend and Independence Mountains.

intense period of magmatism. Precious-metal mineralization at Tuscarora formed at about 39.3 Ma, contemporaneous with a major intrusive episode of the Tuscarora volcanic field, and is the oldest Tertiary volcanic-hosted epithermal deposit in Nevada.

PALEOZOIC ROCKS

The Tuscarora volcanic field formed in an area of complexly deformed Lower Paleozoic rocks that constitute the upper plate (or western assemblage) of the Roberts Mountains allochthon (Roberts, 1964). Upper-plate rocks were deposited in relatively deep water off what was then the western margin of the North American continent and thrust southeastward over generally coeval sedimentary rocks (lower-plate or eastern assemblage) deposited on the craton (Miller and others, 1992; Poole and others, 1992). Two distinct packages of Paleozoic rocks crop out in the Tuscarora volcanic field (fig. 2). A northern package contains boudins of quartzite in a matrix of siltstone and chert. Based on regional data, the quartzite almost certainly is correlative with the Ordovician Valmy Formation (Churkin and Kay, 1967; Miller and Larue, 1983; Coats, 1987). However, a thin limestone unit within the quartzite-bearing package north of Tuscarora contains Devonian conodonts (Coats, 1987), so younger rocks are present. A southern package consists of siltstone, chert, and minor sandstone and limestone; A. E. Saucier (personal communication, 1997) found Silurian to Devonian conodonts in three samples. Both sequences were folded and thrust southeastward before Eocene

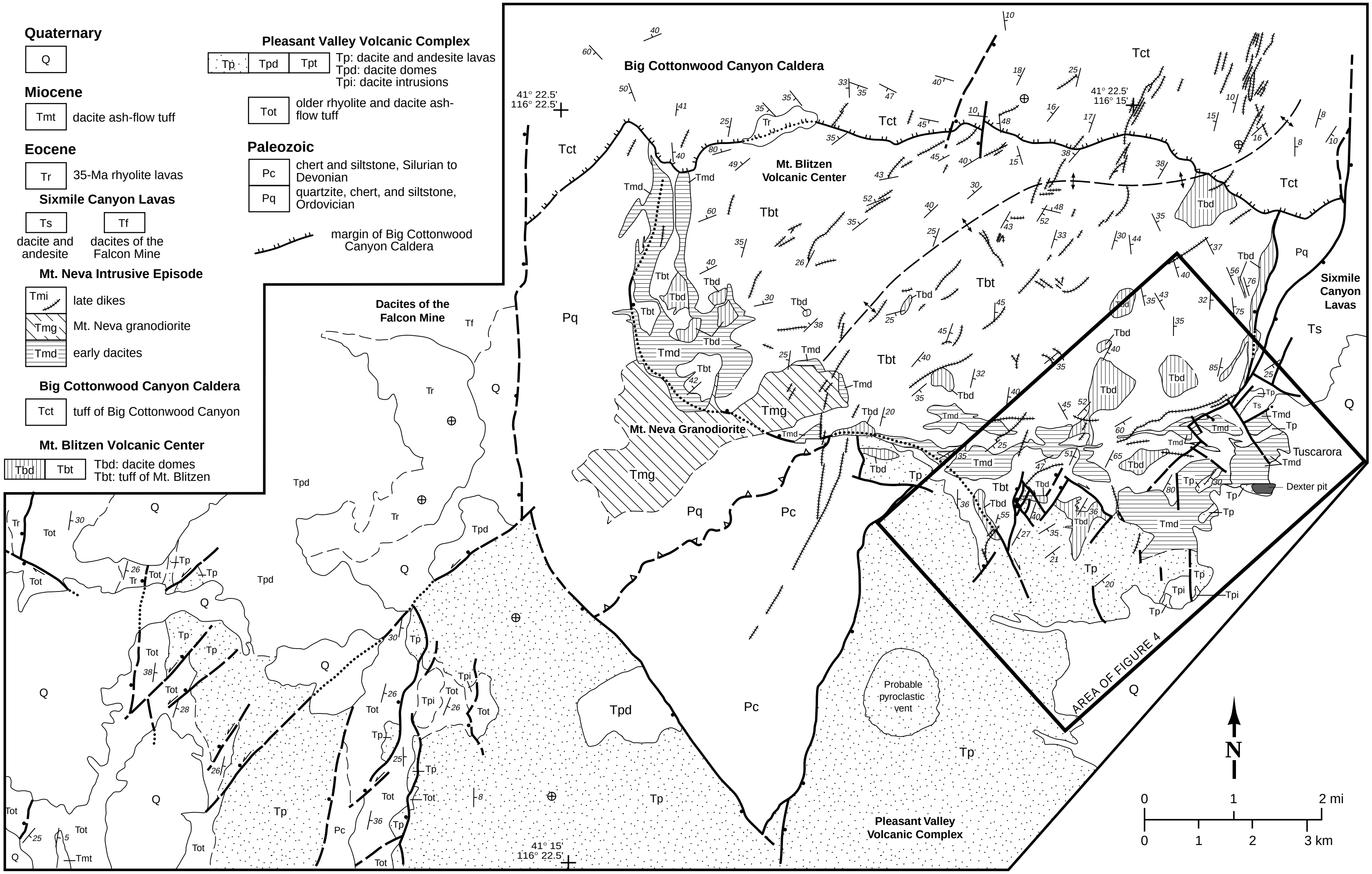

Figure 2. Simplified geologic map of the southern part of the Tuscarora volcanic field, based on detailed mapping of the Toe Jam Mountain, Mount Blitzen, and Tuscarora quadrangles (west to east).

volcanism. We interpret the presence of a major thrust fault that places the northern package over the southern one (fig. 2). Carbonate-bearing, lower-plate rocks, which are the major hosts for gold deposits in the Carlin trend and Independence Mountains, do not crop out in the Tuscarora area but should underlie the Roberts Mountains thrust, probably at present-day depths of ~3 km.

