

TEXT AND REFERENCES ACCOMPANYING NEVADA BUREAU OF MINES AND GEOLOGY MAP 195

Geologic Map of the Cobre SE Quadrangle, Elko County, Nevada

by

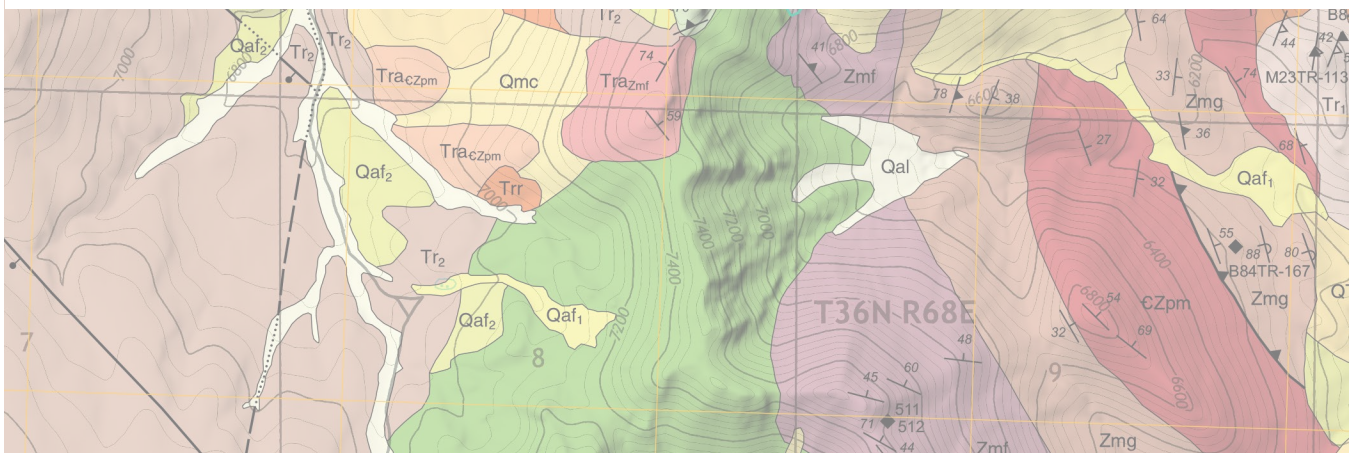
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INTRODUCTION

The Cobre SE quadrangle lies in the northern Toano Range, which is coextensive with the Goshute Mountains to the south (fig. 1), both in eastern Elko County, Nevada. Along with the Pequop Mountains, the Toano Range lies between highly extended terrane of the East Humboldt Range and Wood Hills on the west (fig. 1) and the Pilot Range on the east (Miller et al., 1987; Snoke and Miller, 1988; Thorman et al., 1987). The highlands that define the Toano Range are bounded by broad valleys on the east and west, with the eastern valley being at much lower elevation than the western valley. Typical relief from mountain crest to adjacent valley axis is 900 m to the eastern valley and 600 m to the western valley. Late Pleistocene lakes created distinctive beach deposits in both basins: Lake Bonneville (1,582 m highstand) formed on the east and Lake Waring (1,763 m) on the west.

This map of the Cobre SE quadrangle is related to a larger study of the Toano Range by Glick (1987) and her collaborators. Rocks and structures adjacent to the quadrangle play key roles for understanding aspects of the geology of the Cobre SE quadrangle. A simplified geologic map of the northern Toano Range is shown in figure 2 to illustrate some of these rocks and structures.

METHODS

We used standard geologic mapping methods to conduct detailed investigations during 1984 to 1987 of both bedrock and surficial materials. Mapping in the field was done on 1:24,000-scale topographic base maps and on 1:24,000- and 1:33,000-scale aerial photographs. The aerial photo linework was transferred onto topographic base maps using a PG-2 plotter. Final map linework was accomplished using heads-up digitizing of the scanned plotter lines and was adjusted in places using National Agriculture Imagery Program (NAIP) 2006 imagery in geographic information systems (GIS). Supplemental field study during 2022 to 2024 focused on specific small areas of complex geology and on the rhyolite of the Toano Range, henceforth termed the Toano Range rhyolite.

