NEW STUDIES OF TERTIARY VOLCANIC ROCKS AND MINERAL DEPOSITS, NORTHERN NEVADA RIFT

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ABSTRACT

The northern Nevada rift is a long, narrow, north-northwest-trending alignment of middle Miocene volcanic and hypabyssal rocks and epithermal gold-silver and mercury deposits formed during west-southwest to east-northeast extension. New mapping is underway in three areas along the rift: the Ivanhoe district, the southern Sheep Creek Range, and the Mule Canyon area at the north end of the Shoshone Range. In the Ivanhoe district, Tertiary rocks range in age from late Eocene to middle Miocene, whereas Tertiary rocks in the other two areas are mostly Miocene in age. Compositions are varied in all three locations; a substantial part of the volcanic rocks in the Sheep Creek Range and northern Shoshone Range is dacitic, in contrast to the more basaltic composition that dominates most of the rift. At Ivanhoe, which is on the eastern margin of the rift, both northwest- and northeast-striking faults are common and are mutually crosscutting. Faulting there produced moderate to major amounts of Miocene tilting, with some evidence for 20° of pre-middle Miocene tilting. In the Sheep Creek Range and Mule Canyon area, the dominant faults strike north-northwest, consistent with the rest of the rift; east-northeast-striking faults are related to middle Miocene and younger northwest-directed extension. Oligocene rocks at Mule Canyon dip steeply to the east and northeast, whereas overlying Miocene volcanic rocks dip gently to the southeast. Ore deposits at Ivanhoe (mercury and gold) and Mule Canyon (gold) formed in syn-volcanic hot-spring environments during the middle Miocene, similar to other deposits along the rift. The gold deposits are low-sulfidation, quartz-adularia veins and disseminations in volcanic rocks.

INTRODUCTION

The northern Nevada rift was the site of middle Miocene igneous activity and related precious-metal mineralization. It extends approximately 500 km in a north-northwest direction from east-central Nevada to near the Nevada-Oregon border. The rift appears as a readily visible, fairly narrow positive anomaly on regional aeromagnetic maps that reflects the presence of abundant intrusive mafic rocks (Zoback and Thompson, 1978; Blakely and Jachens, 1991).

Although a general relationship between volcanism, faulting, and mineralization along the rift has been known for some time, relatively little is known about the exact timing and interaction between these events. New mapping along the rift has focused on the southern Sheep Creek Range and northern Shoshone Range area, both near Battle Mountain, Nev., and the Ivanhoe mining district 60 km northeast of Battle Mountain (fig. 1). Mapping in the Sheep Creek/northern Shoshone Range area was initiated to study the volcano-tectonic framework of the newly developed Mule Canyon gold deposit. The Ivanhoe study has served to understand a similar framework for the Hollister gold and Ivanhoe mercury deposits and to expand previous studies of Miocene volcanic rocks and structures in the Snowstorm Mountains and Midas mining district 25 km to the northwest (Wallace, 1993). The intent of both projects is to improve the understanding of the rift and the mineral deposits that formed along it.

REGIONAL GEOLOGIC SETTING

The northern Nevada rift formed in the relatively narrow time span of 16 Ma to 14 Ma (Zoback and others, 1994). Mafic, mantle-derived magmas were emplaced along a deep-seated, north-northwest-trending fracture system that cut Paleozoic, middle Tertiary, and early Miocene formations. This crustal flaw either formed or was reactivated during a change in stress fields related to the northward migration of the Mendocino triple junction along the west coast of North America (Zoback, 1989). The magmas were intruded as closely spaced dike swarms and erupted as lava flows. Dikes and lava flows are abundant in the northern half of the rift, but they are less common to absent in the southern half. The rocks were mostly tholeiitic basalts and basaltic andesites with affinities to contemporaneous lava flows exposed in the Steens Mountains of southern Oregon and the Columbia River Plateau farther north. Locally derived pyroclastic rocks are interbedded with flows in the Snowstorm Mountains (Wallace, 1993), and dacite flows and intrusive rocks are common in the southern Sheep Creek and northern Shoshone Ranges (see below). Rift-related magmatism ceased at about 14 Ma (Zoback and others, 1994). Extensive felsic volcanic rocks related to the Yellowstone hot spot blanketed the rift-related rocks in the northern third of the rift.

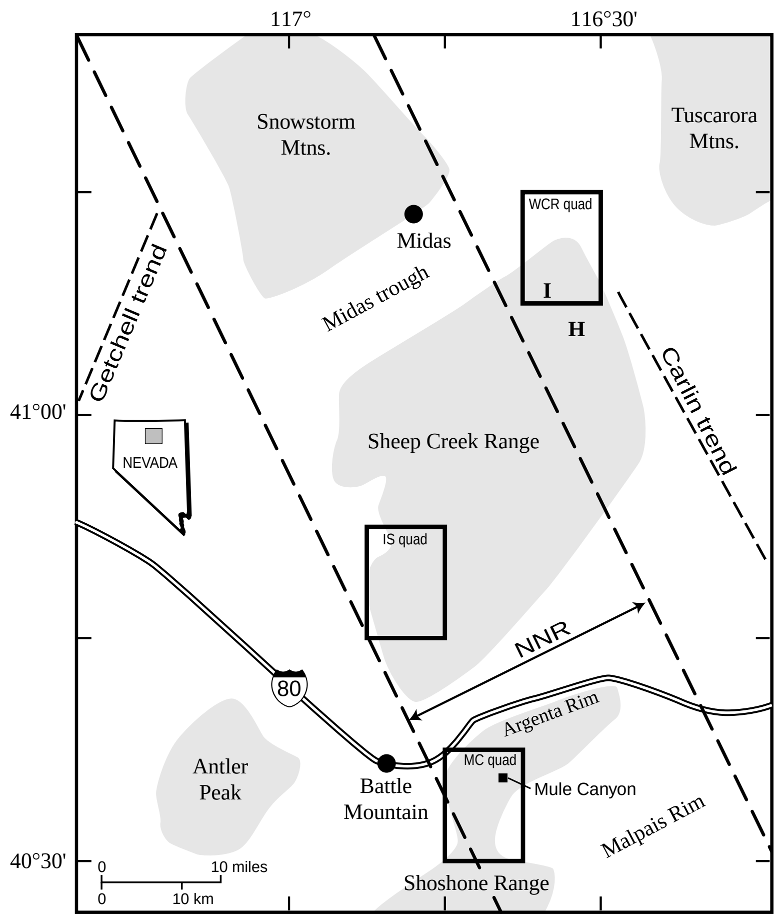

Figure 1. Index map showing geographic features mentioned in text, as well as the Willow Creek Reservoir (WCR), Izzenhood Spring (IS), and Mule Canyon (MC) 7-1/2-minute quadrangles. I, Ivanhoe district; H, Hollister mine; NNR, northern Nevada rift (approximate boundary).

Extension during rifting was in an east-northeast to west-southwest direction. Based on the orientations of rift-related dikes and faults in the younger volcanic sequence, this extension direction persisted until sometime after 10 Ma but before 6 Ma (Wallace, 1991; Zoback and Thompson, 1978; Zoback and others, 1994). At that point, a change in plate motions rotated the extension direction to a northwest-southeast orientation. Along the northern Nevada rift, this change disrupted the rift and formed a series of fault-bounded, east-northeast-oriented grabens. These grabens are spectacularly exposed along the Midas trough, at the north end of the Shoshone Range, and along the northern flank of the Cortez Range. This extension has continued into the Quaternary, as indicated by faults in Quaternary alluvium on the west side of the Sheep Creek and Shoshone Ranges and especially along the mountain front of the Shoshone Range.

Mineral deposits related to the northern Nevada rift include Comstock-type gold-silver vein deposits, hot-spring gold deposits, and hot-spring mercury deposits. Isotopic dates on the gold deposits range from 15-15.5 Ma, indicating syn-volcanic mineralization. The mercury deposits, such as those at Ivanhoe, have not been dated but geologically appear to be the same age as or slightly younger than the gold deposits. Mined gold deposits include, from north to south, Buckskin-National, Midas, Hollister (Ivanhoe), Mule Canyon, Fire Creek, and Buckhorn; unmined altered and geochemically anomalous