THE TUSCARORA VOLCANIC FIELD

Previous reconnaissance work in the Tuscarora volcanic field indicated that several volcanic centers were active between about 42 and 38 Ma (Berger and others, 1991; Crawford, 1992; Boden and others, 1993). Volcanism appears to have been in part contemporaneous with extension in the region (Clark and others, 1985; Brooks and others, 1995), although the amount and significance of extension within the Tuscarora volcanic field remain uncertain.

At least five major episodes of Eocene magmatism occurred in the southern Tuscarora volcanic field in a remarkably intense period of activity between about 39.9 and 39.3 Ma (fig. 2; Henry and Boden, 1997, 1998). From oldest to youngest, these episodes are: (**1**) andesitic to dacitic lava flows and tuffaceous sedimentary rocks of the Pleasant Valley volcanic complex (~39.9-39.7 Ma); (**2**) dacitic domes, small-volume pyroclastic-flow deposits, and epiclastic deposits of the Mount Blitzen volcanic center (~39.8-39.7 Ma); (**3**) rhyolitic ash-flow tuff of the Big Cottonwood Canyon caldera (39.7 Ma); (**4**) a granodiorite pluton and andesitic to rhyolitic dikes and small intrusions of the Mount Neva intrusive episode (39.5-39.3 Ma); and (**5**) andesitic to dacitic lava flows of Sixmile Canyon (~39.3 Ma). Field, petrographic, chemical, and $^{40}Ar/^{39}Ar$ age data indicate that each of the five major sequences consists of genetically related rocks erupted from sources in the southern Tuscarora volcanic field. Two rhyolitic lavas erupted at about 35 Ma in the western part of the area of figure 2 and represent a sixth episode of local, but distinctly younger and volumetrically minor, activity.

Slightly older Tertiary volcanic rocks, including three rhyolitic or dacitic ash-flow tuffs, underlie rocks of the Pleasant Valley complex to the west. A dacitic tuff that directly underlies Pleasant Valley rocks is 39.84±0.10 (2σ) Ma. These tuffs are absent in the central and eastern parts of the area of figure 2, where Pleasant Valley rocks rest directly upon Paleozoic rocks or upon basal Tertiary conglomerate. The source areas of these tuffs, although unknown, were probably not within the southern Tuscarora volcanic field.

Pleasant Valley Volcanic Complex

The Pleasant Valley volcanic complex, the oldest major volcanic sequence of the Tuscarora volcanic field, consists of andesitic to dacitic lava flows and lesser pyroclastic and volcaniclastic rocks (fig. 2). These rocks crop out extensively in the southern parts of the Mount Blitzen and Toe Jam Mountain quadrangles and continue several kilometers farther south. Lavas total about 300 m thick in the southern part of the Mount Blitzen quadrangle but become increasingly interbedded with volcaniclastic deposits and wedge out northeastward toward Tuscarora. Lavas rest directly upon basal Tertiary conglomerate in the Mount Blitzen quadrangle and upon the slightly older ash-flow tuff sequence to the west and south. Known sources include several dacite lava domes in the southwestern part of Pleasant Valley outcrop, a pyroclastic(?) center in the southern part, and several shallow intrusions in the southwest that were probable feeders for the flows. $^{40}Ar/^{39}Ar$ dates on two lava flows and the immediately underlying dacitic tuff indicate that Pleasant Valley lavas erupted between about 39.9 and 39.7 Ma (fig. 3).

Mount Blitzen Volcanic Center

Previous reconnaissance studies called the large Mount Blitzen volcanic center (fig. 2) a stratovolcano (Berger and others, 1991), a caldera (Cruson and Limbach, 1985; Crawford, 1992), or a volcano-tectonic graben (Boden and others, 1993). The Mount Blitzen center is a fault-bounded basin filled with dacitic intrusive and extrusive rocks. The basin is approximately 11 by 6 km; however, it is truncated on the north by the younger Big Cottonwood Canyon caldera, and the original extent in that direction is unknown. Most boundaries are high-angle faults.