Field study was supplemented with chronologic control by K-Ar dating (Miller et al., 1990) as well as fossil identifications by U.S. Geological Survey paleontologists (Glick, 1987). K-Ar methods are described in Miller et al. (1990). Petrographic study of thin sections by the authors helped to identify minerals and textures. Subsequent chronology was by zircon U-Pb at the Stanford University and the U.S. Geological Survey Sensitive High-resolution

Ion Microprobe (SHRIMP) laboratory, and, along with similar dating by White (2023), established the ages of the plutons in the area; data and methods are provided by Miller et al. (2026b).

We also submitted samples of igneous rocks for whole-rock geochemistry that was conducted largely at U.S. Geological Survey laboratories, but a few were analyzed by contract laboratories. Methods are described in Felger et al. (2026) and Miller et al. (2026a).

Geophysical evaluation of the area by Grauch et al. (1988) used magnetic data and gravimetry to outline granitic bodies and to project the near-surface extents of plutons. Magnetization boundaries were the primary data source for identifying margins of plutons.

Tephrochronology was performed on samples of tuffaceous rocks in the Humboldt Formation, which are generally devoid of datable materials. The method analyzes the chemistry of glass shards by microprobe and correlates the result with dated samples. Data and methods are described by Walkup et al. (in press).

GEOLOGY

The geology of the Toano Range was presented by Stewart and Carlson (1978), Hope and Coats (1976), and Coats (1987). Pilger (1972) mapped the structure of the area of Silver Zone Pass, and Lee and Marvin (1981) and Lee et al. (1981) studied a muscovite granite (Toano Spring pluton). Studies subsequent to ours in the Goshute Mountains south of Silver Zone Pass were conducted by Day et al. (1987). The Toano Range terminates at the informally named Loray Pass in the north, north of which lies the Leach Range (Miller et al., 1984). Martindale (1981) mapped the area immediately north of Loray Pass.

The ca. 4- to 6-km-wide bedrock block that underlies the high ridges of the Toano Range in the map area is comprised of a nearly homoclinal section of metamorphosed Neoproterozoic to Cambrian rocks that dips east and northeast and is structurally overlain by little-metamorphosed Paleozoic strata. Neoproterozoic strata near the base are steep adjacent to the Cretaceous Toano Spring pluton, but most strata in the homocline dip at 45–30 degrees. The section is about 3,500 m thick, but only the upper part is exposed in the Cobre SE quadrangle. Cambrian strata of the area include type sections and reference sections for several formations (McCollum and Miller, 1991). The metamorphosed rocks are structurally overlain by younger little-metamorphosed strata along a major fault that dips nearly parallel to bedding in the footwall, and is interpreted