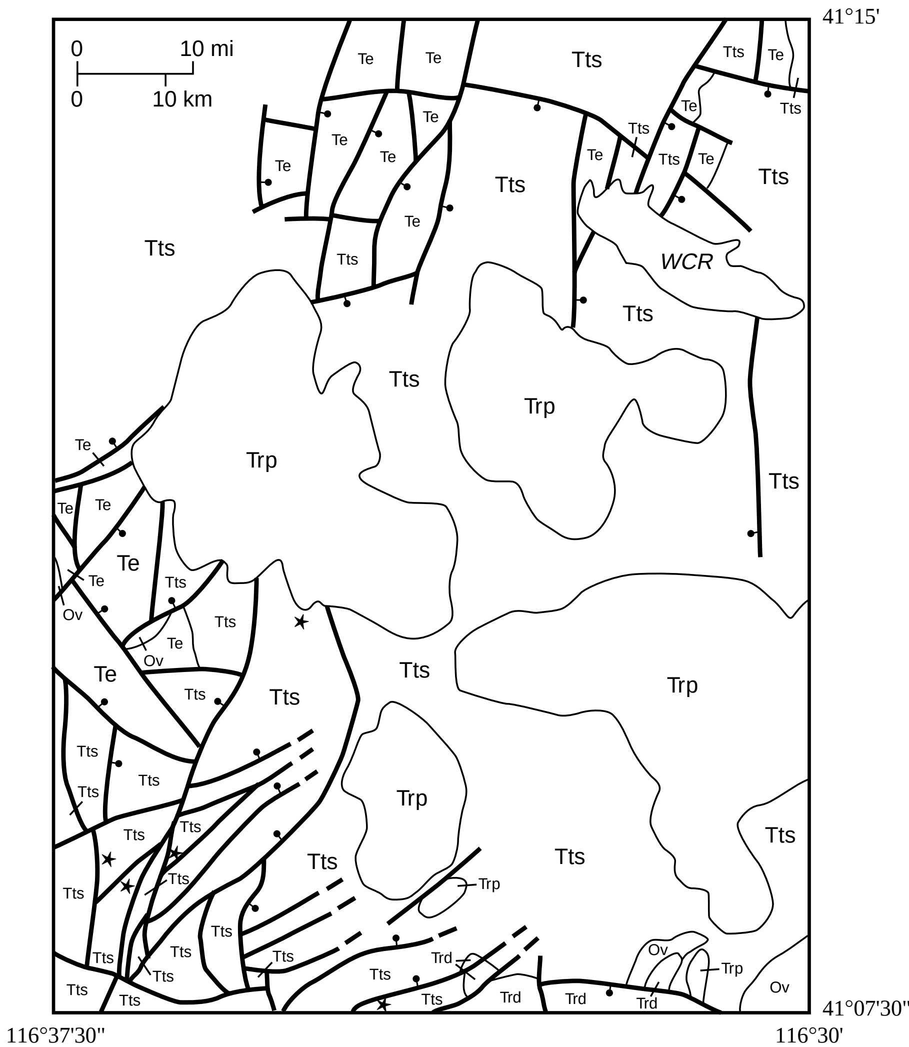

Figure 2. Generalized bedrock geologic map of the Willow Creek Reservoir quadrangle. Units (same labels as in figure 3, except as noted): Ov, Ordovician Valmy Formation; Te, Eocene volcanic rocks (Twt and Td of figure 3); Trd, Miocene rhyodacite; Trp, Miocene rhyolite porphyry; Tts, Miocene tuffs, tuffaceous sediments, andesite, and rhyolite (Ttsl, Ttsu, Tvt, Ta, and Trf of figure 3). WCR, Willow Creek Reservoir; *, mercury deposit. Heavy lines are faults, with ball and bar on downthrown side. The Hollister gold deposit is 1 km south of the center of the southern boundary of the quadrangle. Geology mapped by A.R. Wallace in 1996 and 1997.

volcanic rocks are common along the length of the rift.

IVANHOE DISTRICT

The Ivanhoe mining district is along the east margin of the northern Nevada rift and at the northwestern projection of the world-class Carlin gold trend. It is the site of the Hollister open-pit gold mine and numerous small mercury deposits. Current work has focused on the Willow Creek Reservoir 7-1/2-minute quadrangle (fig. 2). Previous studies in the area include a short description of the general geology and mercury deposits (Bailey and Phoenix, 1944), a description of the geology of the Hollister mine area (Bartlett and others, 1991), and unpublished mapping, sampling, and drilling programs by several mining companies.

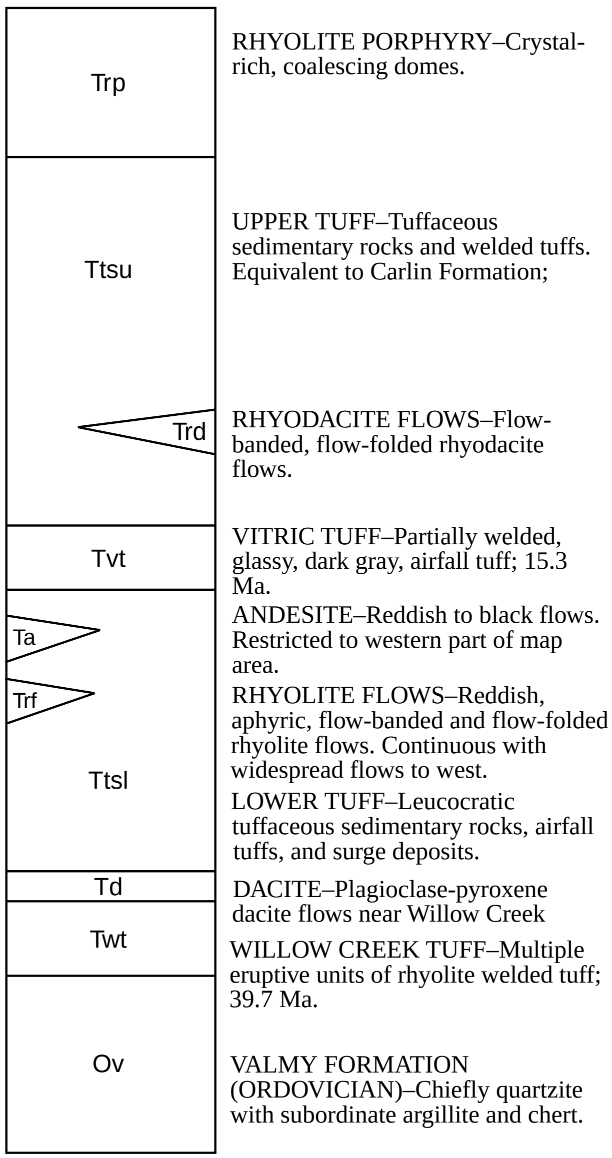

Figure 3. Stratigraphic section for Willow Creek Reservoir quadrangle. Reconnaissance mapping in rest of Ivanhoe district (A.R. Wallace, unpub. mapping, 1997) indicates the same sequence throughout the district. Thicknesses not to scale but show approximate relative thicknesses of units.

STRATIGRAPHY

Rock units in the Ivanhoe area include Paleozoic sedimentary rocks and Tertiary volcanic, sedimentary, and intrusive rocks. A generalized stratigraphic section is shown in figure 3. The Paleozoic rocks include quartzite, quartzite breccias, and phyllite of the Ordovician Valmy Formation. Exposures are limited, although exploration drilling shows that the Valmy Formation is present at variable depths throughout the district (Bartlett and others, 1991).

The oldest Tertiary unit in the area is the informally named Willow Creek tuff. The tuff is composed of several crystal-rich cooling units, the uppermost of which is densely welded. Phenocrysts include sanidine, smoky quartz, plagioclase, and biotite. The rock is a rhyolite, based upon an average SiO_2 content of 73.8 weight percent. The age of the rhyolitic tuff is 39.7 ±0.1 Ma ($^{40}Ar/^{39}Ar$ date on sanidine) and, based upon age and petrographic similarities, it was erupted from the Big Cottonwood Creek caldera 35 km to the east-northeast in the Tuscarora Mountains (Henry and others, this volume). It crops out extensively in the northern part of the study area but is concealed in the main part of the Ivanhoe district and absent at the Hollister mine (Bartlett and others, 1991). In the northern part of the district, dacite to andesite flows (average SiO_2 is 60 weight percent), dated at 37.7±0.1 Ma ($^{40}Ar/^{39}Ar$ date on biotite), overlie the Willow Creek tuff. Approximately 4 km east of the Hollister mine, a weakly altered dacite porphyry of unknown but possibly Eocene age intrudes the Valmy Formation.

Airfall tuffs and waterlain tuffaceous sedimentary rocks overlie the welded tuff and dacite in the northern part of the district and the Valmy at the Hollister mine. A distinctive vitric welded tuff (trachydacite: 67 weight percent SiO_2, 6 weight percent K_2O) near the middle of the section is 15.29±0.06 Ma ($^{40}Ar/^{39}Ar$ date on sanidine). The tuffaceous sedimentary rocks beneath the vitric tuff (the “lower tuffs”) are thickest to the north and locally are absent at the Hollister mine; the age of these strata is being studied. Tuffaceous sedimentary rocks and ash-flow tuffs above the vitric tuff (the “upper tuffs”) are correlative with the lower units of the middle Miocene Carlin Formation, which yield ages of about 14.5-15.1 Ma in the Santa Renia Fields quadrangle immediately to the southeast (Fleck and others, this volume).

Two volcanic units interbedded with the lower tuff sequence are restricted to the western part of the district (fig. 3). The older of the two is an aphyric, flow-banded rhyolite (74 weight percent SiO_2) lava flow sequence that thickens to the west. The younger unit is a massive to vesicular andesite (55 weight percent SiO_2) several meters to tens of meters beneath the vitric tuff. The andesite pinches out to the east and is absent in the eastern half of the Willow Creek Reservoir quadrangle. The unit is petrographically similar to and equivalent in age to a widespread andesite unit in the western Snowstorm Mountains (Wallace, 1993).