The Mount Blitzen center is filled with a thick sequence of dacitic domes (Tbd) and the dacitic tuff of Mount Blitzen (Tbt), which consists of small-volume pyroclastic-flow and epiclastic deposits. Domes occur throughout the center and are most abundant along the margins; a few intrude older rocks outside the center. Pyroclastic rocks are petrographically similar to the domes and probably erupted from them. Epiclastic rocks consist mostly of very coarse to fine fragments of domes and tuff and represent reworking of the primary volcanic rocks. Both pyroclastic and epiclastic rocks contain megabreccia blocks of the dacitic domes, older andesite probably of the Pleasant Valley complex, and, rarely, Paleozoic rocks that were shed from the margins of the center. The composite tuff of Mount Blitzen is at least 1 km thick and could be several kilometers thick. The tuff was tilted into a northeast- to east-northeast-striking anticline through the middle of the center; with some complexity, dips on both limbs average about 35 to 40° (fig. 2). Therefore, oldest rocks are exposed in the middle of the center and are progressively younger outward. However, the base is not exposed and complex stratigraphy, lack of marker beds, and uncertainty in repetition by faults preclude determining an accurate thickness.

Imprecise $^{40}Ar/^{39}Ar$ dates on biotite from samples of

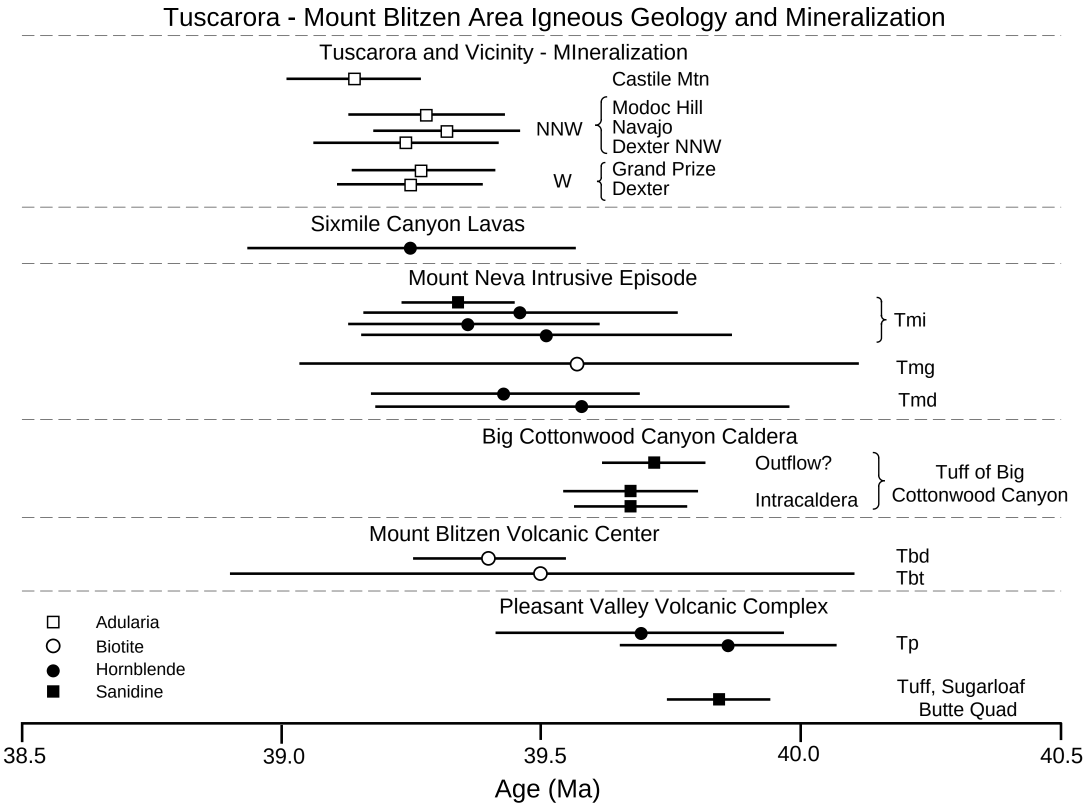

Figure 3. ^{40}Ar/^{39}Ar dates (±2σ) of igneous rocks and mineralization in the Tuscarora volcanic field. Rocks are in stratigraphic order determined from field relations. Sanidine and adularia give the most precise and accurate dates, hornblende is next, and biotite is less precise.

dacitic domes and tuff and, more importantly, dates on sanidine from older and younger rocks bracket activity in the Mount Blitzen center between about 39.8 and 39.7 Ma (fig. 3).

Big Cottonwood Canyon Caldera

The Big Cottonwood Canyon caldera is a large, rhyolitic ash-flow caldera that lies north of and truncates the Mount Blitzen volcanic center (fig. 2). The caldera margin is marked by the juxtaposition of thick intracaldera tuff of Big Cottonwood Canyon (Tct) against Paleozoic rocks and tuff of Mount Blitzen. The caldera extends at least 15 km east-west and an unknown distance to the north, outside the mapped area. All tuff shown on figure 2 lies within the caldera, is lithic-rich, densely to moderately welded, and unless repeated by unrecognized faults, may be several kilometers thick, based on its somewhat irregular 15° to 25° westward dip across the caldera. Tuff near the caldera margin contains abundant debris lenses and individual blocks of andesite, probably of the Pleasant Valley complex, tuff of Mount Blitzen, and Paleozoic rocks up to several hundred meters in diameter. Ponding of the tuff within the caldera and presence of megabreccia show that caldera collapse occurred contemporaneously with ash-flow eruption. Correlative outflow tuff crops out approximately 25 km to the southeast, in the southeastern part of the Tuscarora quadrangle, and a similar distance to the southwest near Willow Creek Reservoir (Wallace and John, this volume). ^{40}Ar/^{39}Ar dates on sanidine from two samples of intracaldera tuff are identical at 39.67 Ma; outflow tuff at Willow Creek Reservoir gives an age of 39.72 Ma (fig. 3).