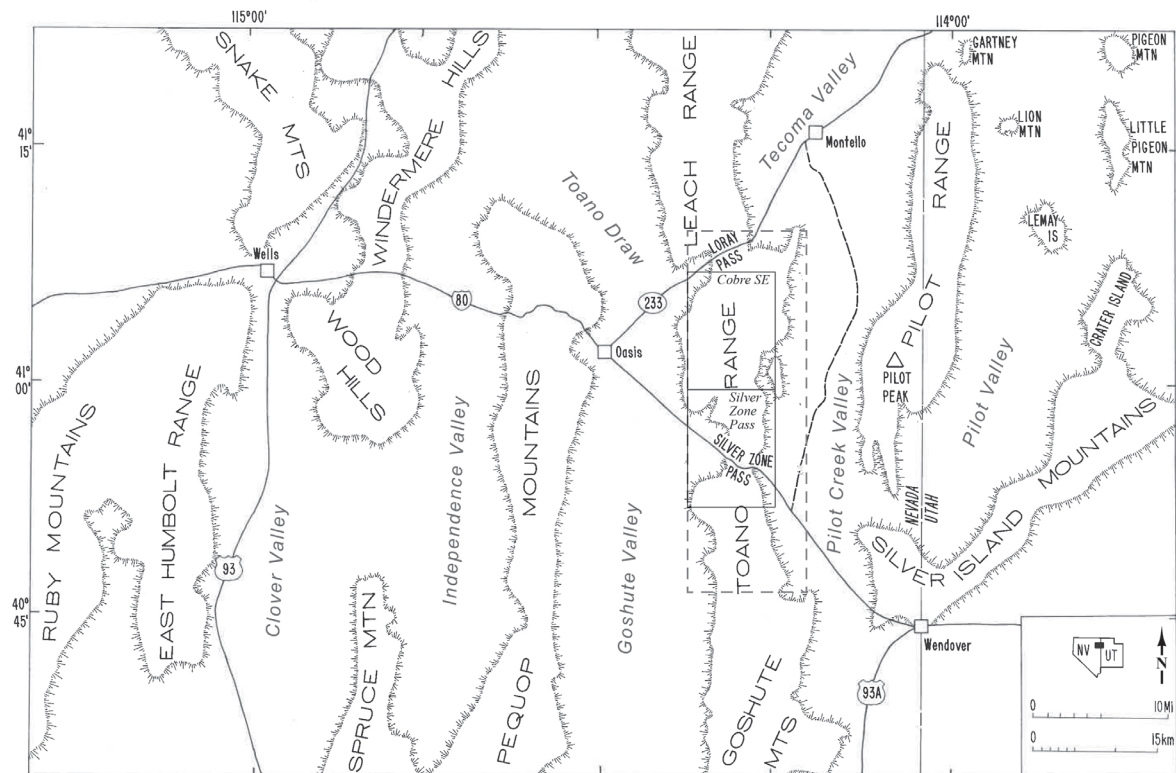


Figure 1. Map of northeastern Nevada and adjacent Utah showing place names, major highways, and locations of figure 2 (dashed line box) and Cobre SE and Silver Zone Pass quadrangles (solid line boxes).