Rhyodacite lava flows (“Craig rhyolite” of Bartlett and others, 1991) represent the dominant volcanic unit east and southeast of the Hollister mine. These flow units are massive to flow folded, and flow tops locally are extremely lithophysal. Although the contact is poorly exposed, the rhyodacite is thought to overlie the lowermost units of the upper tuff (fig. 3). Isotopic dating of this unit is in progress.

The youngest volcanic unit in the Ivanhoe area is a crystal-rich rhyolite (73 weight percent SiO_2). The rhyolite forms exogenous domes that, due to their relative resistance, dominate the landscape in the northern part of the area (figs. 2 and 3).

The domes are composed of constructive accumulations of flows that emanated from central vents, with adjacent domes coalescing into composite domes. The flows contain fluorite and topaz in the groundmass and vesicles, and elevated tin values are present in all analyzed samples. Although the Ivanhoe domes have not been dated (work is in progress), they are similar to domes in the Snowstorm Mountains and northern Sheep Creek Range that have ages of 14.0 to 14.6 Ma (Wallace, 1993; Zoback and Thompson, 1978). The anomalous tin concentrations are similar to those of domes near Izzenhood Ranch in the northern Sheep Creek Range, where wood and placer tin have been reported in and near rhyolite domes (Fries, 1942).

South from about the latitude of the Hollister mine (fig. 1), the Valmy Formation is overlain directly by rocks as young as the rhyolite porphyry domes. This relationship contrasts with those in areas to the north where a thick section of Eocene and younger rocks overlies the Paleozoic basement. Bartlett and others (1991) identified a “paleotopographic ridge” of Paleozoic rocks beneath Tertiary rocks at the Hollister mine area. There, the high is overlain by the upper part of the lower tuffs and in places by the andesite, with a substantial part of the lower tuffs and all of the Willow Creek tuff absent. To the southeast in the Santa Renia Fields area, Carlin Formation units equivalent to and younger than the upper tuffs overlie the Paleozoic basement (T.G. Theodore, oral commun., 1997). These relations indicate that, during much of the middle Tertiary, the area north of Hollister was a topographic low that progressively filled with tuffs and sediments as tuffs that had been deposited on surrounding highlands were eroded. Based upon the ages of the lowermost Carlin Formation, this basin did not fill and expand laterally until about 15 Ma.

Structure

The dominant structures in the Ivanhoe area are high-angle normal faults (fig. 2). The principal strike is northeast near Willow Creek Reservoir, where the faults both cut and are cut by west-northwest-striking faults. Both northeast- and northwest-striking faults are common in the western and southwestern parts of the district. The fault sets in these areas are mutually cross cutting, but the northeast-striking faults generally are younger than the northwest faults. At the Hollister mine, detailed studies indicate similar orientations and relative ages (Bartlett and others, 1991).

Faults in the Snowstorm Mountains have somewhat similar orientations. The older faults have a north-northwest orientation and were active from about 16 to 10 Ma (Wallace, 1993). Younger faults have an east-northeast trend and formed sometime after 10 Ma and before 6 Ma (Zoback and Thompson, 1978). The southern end of the Snowstorm Mountains is marked by the east-northeast-trending Midas trough, with vertical offsets along bounding faults of as much as 1000 m. The master fault along the northern margin of the trough splays into at least four lesser faults just west of Midas and dies as a structural entity east of Midas. The southern structural margin of the trough extends to the extreme northwest margin of the Ivanhoe area. However, major high-angle, east-northeast-trending normal faults do not project eastward beyond that point. These relations suggest that offset along the master fault may have been taken up by the numerous northeast-trending faults in the Ivanhoe area, similar to the scenario at Midas.

Movement along the northeast-striking faults produced notable southeasterly dips in the volcanic rocks. Tilting is most pronounced in the northwest part of the district, where the Eocene Willow Creek tuff was tilted by as much as 53° to the southeast. Near Willow Creek reservoir (fig. 2), faulting repeated the volcanic section at least eight times. Going east, each fault block has a shallower dip than the block to the west, with dips decreasing eastward from 40° to 10°. The extensive faulting did not preserve a complete stratigraphic section, but limited evidence suggests that Eocene rocks dip approximately 20° more than the overlying tuffaceous sediments. If confirmed, as much as 20° of tilting took place prior to deposition of the tuffaceous sediments, and as much as 25° of tilting took place after deposition of the 15.3 Ma vitric tuff and overlying beds of the upper tuffs unit. Although fault blocks throughout much of the district have dips between 15° and 25°, the dips decrease district-wide from the steep dips in the north to horizontal in the middle Miocene Carlin Formation along Antelope Creek 20 km to the south.

A growing body of evidence indicates that gold deposits along the Carlin trend formed at about 42-38 Ma, about the same time that the Willow Creek tuff was emplaced (Emsbo et al., 1996). As exposed at Willow Creek Reservoir, the base of the tuff therefore marks the paleosurface at that time. That area has an elevation of 1650 m and the average elevation of the exposed Carlin deposits is about 1850 m, an elevation difference of only 200 m. The gold deposits along the Carlin trend formed at depths of 3 to 4.5 km (Lamb and Cline, 1997). This suggests the two areas have undergone several kilometers of post-Eocene differential offset, with the Carlin trend rising relative to the Willow Creek Reservoir area. Some, but likely not all, of the offset took place along the northeast-striking faults in the Ivanhoe area. Some of this displacement may have taken place in the Oligocene, accounting for the basin north of the Hollister mine.

Mineral deposits

The Ivanhoe district contains hot-spring mercury and hot-spring gold deposits (Bailey and Phoenix, 1944; Bartlett and others, 1991; Deng, 1991; Hollister and others, 1992). At the Hollister gold mine and nearby areas, gold deposits directly underlie mercury deposits. Company-confidential data from several sources indicate anomalous gold near some mercury deposits elsewhere in the district.

Silicification related to the gold and mercury mineralization is widespread throughout the district and has several forms. Opal and chalcedony partially to completely replaced tuffaceous sediments in the upper and lower tuffs. The most favorable horizon was the tuffaceous sequence between the andesite flows and the vitric tuff. Tuffaceous beds in the upper tuffs locally were silicified as well, particularly at the Rimrock and Silver Cloud mines in the northern and southern parts of the district, respectively. The andesite and vitric tuff in places are altered near the silicified tuffs, although fresh vitric tuff locally overlies silicified tuffs. Broad areas of the rhyodacite flows east of the Hollister mine are pervasively silicified, and rhyolite porphyry domes near the Rimrock mine and east of the Hollister mine also are altered.

Siliceous sinter deposits are preserved at several mercury mines and prospects. Most of these are in the stratigraphic interval between the andesite and vitric tuff. However, like the replacement silica, some sinters formed during deposition of the upper tuffs. In places, distinguishing a sinter from a replacement body is difficult, and the two forms may represent a vertical continuum, as suggested by Bartlett and others (1991). Elongate vents and feeders at several mercury deposits suggest that hydrothermal fluids ascended faults which were subsequently reactivated and thereby exposing the deposits.

The mercury deposits in the silicified tuffs consist of cinnabar and metacinnabar in the opaline rocks. Other sulfides are not evident in surface workings, but drill cuttings contain pyrite. The deposits are relatively small and were mined intermittently between 1915 and 1973; 2,180 flasks of mercury were produced (LaPointe and others, 1991).

The Hollister gold deposit contains several orebodies that underlie mercury-bearing sinters and silicified zones. Ore horizons are in the lower tuffs directly beneath the andesite and locally in the upper tuffs where the andesite is absent (Bartlett and others, 1991). Some ore is present in the andesite and in the Valmy Formation. Grade distributions shown by Bartlett and others (1991) indicate northeast- and northwest-trending fault-related ore controls, and the andesite and replacement silica bodies served as hydrologic barriers to ascending gold-bearing fluids.

The gold and mercury deposits likely formed from the same hydrothermal system. Adularia from the Hollister deposit yielded a K-Ar age of 15.1±.0.4 Ma (Bartlett and others, 1991), consistent with the 15.3 Ma age of the altered vitric tuff. However, surface sinters beneath the vitric tuff and weak silicification in the younger rhyolite porphyry domes indicate that the mineralizing process may have spanned several hundred thousand to perhaps a million years. Similarly, gold mineralization in the Midas district took place at about 15.3 Ma (recalculated from McKee and others (1976) using modern decay standards), and sinter deposits several kilometers northeast of the district formed in younger volcanic rocks.

SOUTHWESTERN SHEEP CREEK RANGE

New studies in the Sheep Creek and Shoshone Ranges have focused on the Izzenhood Spring 7-1/2 minute quadrangle in the southwestern part of the Sheep Creek Range, and on the Mule Canyon 7-1/2 minute quadrangle in the northernmost part of the Shoshone Range (fig. 1). These areas lie astride the northern Nevada rift. The Mule Canyon quadrangle contains the Mule Canyon mine, the largest known hot-spring gold deposit in the rift.