Mount Neva Intrusive Episode

The Mount Neva pluton, several other irregularly shaped intrusions, and innumerable dikes were emplaced into and immediately adjacent to the Mount Blitzen volcanic center (fig. 2). Dikes of the Mount Neva episode cut the tuff of Big Cottonwood Canyon, so they and probably the other intrusions postdate formation of the Big Cottonwood Canyon caldera.

Intrusions of the Mount Neva episode developed in three distinct pulses: (**1**) early porphyritic dacite (Tmd), (**2**) the Mount Neva granodiorite (Tmg), and (**3**) late dikes (Tmi). Early dacites form numerous irregularly shaped intrusions along the western, southern, and eastern margins of the Mount Blitzen volcanic center and a few dikes within the center. These intrusions are particularly abundant along the southeastern margin of the center in the Tuscarora mining district. This distribution indicates that the intrusions rose along the faults that bound the center.

The Mount Neva granodiorite (Tmg), the largest intrusion of the area, cuts across the southwestern margin of the Mount Blitzen volcanic center. It is about 5 km by 1 to 2 km, elongate east-northeast, and has steep contacts with surrounding rocks.

Numerous late dikes, ranging in composition from andesite to low-silica rhyolite, were the last manifestations of the Mount Neva episode. Although we mapped five types on the basis of phenocryst assemblage and inferred composition, all dikes are shown as a single unit on figure 2. These dikes are most abundant in a broad, northeast-striking band through the middle of the Mount Blitzen center, where they intrude tuff of Mount Blitzen (Tbt) and coincide with the northeast-striking anticline. Dikes die out within three to four kilometers north and south of the Mount Blitzen center. Both the dikes and the anticline coincide with a prominent aeromagnetic anomaly. Based on these data, we interpret the dikes to be apophyses from a large, underlying intrusion.

^{40}Ar/^{39}Ar dates on representatives of all three intrusive pulses indicate that the Mount Neva intrusive episode may have begun as early as about 39.5 Ma and lasted until 39.3 Ma (fig. 3). On the basis of spatial coincidence and similar rock compositions, we interpret the Mount Neva episode to be a late phase of activity of the Mount Blitzen volcanic center.

The physical characteristics and evolution of the Mount Blitzen center and Mount Neva intrusive episode are similar to those of many calderas. Indeed, Cruson and Limbach (1985) and Crawford (1992) designated the Mount Blitzen center a caldera. It is a deep, fault-bounded basin filled with a thick sequence of tuff that commonly contains megabreccia. The preserved basin is roughly circular, although its original dimensions are uncertain because it is truncated on the north. The late intrusions of the Mount Neva episode are similar to late activity recognized in almost all calderas. The anticline that developed in the tuff of Mount Blitzen, if resulting from emplacement of the underlying intrusion, is somewhat similar to resurgent domes in many calderas. The Mount Blitzen center is different from most calderas in that the tuff consists of complexly interbedded, small-volume pyroclastic flows and epiclastic rocks. These deposits contrast with the thick, massive intracaldera tuff that is typical of most calderas, for example, the tuff of Big Cottonwood Canyon. Also, the anticline is far more elongate and steeper than typical resurgent domes.

Sixmile Canyon Lavas

The youngest major volcanic episode in this area consists of dacitic to andesitic lava flows and minor tuffs that crop out north of Tuscarora and east of the Big Cottonwood Canyon caldera (fig. 2). Although rock types are similar to those of the Pleasant Valley volcanic complex, Sixmile Canyon lavas are faulted down against and, in one location, overlie the tuff of Big Cottonwood Canyon. Along with a single ^{40}Ar/^{39}Ar date on hornblende of 39.25±0.31 Ma (fig. 3), the field relations show that the Sixmile Canyon lavas are younger than Pleasant Valley rocks. Compositional, petrographic, and age similarities suggest the lavas may be extrusive counterparts to dacitic rocks of the Mount Neva intrusive episode.

A group of dacitic lava flows that crop out in the northeastern part of the Toe Jam Mountain quadrangle (dacites of the Falcon Mine; fig. 2) may be contemporaneous with the Sixmile Canyon lavas. These rocks have been only briefly studied but are younger than the tuff of Big Cottonwood Canyon and older than 35.3-Ma rhyolite lava

35-Ma Rhyolitic Volcanism

Two rhyolite lava flows erupted in the western part of the mapped area at about 35 Ma. A small (1.5 x 0.5 km) lava dome and associated tuff erupted along the southern margin of the Big Cottonwood Canyon caldera. Although it lies on the ring fracture of the caldera, its age of 35.05±0.10 Ma shows that it is much too young to be genetically related to caldera magmatism. A much larger but possibly composite flow (~8 km in diameter) appears to have erupted from a vent in the northeastern part of the Toe Jam Mountain quadrangle and flowed to the south and west. A sample from near the possible vent area gives an age of 35.29±0.10 Ma.