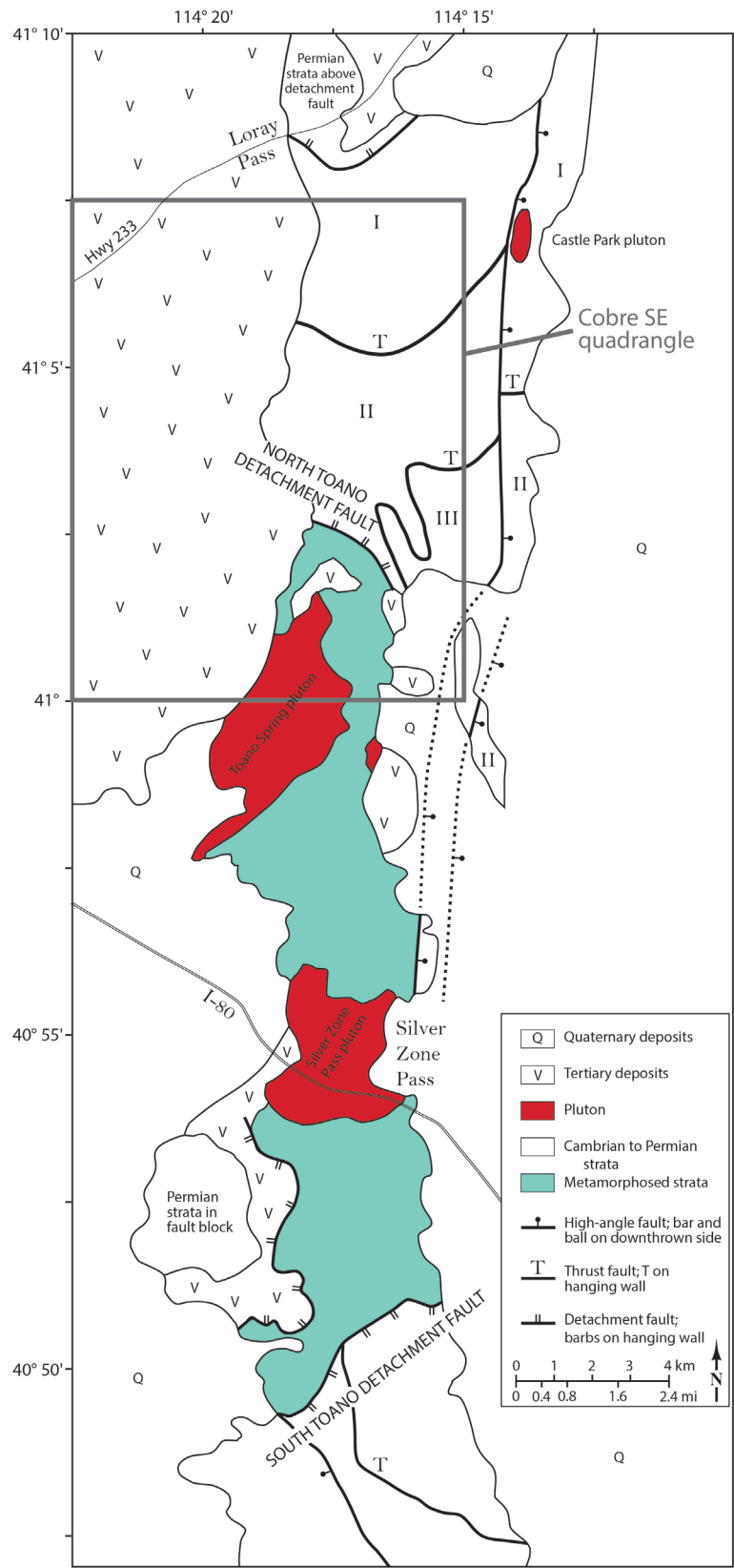


Figure 2. Simplified structural map of the northern Toano Range (after Glick, 1987). Roman numerals indicate thrust-faulted plates of Glick (1987).

as a detachment fault (Glick, 1987) that we term the “north Toano detachment fault” (NTD).

Paleozoic strata in the hanging wall of the NTD dip east and northeast and encompass Cambrian to Devonian strata. The Paleozoic rocks are cut by two main thrust faults that transport higher strata generally eastward relative to strata in lower thrust plates, based on map relations. The structural blocks or plates outlined by the thrust faults are termed I, II, and III (fig. 2) from the structural top (in the north) downward (to the south), following Glick (1987).

The Cretaceous Toano Spring pluton, a NNE-elongate ~3 x 11 km pluton, spans much of the southern part of the quadrangle. It is one of several Mesozoic muscovite (S-type) granites in the eastern Great Basin. The granite intrudes steeply dipping strata of Unit F of the McCoy Creek Group, apparently causing the steep dips that are localized near the pluton. Lee et al. (1986) showed that the Toano Spring body is geochemically and isotopically similar to Late Cretaceous granite bodies in east-central Nevada. The Toano Spring pluton was dated by zircon U-Pb approaches by White (2023) at 87 Ma (table 1). It has yielded Cretaceous and early Tertiary K-Ar ages of 71.7 ± 2.0 Ma and 62.9 ± 1.9 Ma for primary muscovite (Miller et al., 1990). Muscovite analyzed by $^{40}\text{Ar}/^{39}\text{Ar}$ yielded a simple spectrum with a plateau age of 77.1 ± 0.3 Ma, which we consider to be a cooling age following crystallization. This age is similar to the 75 Ma U-Pb age for apatite (a cooling age) obtained by White (2023). The probable deep (8–10 km) stratigraphic level of intrusion supports a prolonged cooling of the pluton and its host rocks (Miller and Hoisch, 1992). The Toano Spring pluton is not recognizable by geophysical methods, unlike the Silver Zone Pass pluton (Grauch et al., 1988). The latter does not extend north to the Cobre SE quadrangle based on aeromagnetic delineation of pluton margins. However, a ~5-km-wide band of possible buried pluton crosses the northern part of the quadrangle (Grauch et al., 1988), and may be related to the Eocene Castle Park pluton (table 1) that crops out east of the quadrangle (Glick, 1987).