Stratigraphy

Rock units in the southwestern part of the Sheep Creek Range include Paleozoic sedimentary rocks and Miocene igneous rocks. These rocks are overlain by Quaternary surficial deposits that mantle much of the northeastern part of the Izzenhood Spring quadrangle (fig. 4).

Paleozoic sedimentary rocks

Lower Paleozoic sedimentary rocks crop out along the west flank of the Sheep Creek Range, which includes the southwest corner in the Izzenhood Spring quadrangle (fig. 4). They form more extensive outcrops in the adjacent Stony Point and Russells quadrangles. Paleozoic rocks consist of the Ordovician Valmy Formation and the Devonian Slaven Chert. The Valmy Formation consists of interbedded chert, quartzite, sandstone, siltstone, and argillite. The Slaven Chert consists of medium-gray to black chert, less abundant sandstone, argillite, and greenstone, and local beds of black barite. Both formations are complexly juxtaposed by thrust faults.

Miocene igneous rocks

Miocene igneous rocks unconformably overlie the Paleozoic rocks and cap most of the Sheep Creek Range. In the Izzenhood Spring quadrangle, a sequence of four major rock units has been identified: basalt-dacite unit, porphyritic dacite, porphyritic rhyolite, and olivine basalt.

Basalt-dacite unit

The oldest igneous rocks in the southwestern Sheep Creek Range consist of aphanitic to sparsely porphyritic basalt, basaltic andesite, andesite, and trachydacite lava flows that form cliffs along the west flank of the range and much of the uplands of the Izzenhood Spring quadrangle (fig. 4). These rocks consist of numerous thin lava flows that range in composition from basalt to trachydacite (about 47 to 66 weight percent SiO_2) (fig. 5). More than 20 flow units are present in

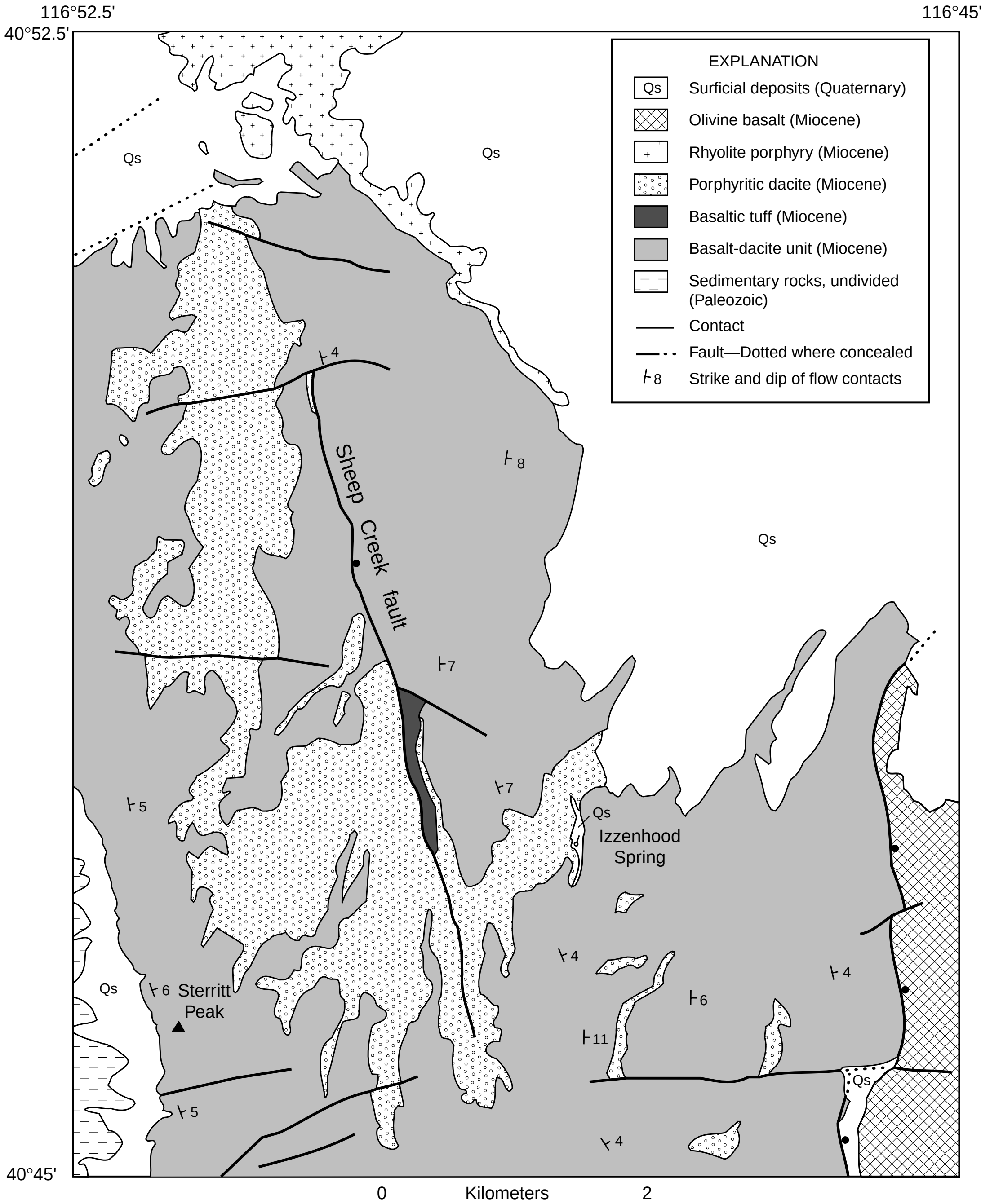

Figure 4. Generalized geologic map of the Izzenhood Spring 7-1/2 minute quadrangle. Geology mapped by D.A. John and C.T. Wrucke in 1997.

the 150- to 200-meter-high cliffs exposed along the western edge of the range, and many other flows are present farther east. Individual flows are marked by glassy, highly vesicular flow bases and tops and devitrified, massive flow interiors. All rocks in this sequence are aphyric to sparsely porphyritic, containing <2 volume percent phenocrysts. Basalt and basaltic andesite flows contain fine- to medium-grained plagioclase and (or) clinopyroxene phenocrysts in intergranular to intersertal groundmasses of plagioclase, clinopyroxene, and magnetite. Trachydacite lava flows commonly also contain sparse sieve-textured sanidine phenocrysts and have trachytic to pilotaxitic groundmasses. On the east side of the Sheep Creek fault, several areas of basaltic tuff as much as 120 m thick underlie porphyritic dacite lava flows and a dacite sill