EXTENSION IN AND AROUND THE TUSCARORA VOLCANIC FIELD

The Tuscarora volcanic field formed in the Eocene during probable northwest-directed extension, some of the earliest Tertiary extension in the region (Clark and others, 1985; Brooks and others, 1995; Janecke and others, 1997). However, details on timing, amount, and significance of early to mid-Tertiary extension in the Tuscarora volcanic field are not fully resolved (Henry and Boden, 1998). Most Eocene rocks in the Mount Blitzen and Tuscarora quadrangles are nearly flat lying or dip gently and appear negligibly extended. Uncertainty about the influence of extension centers on the origin of the fault-bounded Mount Blitzen volcanic center and the northeast-striking anticline in the tuff of Mount Blitzen (fig. 2). Our favored interpretation is that the Mount Blitzen center resulted dominantly from volcanic subsidence and the anticline from magmatic resurgence. Northwest-directed extension is manifest by the northeast strike of the anticline and Mt Neva dike swarm. Alternatively, the Mount Blitzen center is a tectonic graben and the anticline a result of tilting by displacement along oppositely dipping normal faults that form the western and eastern margins of the center.

A later episode of extension definitely occurred between about 35 and 15 Ma and affected the Toe Jam Mountain quadrangle and areas farther west. A transition zone between less extended rocks to the east and moderately extended rocks to the west strikes northward through the eastern part of the quadrangle. Rocks of the Pleasant Valley complex in the southeastern part of the quadrangle are approximately flat lying. To the west, Pleasant Valley rocks and rocks at least as young as the 35.3-Ma rhyolite lava flow are tilted eastward, typically between 25° and 35°, and repeated by a series of west-dipping normal faults. A 15.3-Ma dacitic ash-flow tuff unconformably overlies the tilted rocks in the southwestern corner of the quadrangle. This Miocene tuff dips approximately 5° eastward, which indicates still later, but minor extension.

PRECIOUS-METAL DEPOSITS AT TUSCARORA

Productive deposits at Tuscarora occur along and just outside the southeastern margin of the Mount Blitzen volcanic center (fig. 2). Total production, from early working of placer deposits and subsequent discovery of silver-rich veins to recent mining of the Dexter gold-silver stockwork zone by open-pit methods, is about 200,000 oz gold and 7.5 million oz silver along with 7 tons Cu and 70 tons Pb (LaPointe and others, 1991). Other nearby areas of mineral deposits, which had little or no production, include mercury workings at Berry Basin, west of Tuscarora, and at the Red Bird (Silverado) mine just north of Tuscarora.

Lode deposits at Tuscarora are of two types: silver-rich deposits and gold deposits (Nolan, 1936). Silver-rich deposits are restricted to a relatively small area north and east of Tuscarora, whereas gold deposits occur in a larger area that extends southwest from Tuscarora (fig. 4). The two types overlap west of the Dexter pit, but paragenetic relations are unknown. Steeply to moderately dipping veins are present in both deposit types. The silver deposits are mainly along the north-northwest to northwest striking Navajo-Commonwealth vein system and the east-northeast striking Grand Prize-Argenta vein system (fig. 4). Gold deposits are along the north-northeast to north-northwest striking Modoc and Eureka vein systems, but are also associated with stockwork veining at the Dexter mine and in the Battle Mountain area (fig. 4).

Although both deposit types belong to the quartz-adularia (low sulfidation) epithermal class, they have somewhat different ore and gangue mineral assemblages, alteration patterns, and geochemistry. Quartz and adularia are gangue minerals for both types, but calcite, base-metal sulfides, and manganese minerals are more abundant in the silver-rich deposits. Ore minerals in unoxidized samples from the silver-rich deposits consist mainly of pyrargyrite and acanthite with minor electrum. Electrum and acanthite are the main ore minerals in the gold deposits.

Silver/gold ratios based on production records ranged from four or five for the gold deposits to 150 in the silver-rich deposits (Nolan, 1936). On the basis of samples collected for this study, mean silver/gold is about 25 for gold deposits and 300 for silver-rich deposits (table 1). The two types form distinct fields on a scatter plot of silver against gold (fig. 5), but there is some overlap, mainly for samples from the Modoc mine and the southern part of the Navajo vein. Gold and silver are strongly correlative in both deposit types (fig. 5), although some oxidized samples are highly enriched in silver relative to gold.

Samples of silver-rich ore commonly have high calcium and magnesium concentrations relative to those for the gold deposits, probably reflecting higher carbonate content, and base metals are generally high in the former and low in the latter (table 1, fig. 5). Samples from the silver-rich deposits commonly contain more than 1 ppm selenium to a maximum of 78 ppm, whereas samples from the gold deposits generally have less than 1 ppm. Arsenic, antimony, and mercury are moderately to strongly enriched in samples from both types of deposits; bismuth, molybdenum, and tellurium are generally low (table 1). Thallium is slightly enriched in both types.

Main host rocks for the precious-metal deposits are early porphyritic dacites (Tmd) of the Mount Neva intrusive episode and dacitic lavas and tuffaceous sediments of the Pleasant Valley complex. East-northeast-striking silver-rich veins (e.g., the Grand Prize and Argenta veins) are subparallel to dikes of the Mount Neva episode, and north-northwest-striking veins (e.g., the highly productive Navajo vein) are subparallel to right-lateral transfer faults that make up part of the southeastern margin of the Mount Blitzen center (figs. 2 and 4).