Miocene strata are widely exposed west of the high Toano Range and in limited exposures on the east side (fig. 2). Typical rocks of the Miocene Humboldt Formation are siltstone, sandstone, limestone, and tuffaceous versions of these rocks, as well as thick tuffs. A widespread unusually U-rich topaz rhyolite unit lies within this sequence, as well as occurring in two remnant volcanic domes or necks. At least two thick rhyolite lava flows are present but poor exposure and numerous small faults make it difficult to determine the number of flows. In addition, the area contains breccias and lithic tuff are related to this topaz rhyolite (Glick, 1987; Price et al., 1992).

Piedmonts in the quadrangle are underlain by a wide variety of Quaternary sediments; in many places alluvial-fan sediment lies on shallowly dipping Miocene strata. Colluvium is present on many steep mountain slopes but is distinguished as a map unit mainly in areas of complex bedrock geology that render the underlying rock units uncertain.

Structure

Rocks of the northern Toano Range were grouped in a series of structural blocks bounded by high- and low-angle faults by Glick (1987). As shown in figure 2, Paleozoic rocks form a stack that can be divided into three imbricated thrust plates. The stack lies in the hanging wall of the NTD fault, which places less metamorphosed Paleozoic rocks on greenschist facies Paleozoic and Proterozoic metamorphic rocks that locally reach higher metamorphic grade near plutons. Similar structures occur south of Silver Zone Pass (fig. 2), thus defining a core of the range consisting of metamorphosed strata that center on Mesozoic plutons, all of which underlies the detachment faults. Normal faults bordering the eastern Toano Range drop Paleozoic rocks of plate II down against this core east of the Cobre SE quadrangle (fig. 2). Normal faults bordering the western Toano Range apparently cut some Miocene strata and the topaz rhyolite, but strata of the upper Miocene section were deposited upon the rocks of the range core. The tilting of Miocene strata mirrors that of rocks in the core of the range, down to the east, but is of lesser magnitude. We propose that part of the tilting was accomplished by an unseen underlying fault that tilted all rocks exposed in the Toano Range. Although most normal faults along the western side of the Toano Range are not exposed and located by offset strata, a fault that lies a short distance southwest of the quadrangle merits mention because it is identified by scarps in alluvial-fan deposits near 41.00873° – 114.389224° latitude/longitude and is probably Quaternary in age. Younger faults may be present along the west side of the Toano Range.

North Toano detachment fault

The NTD fault truncates footwall metamorphosed strata at low angles to bedding, brecciating the rocks. Strata in the hanging wall are at low to moderate angles to the underlying detachment fault (cross section B–B'). Cambrian strata are present in both the footwall and hanging wall, but the strata are distinct, with footwall strata representing moderate water-depth shelf-to-slope depositional setting

and hanging wall strata representing a shallow water shelf setting (McCollum and Miller, 1991).