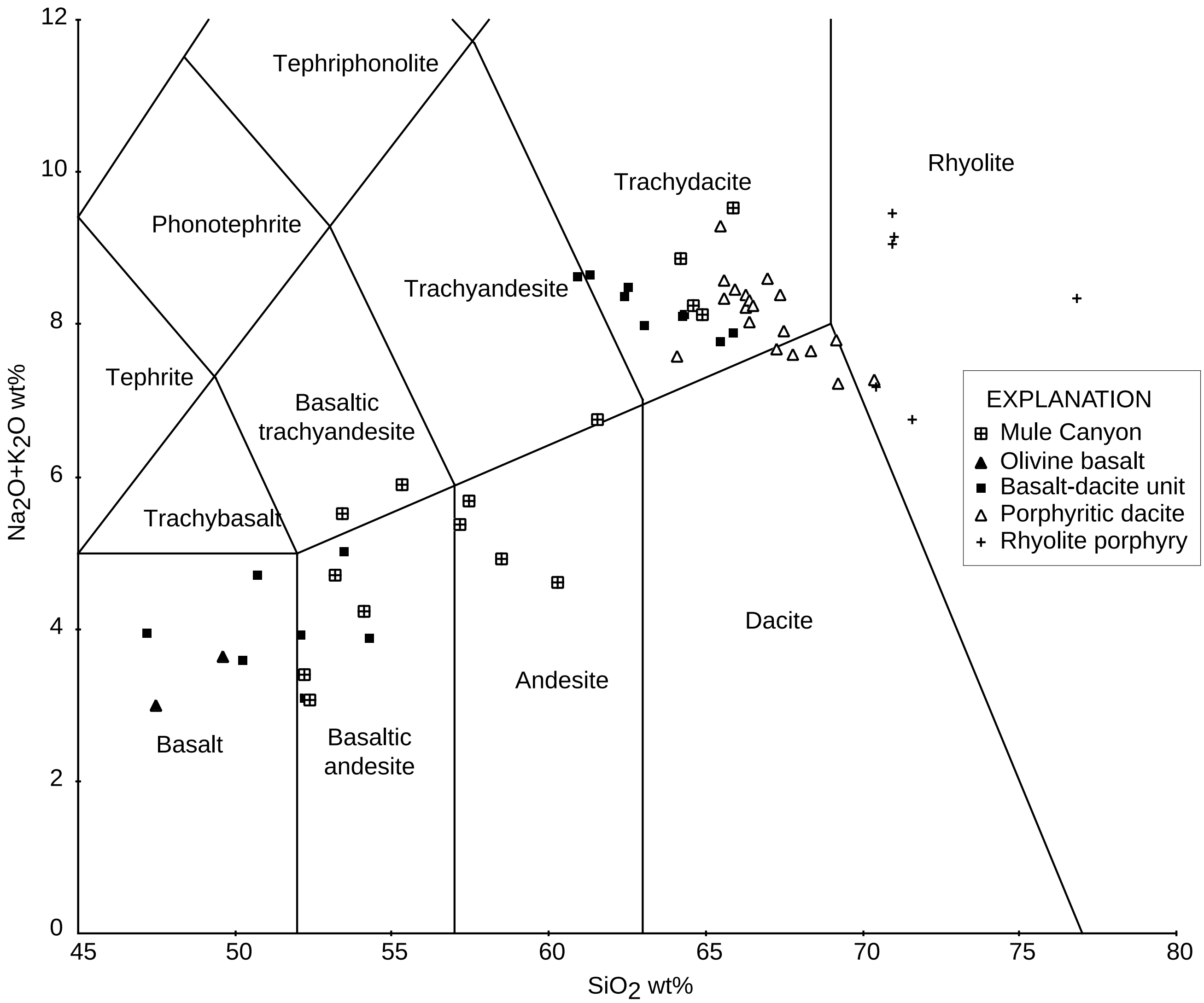

Figure 5. Total alkali-silica diagram for rocks in the Izzenhood Spring quadrangle and from the Mule Canyon mine area, northern Shoshone Range. Major-element oxides recalculated to 100 percent volatile-free. Rock names are IUGS classification (Le Bas and others, 1986).

(fig. 4). The tuffs are dark brown to brick red, finely bedded, poorly to densely welded, and nearly aphyric. They are very similar to pyroclastic units (lapilli ash tuffs) in the Mule Canyon mine that there host much of the gold mineralization (Thomson and others, 1993; Serenko, 1995).

Chemical and petrographic analyses indicate that there is no regular pattern of compositional variation with stratigraphic position in this sequence. However, the lowest flows in the sequence have basalt to basaltic andesite compositions, whereas most of the upper parts of the sequence have more silicic compositions. Basalts locally are present in the upper parts of the sequence. In addition, there is an apparent gap in compositions between about 54 to 61 weight percent SiO_2 in the Sheep Creek Range (fig. 5). Rock units in the Mule Canyon area in the northern Shoshone Range have SiO_2 contents in this compositional gap (see below).

McKee and Silberman (1970) reported a whole-rock K-Ar age of 15.2±0.5 Ma (recalculated using modern decay constants) on a lava flow collected along the crest of the Sheep Creek Range about 1 km south of the Izzenhood Spring quadrangle. Additional K-Ar and $^{40}Ar/^{39}Ar$ dating of this and other Tertiary units in the southwestern Sheep Creek Range is underway.

Porphyritic dacite unit

Much of the central part of the Izzenhood Spring quadrangle is underlain by bodies of porphyritic dacite (fig. 4). Most of these rocks form the uppermost parts of a large dacite stock that is inferred to underlie much of the southwestern part of the Sheep Creek Range. Thick sequences of lava flows of similar composition and appearance are present in the northern Shoshone Range, principally in the Mule Canyon quadrangle, along the Argenta Rim, and on much of the upper slopes of the Malpais Rim farther to the south (fig. 1; Struhsacker, 1980; Thomson and others, 1993).

The texture of the porphyritic dacite varies significantly. Margins of the intrusions are black vitrophyres. Locally, the upper few meters of the vitrophyre is strongly vesiculated, forming a scoriaceous-like rock. The vitrophyre grades downward and inward into irregular zones of spherulitic devitrification characterized by abundant reddish-brown spherulites that are 0.5 to 6 cm in diameter. The spherulitic zones grade downward and inward to massive, dark-red to lavender-gray, devitrified dacite that is subhorizontally layered, giving the rock the appearance of lava flows. The dacite generally contains 5 to 20 percent phenocrysts consisting of plagioclase, clinopyroxene, magnetite, and minor olivine. The phenocrysts range in size from 0.1 to 4 mm but are mostly <1 mm. The phenocrysts commonly occur in small glomeroporphyritic clots.

Chemical analyses of the porphyritic dacite indicate a relatively restricted range of composition between about 64 to 69 weight percent SiO_2, making the rocks trachydacites and dacites, according to the IUGS chemical classification (fig. 5). These rocks have notably high K_2O contents (fig. 6) that are comparable to compositions reported by Struhsacker (1980) for similar lava flows in the Malpais Rim area about 30 km to the southeast. No radiometric ages are available at present for the porphyritic dacite unit in the Sheep Creek Range, but Struhsacker (1980) reported a K-Ar age of 16.1±0.6 Ma for a lava flow in the Malpais Rim area.

<u>Rhyolite porphyry unit</u>

Coarse-grained rhyolite porphyry domes and related lava flows crop out in the northwest corner of the Izzenhood Spring quadrangle (fig. 4). These rocks are the southernmost part of a large rhyolite dome field that forms much of the area between the Sheep Creek Range and the Midas trough about 35 km to the northwest (fig. 1; Stewart and Carlson, 1978; Stewart and McKee, 1977; Wallace, 1993).

In the Izzenhood Spring quadrangle, rhyolite porphyry is both intrusive and extrusive; the northern half of the porphyry is in domes that intrude the basalt-dacite unit, whereas the southern half of these exposures are lava flows that overlie the basalt-dacite unit. The intrusive rocks are devitrified, commonly strongly flow banded, and spectacularly jointed, as described by Stewart and McKee (1977, p. 46-47). Extrusive parts of the unit are chilled against the underlying basalt-dacite unit forming black vitrophyre that grades upward into red to pinkish-gray, devitrified, subhorizontally flow-banded rock. The rhyolite porphyry contains about 15 to 30 percent seriate phenocrysts of sanidine, quartz, plagioclase, and fayalitic(?) olivine in glassy to microcrystalline groundmasses. Feldspar and rounded quartz phenocrysts are as much as 8 mm across. McKee and Silberman (1970) reported sanidine K-Ar ages of 14.2 and 14.3 Ma (recalculated) for rhyolite porphyry flow domes about 7 km north of the Izzenhood Spring quadrangle.

<u>Olivine basalt unit</u>

The southeastern part of the Izzenhood Spring quadrangle is underlain by dark-gray to black olivine basalt lava flows that are downfaulted against the basalt-dacite unit (fig. 4). The basalt flows make up most of the large tableland of the Sheep Creek Range to the northeast (Stewart and McKee, 1977). They contain scattered, small (<2 mm) olivine phenocrysts in a fine-grained, subophitic groundmass of plagioclase, clinopyroxene, and magnetite. They also contain abundant, very fine-grained vesicles, producing a spongy texture. No radiometric ages are available for this unit in the Izzenhood Spring quadrangle, but McKee and Silberman (1970) reported a whole-rock K-Ar age of 10.3 Ma (recalculated using modern decay constants) for a possibly correlative olivine basalt lava flow farther northeast in the Sheep Creek Range.

Surficial deposits

Late Quaternary surficial deposits cover most of the northeastern quarter of the Izzenhood Spring quadrangle and are extensively exposed on the west side of the quadrangle (fig. 4). The most extensive units are thin(?) deposits of caliche and eolian silt and sand that cover a pediment surface in the northeast quarter of the quadrangle. Prominent sand dunes and other alluvial deposits are present in the northwest corner of the quadrangle, and extensive talus deposits are present along the west edge of the quadrangle, where they cover the contact between Paleozoic sedimentary rocks and the basalt-dacite unit.

Late Cenozoic structure

The Sheep Creek Range is a gently east-tilted horst formed by late Cenozoic Basin and Range faulting. The range is bounded on the west by a north-northwest-striking fault with late Quaternary displacement (Dohrenwend and Moring, 1991) that parallels the northern Nevada rift and results in nearly 1 km of topographic relief between the crest of the range and the Humboldt River valley to the west (fig. 1). Total offset on this fault estimated using gravity data is 2 to 2.5 km (D.A. Ponce, oral commun., 1997). This range-bounding fault may be a reactivated middle Miocene fault that was active during formation of the northern Nevada rift. The Sheep Creek Range has undergone relatively little post-middle Miocene tilting.