Silver-rich ore consists mainly of sulfide-bearing replacement veins, although late-stage barren comb quartz veins are also present. Gold ore consists of or is associated with comb quartz fissure veins that locally contain sulfide minerals. In places, as at the recently productive Dexter mine, low-grade gold ore occurs as relatively large areas of silicified rock and stockwork veins. As noted by Nolan (1936), silver-rich ore is associated with relatively narrow zones of quartz-adularia-clay alteration, whereas gold is associated with widespread quartz-adularia-clay alteration

A reconnaissance fluid-inclusion study indicates that the silver-rich Grand Prize vein formed from nonboiling fluids at 245°-255°C (J. Cline, personal communication, 1993). By contrast, a sample of Dexter gold ore contains two populations of fluid inclusions; one with variable liquid/vapor ratios suggestive of boiling and homogenization temperatures of 200°–220°C, and another with constant liquid/vapor ratios and homogenization temperatures of 225°C–250°C. Under these conditions, and assuming hydrostatic or hydrodynamic gradients and minor amounts of dissolved CO_2, inferred paleodepths of trapping range from about 200 to 400 m (Haas,

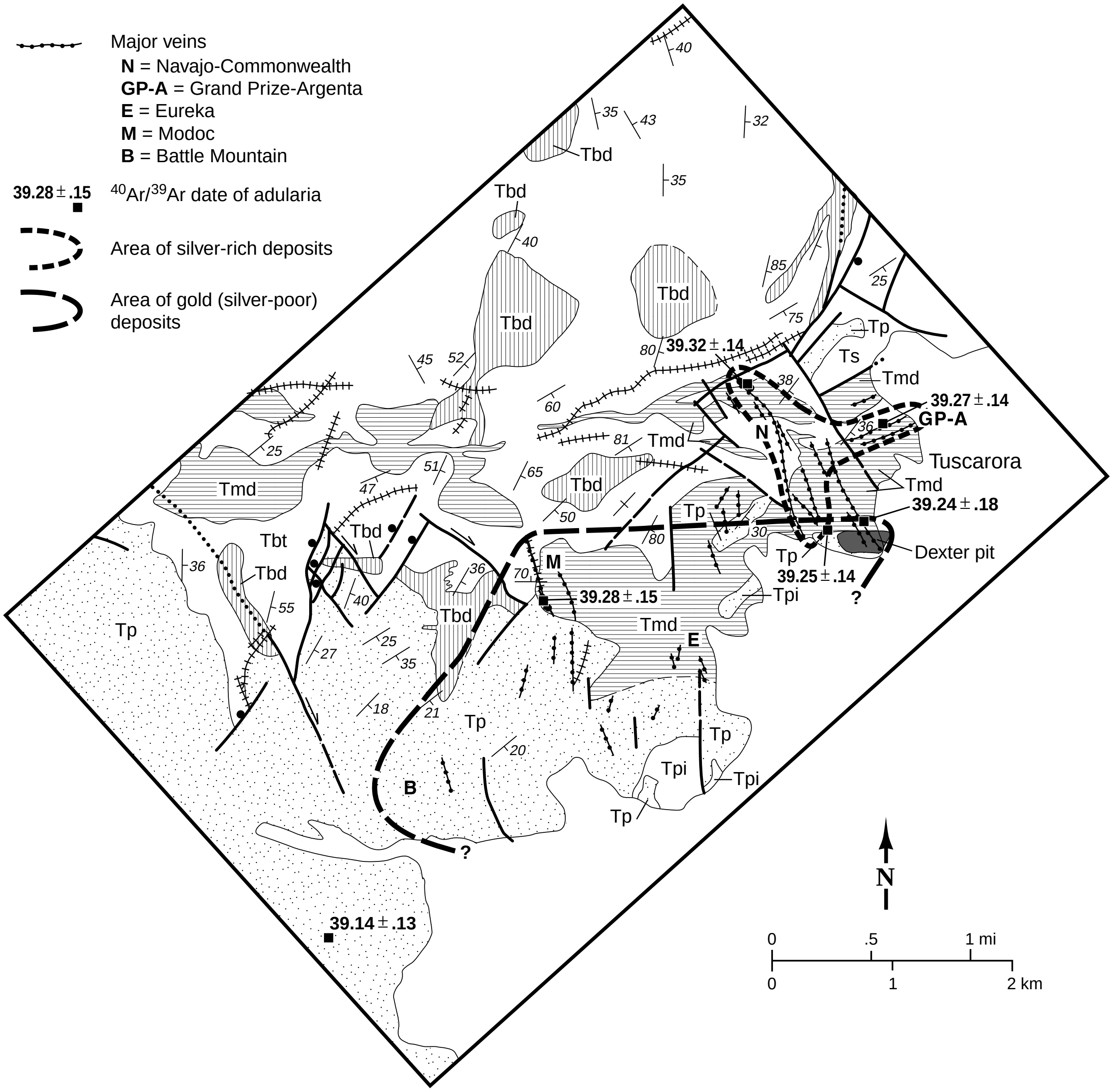

Figure 4. Geologic map of the Tuscarora mining district, showing major veins, ^{40}Ar/^{39}Ar ages of adularia, and general areas of the silver-rich and silver-poor deposits. Geologic units are as in figure 2.