Footwall of the North Toano detachment fault

Strata in the footwall of the NTD fault are Neoproterozoic to Cambrian in age and record low-grade metamorphism and penetrative strain throughout. Minor folds trend northeast and verge northwest. In addition, low-angle normal faults that are subparallel to bedding cut out the section. We interpret the faults as having been tilted along with bedding, a common relation in the region (e.g., Miller et al., 1987). One thrust fault, placing McCoy Creek Group Unit G over the Prospect Mountain Quartzite, also is nearly parallel to bedding. The higher plate contains overturned rocks well above the thrust, which may be interpreted as part of a west-verging fold but relations are somewhat ambiguous because much of the section is cut out by a splay of the NTD fault. All quartzofeldspathic and micaceous rocks are penetratively deformed, displaying crystal-plastic fabrics of aligned micas and elongate quartz with mosaic structure and subgrain development mantling cores of large grains. Feldspars are not ductilely deformed. Nearly all rocks have mineral assemblages consistent with greenschist facies metamorphism but an area 0.5 km northeast of the Toano Spring pluton exhibits amphibolite facies (Glick, 1987). The characteristic amphibolite facies assemblage is muscovite-biotite-garnet-staurolite. Following most or all of the ductile deformation, high-angle faults (present orientation) cut rocks of the footwall. The high-angle faults strike east, have inconsistent offset, and are cut by the Cretaceous Toano Spring pluton (Miller and Berg, 2022). The Toano Spring pluton rocks are ductilely deformed in several places but patterns of the apparent bands of deformed rocks within the pluton are difficult to define. Metamorphic mineral growth adjacent to the Toano Spring pluton led to porphyroblasts crosscutting the earlier penetrative fabrics. Dikes of muscovite granite are common in footwall rocks near the Toano Spring pluton but are not observed in the hanging wall of the NTD (Glick, 1987), which contains sparse hornblende-epidote-plagioclase phyrlic dikes with aphanitic matrices.

Hanging wall of the north Toano detachment fault

Strata in the hanging wall of the NTD fault are apparently unmetamorphosed but conodont alteration in Cambrian and Ordovician rocks indicates that they reached temperatures on the order of 300°C, with a few reaching

higher temperatures (Glick, 1987). Silty and shaley rocks do not show mica growth, unlike rocks of the footwall.

Structures in the hanging wall are diverse but can be divided into low-angle thrust faults that duplicate section (thrust faults) and minor structures within the structural plates that the thrust faults define. Glick (1987) termed the plates I to III, from structural top to base. Strata within the plates dip eastward about 45–50 degrees (cross sections A and B). Numerous splay faults, minor folds, and high-angle faults occur near the thrust faults. Folds plunge north-northeast to north-northwest and verge east with only one exception. A major recumbent anticline in plate II also verges eastward. The folds are consistent with eastward transport of the thrust plates, as are stratigraphic offsets. Plates I and II are comprised of sections from Cambrian to Devonian in age (part of the section lies east of the Cobre SE quadrangle), whereas plate III is comprised of Ordovician to Devonian strata. Facies changes are evident in Ordovician strata, with plate I strata of the lower Pogonip Group having more quartzite and dolomite beds than the same unit in plates II and III. The stack of thrust faults is interpreted as part of a duplex with greater than 3 km of eastward transport. The thrust faults were tilted down to the east along with Cenozoic strata, as described in a later section. Middle Paleozoic dolomitic strata (units SOle and DSLm) are anomalously thick in plate II near the feature labeled “Dg knob” on the map (~114.262196°W, 41.084080°N and shown in the eastern part of cross section A–A'). Markers for stratigraphic position are generally lacking in these units, making internal structure difficult to define. We interpret the thickened units as being folded by mesoscale folds, shown diagrammatically in cross section A–A'.

Sense of vergence and other inferences shown in the sections are not constrained by map data, but folds are shown to illustrate an observed thickening of the section. East-dipping thrust faults nearly parallel to bedding or east-dipping with respect to bedding are present in Ordovician strata in plate III (Examples are midway between “Dg knob” and the northern map border). They, and associated east-striking lateral ramp faults, result in small stratigraphic duplications, similar to thrust faults mapped within the Ordovician strata of several areas to the east in Utah where they have been shown to be Jurassic in age (e.g., Allmendinger and Jordan, 1984; Miller and Allmendinger, 1991). These nearly bedding-parallel thrust faults predate the imbricate flat-lying (present orientation) thrust faults.