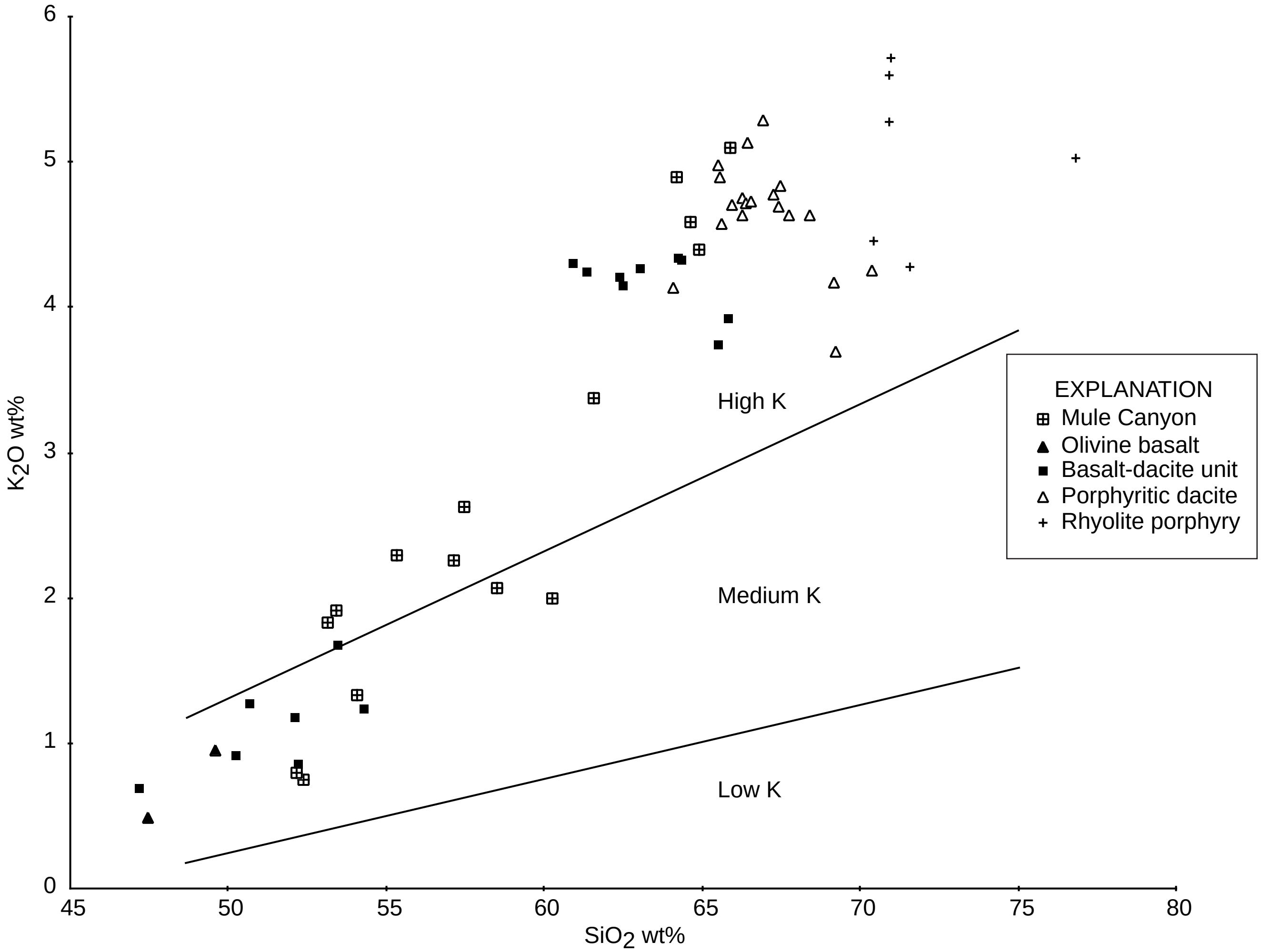

Figure 6. K_2O-silica diagram for rocks in the Izzenhood Spring quadrangle and from the Mule Canyon mine area, northern Shoshone Range. Major-element oxides recalculated to 100 percent volatile-free. High-, medium-, and low-potassium fields from LeMaitre and others (1989).

Average dips on lava flows in the basalt-dacite unit are about 5° east, with strikes ranging from about N30°W to N-S (fig. 4). The structure of the Izzenhood Spring quadrangle is dominated by high-angle normal faults. Relatively few faults have been mapped in the Miocene igneous rocks in the quadrangle, probably due in part to the lack of marker units. Two orientations of high-angle faults are evident: north- to north-northwest and east-northeast to east-southeast (fig. 4). The east-northeast-striking faults generally appear to cut the north-northwest-striking faults and are subparallel to young faults at the southern end of the Sheep Creek Range and the Argenta and Malpais Rims to the south (fig. 1; Stewart and McKee, 1977; Dohrenwend and Moring, 1991). The north-northwest-striking faults parallel the northern Nevada rift and probably influenced emplacement of the large porphyritic dacite stock that is elongated in this direction (fig. 4).

The most prominent fault in the Izzenhood Spring quadrangle is the N20°W-striking Sheep Creek fault in the upper parts of Sheep Creek (fig. 4). The fault dips about 70° east and is traceable along strike for 7 km. It is truncated on the north by an east-northeast-striking fault and appears to die out to the south (fig. 4). For much of its length, the fault juxtaposes the porphyritic dacite unit on the west with the basalt-dacite unit on the east. A prominent north-striking fault in the southeast corner of the quadrangle drops the olivine basalt unit against the basalt-dacite unit (fig. 4). This fault is offset in several places by east- to east-northeast-striking faults.

Zoback and others (1994) have shown that the east-northeast-striking faults reflect a change in the regional stress regime that began at about 10 Ma. North-northwest-striking faults characteristic of the northern Nevada rift formed during a period of extension when the least principal stress direction was oriented approximately N65-70°E. Between about 10 to 6 Ma, the least principal stress direction rotated approximately

40° clockwise, and the northeast- to east-northeast faults bounding the southern end of the Sheep Creek Range and the northeast end of the Shoshone Range (Argenta Rim) formed in this modern, approximately N70°W extension direction. The east-northeast-striking faults, such as those forming the Argenta Rim, are dominantly left-lateral oblique-slip faults that laterally displace the northern Nevada rift as much as 3.5 km along the Argenta Rim (Zoback and others, 1994).

Mineral Deposits

No mineral deposits or areas of hydrothermal alteration are present in the Tertiary rocks in the Izzenhood Spring quadrangle. Numerous prospect pits, several open-pit mines, and an underground mine are present in the Paleozoic rocks along the southwestern flank of the Sheep Creek Range, primarily in the Russells and Stony Point quadrangles. Most of the prospects and open pits were dug for bedded barite deposits in the Devonian Slaven Chert. However, little, if any, barite was produced from these workings. The underground workings are at the Snowstorm Mine in the Stony Point quadrangle. This mine produced silver-lead-gold ore at various times beginning in 1910.

NORTHERN SHOSHONE RANGE

Studies in the northern Shoshone Range, including collaborative work with Newmont Gold Company in the Mule Canyon mine area, are just beginning. Consequently, the following discussion is limited to new observations and preliminary interpretations. Studies in the northern Shoshone Range are focused on the Mule Canyon 7-1/2 minute quadrangle and include geologic mapping of the quadrangle based on mapping provided by Newmont Gold Co. for their claim block in and around the Mule Canyon mine and new mapping by C.T. Wrucke and D.A. John, petrographic, geochemical, and radiometric dating studies of Tertiary igneous rocks, and petrographic and SEM studies of hydrothermal alteration and gold mineralization in the Mule Canyon mine.

Tertiary Stratigraphy

Tertiary stratigraphy in the Mule Canyon quadrangle is more complex than it is in the southern Sheep Creek Range and includes early Oligocene to early Miocene volcanic and sedimentary rocks, in addition to middle Miocene igneous rocks related to the northern Nevada rift (Stewart and McKee, 1977; Struhsacker, 1980; Thomson and others, 1993). The oldest unit is the approximately 34-Ma Caetano Tuff, a regionally widespread, but only locally exposed, rhyolite ash-flow tuff that unconformably overlies Lower Paleozoic sedimentary rocks in the western part of the quadrangle. The Caetano Tuff is overlain by a poorly exposed sequence of Oligocene or early Miocene sedimentary rocks, including debris flows, conglomerate, sandstone, siltstone, and minor fresh-water limestone. The sedimentary rocks are overlain by thick sequences of middle Miocene igneous rocks related to the northern Nevada rift, which were deposited mostly into narrow, north-northwest-elongated grabens that were developing during volcanism. From oldest to youngest, these units include the Mule Canyon mine sequence, a series of mafic to intermediate composition lava flows and pyroclastic rocks that host most of the gold mineralization in the Mule Canyon deposit; basaltic andesite lava flows ("shear-banded normal flows"); porphyritic dacite lava flows; aphyric dacite lava flows ("roddy-platy dacite"); and capping basalt lava flows. In contrast to most of the lava flows in the southwestern Sheep Creek Range, the Mule Canyon sequence was erupted from nearby sources, including small cinder and spatter cones and other vents. Numerous north-northwest-trending dikes intrude the older rocks and probably were feeders for the lava flows. Some of these dikes intrude faults that controlled hydrothermal alteration and gold mineralization in the Mule Canyon mine, and the dikes are thought to be closely related to gold mineralization (Thomson and others, 1993; Eric Saderholm, oral commun., 1997).

Most of the Tertiary rocks in the Mule Canyon mine area are poorly dated, and new K-Ar and $^{40}Ar/^{39}Ar$ dating of these rocks and of hydrothermal alteration is in progress. Available K-Ar ages suggest that the upper part of the Mule Canyon mine sequence and the overlying basaltic andesite and dacite lava flows are about 16 to 17 Ma and that the capping basalt lava flows are about 10.6 Ma (see Thomson and others, 1993). However, no samples collected in the Mule Canyon quadrangle have been dated.