1971; Hedenquist and Henley, 1985, Bodnar and others, 1985).

^{40}Ar/^{39}Ar dates on six samples of adularia, four from areas of gold stockwork zones and two from silver-rich veins, have a narrow range between 39.32±0.14 (2σ) to 39.14±0.13 Ma, with all but one ≥39.24 Ma (fig. 3). All ages are indistinguishable within their analytical uncertainties and allow two hypotheses relating the two types of mineralization. Either both types of mineralization formed concurrently and are zoned counterparts, or each type represents temporally separate, compositionally distinct hydrothermal events, albeit closely spaced in time (within about 100,000 years). This is not an unreasonably brief time in light of data from modern geothermal fields, where measured flow rates and fluid compositions indicate that a million ounces of gold can be transported in about 500 to 600 years (Seward, 1989; Krupp and Seward, 1987). If 10 percent of transported gold is deposited, a million-ounce gold deposit could be produced in as little as 5,000 to 6,000 years. Indeed, ^{40}Ar/^{39}Ar data from the giant volcanic-hosted gold-silver deposit at Round Mountain (18 million ounces of gold) indicate that this deposit formed in less than 100,000 years and probably less than 50,000 years (Henry and others, 1996, 1997).

Table 1. Geochemical characteristics of Tuscarora area mineral deposits (n=48).

	Ag/Au	Ag ppm	As ppm	Au ppm	Ba ppm	Bi ppm	Ca %	Cu ppm	Fe ppm	Hg ppm
Silver-Rich Deposits										
Mean	309.2	486.4	246.5	1.48	695	0.64	2.60	19.09	4.99	0.58
Median	106.7	31.4	108	0.341	494	0.61	0.15	11.4	2.73	0.256
High	2054	4854	1515	24.7	2019	1.23	24.71	92.4	19.15	5.03
Low	12.1	0	14	0.003	49	0.34	0.04	1.1	0.67	0.017
Gold Deposits										
Mean	24.8	69.77	809.3	3.659	859.8	0.53	0.06	7.71	1.51	0.687
Median	11.9	2.78	47.9	0.208	700	0.48	0.06	5.83	1.35	0.404
High	147	777	8901	17.7	1502	1.04	0.16	20	6.26	2.28
Low	1.4	<0.02	5.1	0.016	89	0.39	0.01	2.22	0.29	0.024

	Li ppm	Mn ppm	Mo ppm	Pb ppm	Sb ppm	Se ppm	Te ppm	Tl ppm	V ppm	Zn ppm
Silver-Rich Deposits										
Mean	26.7	4152	9.02	434.5	35.81	5.99	0.2	1.69	41.0	451.9
Median	23	301	3.54	87.6	7.43	1.58	0.18	1.47	33	90.2
High	68	56482	56.6	3745	355	77.9	0.66	5.69	141	5699
Low	6	32	1.08	16	0.8	0	0	0.87	4	4.3
Gold Deposits										
Mean	49.4	202	5.33	50.5	61.63	2.09	0.22	1.38	18.8	49.3
Median	40	23	2.53	18.4	4.75	0.26	0.12	1.21	18	5.72
High	108	1071	26.6	463	656	23.8	1.8	2.24	45	398
Low	23	7	1.16	1.78	1.56	0	0	0.7	6	2.48

We believe that the silver-rich and gold deposits are not zoned counterparts but represent discrete hydrothermal events that were closely spaced in time. This is supported by the consistent and distinctive mineralogical and geochemical characteristics of both deposit types over large areas with little spatial overlap. In any case, the timing and location of both styles of precious-metal deposits are consistent with hydrothermal circulation having been driven by intrusions of the Mount Neva episode, in particular the early dacites.

The deposits at Tuscarora are volcanic hosted and epithermal, but siliceous, upper-plate Paleozoic rocks that are present in the walls of both the Mount Blitzen volcanic center and Big Cottonwood Canyon caldera underlie the volcanic host rocks. More prospective, carbonate-bearing, lower-plate rocks, which are the principal hosts for Carlin-type deposits, underlie the siliceous rocks, probably at depths no greater than the inferred 3- to 4-km paleodepths of Carlin ore bodies (Kuehn and Rose, 1995; Leonardson and Rahn, 1996, Lamb and Cline, 1997). For example, these rocks crop out and host gold deposits in the Independence Mountains just 15 to 20 km to the east. The dacite intrusions of the Mount Neva episode, which we interpret to have driven hydrothermal circulation, must intrude the Paleozoic rocks. The hydrothermal fluids that generated volcanic-hosted deposits at Tuscarora almost certainly interacted with these deeper seated rocks. Although specific conditions of alteration at depth are speculative, the hydrothermal system could have generated Carlin-type, distal-disseminated, skarn, or manto deposits in the lower-plate rocks. With the major exception of relatively high silver/gold, the trace element signature of Tuscarora deposits is similar to that of Carlin-type deposits: moderate to high levels of arsenic, antimony, mercury, and thallium and generally low levels of base metals and magmatic components such as bismuth, tellurium, and molybdenum.

In summary, the precious-metal deposits at Tuscarora are located along and mainly just outside the southeastern margin of the Mount Blitzen volcanic center. The productive, east-northeast- and north-northwest-striking veins in the district are subparallel to dikes and north-northwest faults that both transect and in part bound the Mount Blitzen volcanic center. The orientations of these structures and senses of displacement are consistent with a modest amount of northwest-directed extension. Ore deposition occurred at or near the close of a major pulse of volcanic activity in the region and is temporally and spatially associated with the early dacite intrusions of the

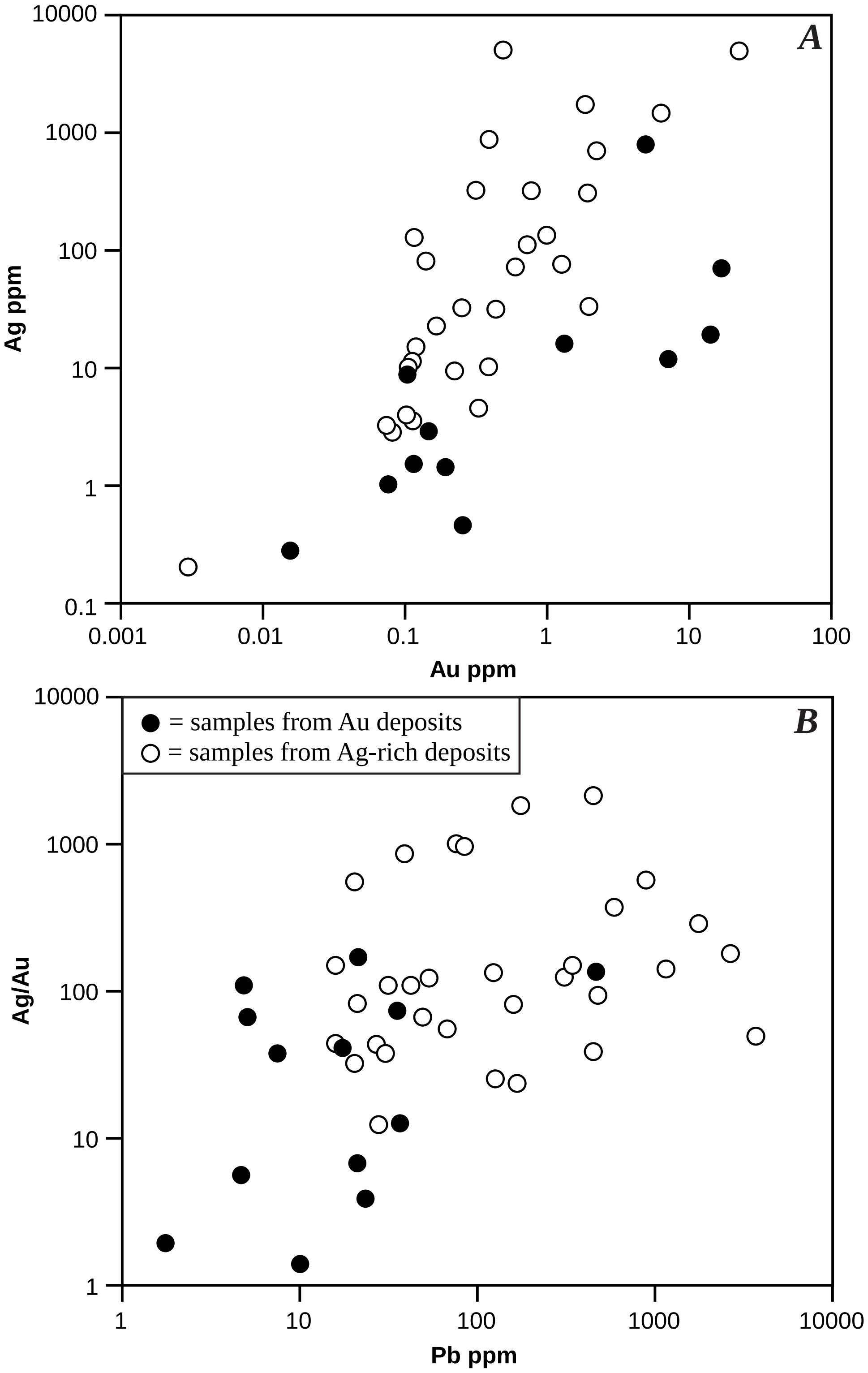

Figure 5. Scatter plots of ***A***, Au versus Ag, and ***B***, Ag/Au versus Pb. Ag-rich deposits have similar Au contents, but generally much higher Ag contents, than do Au or Ag-poor deposits. Ag-rich deposits also have higher Pb concentrations than do Ag-poor deposits.

Mount Neva intrusive episode. These intrusions are inferred to be the heat source that drove hydrothermal fluids that produced the deposits at Tuscarora. Mineral deposits at Tuscarora consist of silver-rich and silver-poor ore that we consider to represent two separate, short-lived hydrothermal events closely spaced in time, i.e., both having formed, as indicated from precise $^{40}Ar/^{39}Ar$ dating, within about 100,000 years.

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