Preliminary chemical analyses suggest a fairly wide range of rock compositions in the Mule Canyon mine area between about 52 to 66 weight percent SiO_2, indicating that these rocks are similar to rocks in Sheep Creek Range (figs. 5 and 6). Interestingly, no rocks analyzed to date have basaltic compositions using the IUGS classification (Le Bas and others, 1986). Rocks thought to be most closely associated with gold mineralization here (mafic dikes) have basaltic andesite compositions.

Cenozoic structural history

Late Cenozoic structure in the Mule Canyon quadrangle is dominated by north-northwest- and east-northeast-striking high-angle faults that border two narrow north-northwest elongated grabens. These faults and grabens and rocks that fill the grabens are surface expressions of the northern Nevada rift (Struhsacker, 1980; Thomson and others, 1993; Serenko, 1995). In addition, the steep dips of the early Oligocene Caetano Tuff suggest that there were two periods of tilting that probably were related to several episodes of extensional faulting during development of the rift.

In the Mule Canyon area, the northern Nevada rift is about 13 to 16 km wide and is bounded by N15-30°W-striking high-angle normal faults, the West fault on the west and the Dunphy Pass fault on the east (Struhsacker, 1980; Thomson and others, 1993). A third, subparallel fault in the Mule Canyon mine area divides the western part of the rift into two grabens. These faults were active during formation of the rift, and volcanic rocks erupted during rift formation were deposited into grabens bounded by these faults. The Mule Canyon mine sequence is mostly limited to the western graben, which is about 2 to 3 km wide, whereas the eastern part of the rift is primarily filled by the overlying dacite and capping basalt units.

Northeast- to east-northeast-striking-faults generally crosscut the north-northwest-faults. Some of these faults, such as the faults that form the Malpais and Argenta Rims and are present in Whirlwind Valley, have late Quaternary displacement (Wallace, 1979; Struhsacker, 1980; Dohrenwend and Moring, 1991; Zoback and others, 1994). Other, older northeast-striking faults were active during gold mineralization at Mule Canyon, and high-grade gold ore was deposited at the intersection of some of these faults with the north-northwest-striking faults.

In the Mule Canyon quadrangle, there is a pronounced angular unconformity between the Caetano Tuff and the overlying Mule Canyon mine sequence. Isolated outcrops of the Caetano Tuff on the west side of the quadrangle strike N10-30°W and dip 35-75°NE. At least part of the overlying Oligocene to early Miocene sedimentary rock sequence also has steep northeast dips. In contrast, the Mule Canyon mine sequence and overlying rocks have shallow (10-20°) southeast dips, probably resulting from late Miocene and younger, northeast-striking faults at the Malpais and Argenta Rims (Struhsacker, 1980). The regional extent and exact age of the earlier tilting event are unknown. Oligocene rocks are absent in the southwestern Sheep Creek Range, and the Caetano Tuff only has gentle dips (<30°) on the east side of Battle Mountain Range 25 km to the west.

Mule Canyon deposit

Reconnaissance work to date includes petrographic and geochemical studies of igneous host rocks in the Mule Canyon mine area and petrographic and SEM studies of samples from two high-grade (>1 oz/ton Au) ore zones. Preliminary observations of these ore zones are summarized below and generally are similar to relations reported by Thomson and others (1993) and Serenko (1995). These observations suggest that there may have been multiple pulses of gold deposition and multiple generations of arsenic minerals.

Ore in the North Zone is hosted by mafic "normal" lava flows near the top of the Mule Canyon mine sequence and by mafic dikes. High-grade ore (as much as 30 oz/ton Au) is confined to narrow breccia zones near the margins of the dikes. Breccia fragments are pervasively altered to fine-grained adularia + quartz + pyrite and(or) marcasite ± minor arsenopyrite. Marcasite in breccia fragments is locally rimmed by arsenopyrite and silver selenides. At least three stages of brecciation are evident. Early breccia matrix is fine-grained pyrite cut by quartz + electrum ± pyrite. Late breccia matrix is quartz + minor pyrite. Much of the high-grade ore is oxidized, and visible and microscopic electrum has only been found in oxidized rocks in close association with Fe-oxides or jarosite. Electrum forms irregular crystals as much as 0.25 mm long (fig. 7*A*). Electrum composition ranges from about 70 to 80 weight percent gold and varies within single crystals. Minor argentite is present in gold-bearing breccia matrix.

High-grade ore in the Main pit (as much as 40 oz/ton Au) is in narrow zones at the intersection of N10-30°W-trending, steeply dipping dikes and faults and N30°E-striking faults. High-grade ore is primarily present in the margins of mafic dikes where they intrude mafic "flow tongue" units and lapilli ash tuffs in the upper part of the Mule Canyon mine sequence. The ore is unoxidized and locally contains as much as 20 weight percent sulfur (Eric Saderholm, oral commun., 1997). High-grade ore samples contain multiple generations of narrow (mm- to a few cm-wide) veins that cut intensely altered wallrock. Wallrocks in ore samples are pervasively replaced by adularia ± sericite + pyrite/marcasite or arsenopyrite (fig. 7*B*). Adularia is locally altered to sericite, making the rock highly friable. Adularia alteration is surrounded by broad zones of argillic and propylitic alteration (Thomson and others, 1993; Serenko, 1995) that contain much lower gold contents. At least 4 generations of veins are evident in high-grade ore samples. From oldest to youngest, they are: (1) narrow pyrite or marcasite ± quartz, (2) quartz + adularia + pyrite or marcasite, (3) vuggy quartz + pyrite locally containing arsenopyrite or arsenian pyrite inclusions ± minor adularia (figs. 7*C* to 7*E*), and (4) thicker (cm) quartz + coarse-grained pyrite or marcasite locally containing argentite inclusions. Arsenian pyrite locally rims marcasite in type 2 veins (fig. 7*F*). Sphalerite inclusions locally are present in marcasite (fig. 7*F*). Chalcopyrite and tetrahedrite locally are present in type 4(?) veins. No gold has been detected in these samples using petrographic and SEM techniques. Serenko (1995) also was unable to detect gold using these techniques in similar types of samples, but on the basis of laser-ablation ICP analyses, he suggested that gold is contained in arsenopyrite.

DISCUSSION

The current studies demonstrate several new facts about the volcanic rocks, structures, and deposits along the northern Nevada rift. These include: (**1**) rift-related magmas were not simply mafic in composition, but rather consisted also of intermediate-composition and locally felsic magmas; (**2**) pre-

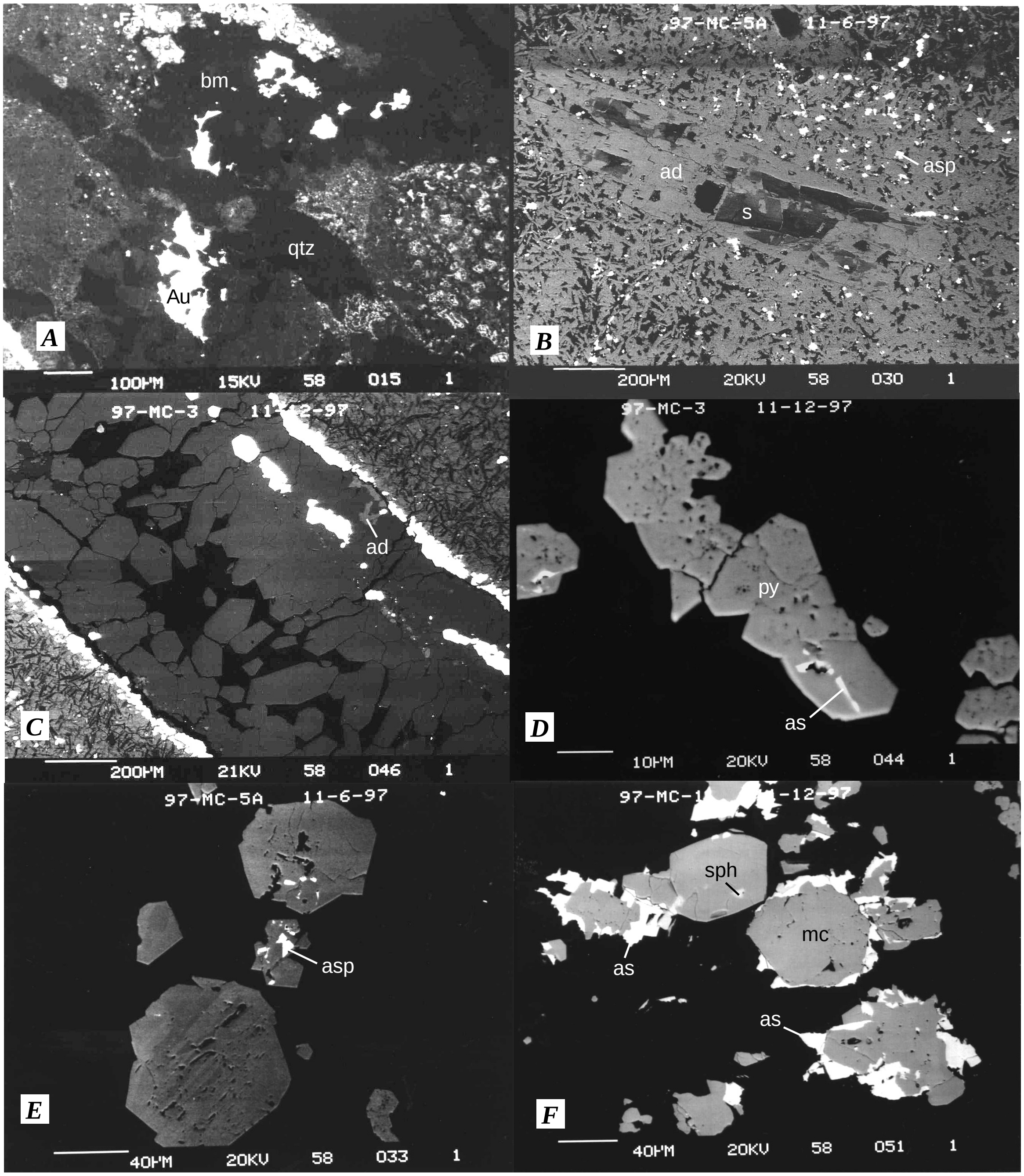

Figure 7. Back-scattered, scanning electron microscope images of ore textures from the Mule Canyon deposits. (***A***) Coarse electrum (Au) in quartz-adularia breccia matrix (bm) crosscut by barren quartz veinlet (qtz). Breccia fragments altered to adularia (ad) + quartz. Surface outcrop from North zone. (***B***) Adularized mafic dike from Main pit. Fine laths of adularia replace the groundmass and coarser adularia (ad) replaces a plagioclase phenocryst. Dark areas of the phenocryst are sericite (s). Disseminated, fine-grained arsenopyrite (asp) in groundmass. (***C***) Vuggy quartz + adularia + pyrite vein from high-grade ore in Main pit. Symmetric vein containing an outer band of pyrite + adularia (ad), an inner zone of pyrite + adularia, and terminated quartz that fills the center of the vein. Wallrock is pervasively altered to adularia + sericite (dark laths). (***D***) Enlargement of (*C*) showing white zones of arsenian pyrite (as) in pyrite (py) along outer edge of vuggy quartz-adularia-pyrite vein. (***E***) Marcasite (mc) crystals containing inclusions of arsenopyrite (asp). Quartz-marcasite vein from Main pit. (***F***) Arsenic-rich (as) rims on marcasite crystals in quartz vein from Main pit. Sphalerite inclusions (sph) are also present in marcasite crystals.

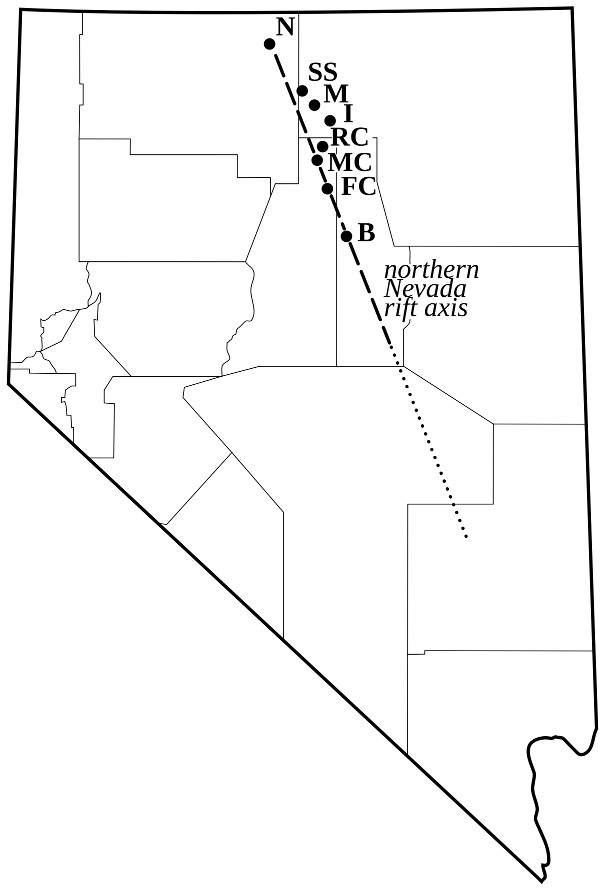

Figure 8. Distribution of epithermal and hot-spring gold, silver, and mercury deposits and occurrences associated with the northern Nevada rift. Dashed line is axis of aeromagnetic anomaly associated with rift; dotted extension is continuation of anomaly with no surface expression of rift (Blakely and Jachens, 1991). N, National/Buckskin; SS, Snowstorm Mountain; M, Midas; I, Ivanhoe, RC, Rock Creek; MC, Mule Canyon; FC, Fire Creek; B, Buckhorn.

rift extension and block tilting took place between the early Oligocene and middle Miocene, producing a paleotopography marked by numerous highlands and basins; (**3**) rifting produced an elongate, fault-controlled basin in which rift-related volcanic rocks accumulated; and (**4**) high-grade, near-surface epithermal gold deposits, locally associated with hot-spring mercury deposits, formed along rift-related faults during volcanic activity.

Previous discussions of magmas related to the rift describe them as predominantly basaltic in composition, with minor rhyolite and dacite (Zoback and Thompson, 1978; Zoback and others, 1994), and basalts indeed are common along the rift. However, as shown herein, substantial amounts of intermediate-composition igneous rocks were also emplaced during rifting. This especially is true in the Mule Canyon and southern Sheep Creek Range areas, where dacites are common, and in the Ivanhoe area, where a unit described previously as a basalt (Bartlett and others, 1991) has an andesitic composition. Additionally, felsic pyroclastic and intrusive rocks are interbedded with rift-related basalt flows in the Snowstorm Mountains (Wallace, 1993), and early-rift rhyolite flows are present at Ivanhoe. As a result, the rift does not fit into a strict bimodal petrogenetic model, but instead includes a wide range of magma types.

Based on evidence at Mule Canyon and Ivanhoe, faulting and block tilting took place sometime between the early Oligocene and middle Miocene. At Mule Canyon, shallow-dipping Miocene basalt flows overlie steeply dipping Oligocene tuffs. At Ivanhoe, tilting of as much as 20° took place after the late Eocene and before the eruption of middle Miocene volcanic rocks. Faulting related to this event likely produced an irregular middle Tertiary paleotopography, with highlands in the Sheep Creek Range, Carlin-Hollister, and Snowstorm Mountains areas, and a basin between Hollister and the Snowstorm Mountains. Pre-middle Tertiary volcanic rocks were stripped from the highlands, and tuffaceous sediments accumulated in the basins. In northeastern Nevada, the major tectonic event during this period was extensional faulting at about 20 Ma, although relatively little tilting was associated with that event (Thorman and others, 1991).

Rift-related faulting produced a north-northwest-trending graben or series of grabens in which volcanic rocks accumulated. Dikes and elongate intrusions were emplaced along many of the faults, producing dikes swarms in many locations (Zoback and others, 1994). In the Snowstorm Mountains, the trough was approximately 30 km wide, based upon the distribution of rift-related flows (Wallace, 1993). The graben was deepest along its central axis and shallower to the east and west, with flows thinning and pinching out in both directions, as at Ivanhoe. The 30-km-wide surface expression of the trough contrasts with the 3- to 5.5-km-wide magnetic anomaly that represents the magmatic feeder system for the volcanic rocks (Zoback and others, 1994). In the Mule Canyon area, the graben is only 10 to 15 km wide, and is shallower to the west than to the east. The dike swarm that is associated with that segment of the rift is 2-3 km wide and is in the western part of the graben.

Gold deposits associated with the rift (fig. 8) formed in shallow epithermal to hot spring environments. The epithermal deposits formed along faults (Midas), and along the margins of rift-related dikes (Mule Canyon). The Hollister deposit, which directly underlies a hot-spring mercury deposit, is disseminated in Miocene tuffaceous sedimentary rocks. All deposits formed in the narrow time interval of 15 to 15.5 Ma. The epithermal deposits are low-sulfidation, quartz-adularia systems. The Mule Canyon deposit contains gold-rich, arsenical rims on pyrite, similar to sedimentary rock-hosted deposits in the Carlin trend. In contrast, the Midas deposit contains very little arsenic and abundant selenium, and gold is present as electrum and native gold.

ACKNOWLEDGMENTS

Eric Saderholm of Newmont Gold Ltd. provided much information on the Mule Canyon deposit. Chris Henry of the Nevada Bureau of Mines and Geology provided three new $^{40}Ar/^{39}Ar$ dates on rocks from the Ivanhoe district. Analyses were performed at the New Mexico Geochronological Laboratory under the direction of Bill McIntosh; all dates are relative to an age of 520.4 Ma for Mmhb-1. Helpful reviews of the manuscript were provided by R.J. Fleck, C.D. Henry, and C.T. Wrucke. Susan Tingley drafted some of the figures.

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