Low-angle normal faults (shown on the map with the detachment fault symbol) are found within plates I and II. They are within 20 degrees of horizontal and place younger strata over older. Unlike the thrust faults, the low-angle

normal faults exhibit simple fault planes with few associated minor structures. Probable lateral ramp faults associated with the low-angle normal faults strike west to northwest. One low-angle normal fault cuts a Jurassic bedding-plane thrust fault within plate I near the north boundary of the map, and to the east of the Cobre SE quadrangle these normal faults are in turn cut by range-front faults. These parallel thrust and normal faults are consistent with the model of Camilleri et al. (1997) of Cretaceous thrusting (second pulse of thrusting of Zuza et al., 2020) followed by Cretaceous denudation in this hinterland position within the Sevier orogenic belt.

High-angle faults within the thrust plates form two sets with east and northwest strikes. The east-striking faults mainly occur in plate I, and do not have consistent offset relations. They generally are cut by the thrust faults, but a few cut minor east-dipping Jurassic thrust faults and may represent lateral ramps. Northwest-striking faults are most common in a zone northeast of the NTD fault, where they consistently dip to the northeast or are sinistral, and in some cases they cut or merge with the thrust fault at the base of plate II. About 2 km east of sample M87TR-77, an area of complex geology is outlined by several north-striking, east dipping faults that cut an east-striking fault. Rock units are folded to overturned in places. Structures of this area are cut by a northwest-striking fault. It is unclear if the east-dipping faults are bedding-parallel low-angle normal faults that were rotated to steeper orientations and what significance this faulted zone has.

Rocks of plate I are truncated north of the Cobre SE quadrangle by a composite detachment fault (fig. 2). Its lower strand places Mississippian rocks upon Silurian and Ordovician strata, and its upper strand places Permian rocks upon Mississippian (Miller et al., 1984; Martindale, 1981). Eocene volcanic rocks lie on both strands of the detachment fault (fig. 2, table 1; Miller et al., 2011).

Range-bounding normal faults

Bounding faults east of the Toano Range are exposed east of the Cobre SE quadrangle as two strands, about 1 km apart, that front much of the range (fig 2). Younger basin-bounding normal faults are interpreted to lie farther east, where they bound thick low-density basin fill deposits beneath Pilot Creek Valley (Glick, 1987). Complementary basin-bounding normal faults on the west side of the Toano Range may have diminishing throw northward as evidenced by reduced relief of the mountain range to the north and the presence of widespread Miocene rhyolite that were sourced from volcanic extrusive centers in the nearby bedrock block.

The rhyolite lies both on bedrock and on Humboldt Formation strata and is cut by several faults that drop it down to the west, but net throw on the faults is no more than several tens of meters. The strata beneath the rhyolite, the rhyolite, and strata above it all dip to the east. The majority of the section dips 20 to 30 degrees, but unit Thcs lies angularly above the lower strata and dips gently east. The rhyolite lies within the section of Humboldt Formation tuffaceous sandstone, as evidenced by conglomerate beds that lie north of and along strike with rhyolite outcrops. The conglomerate contains clasts of the rhyolite, blackened quartz grains, and sanidine, and is concordantly underlain and overlain by tuffaceous Humboldt Formation strata. None of the strata can be shown to be faulted against Paleozoic rocks at the range front. In addition, several rock avalanches exist along the west side of the range, where rhyolite forms breccia and rubble masses that apparently indicate steep slopes existed in the middle Miocene. We suggest that early range front faulting created steep slopes and down-faulted early basinal deposits west of the faults, and both faults and early deposits were overlapped by rhyolite flows. Subsequent offset along the range-front fault displaced the rhyolite and Humboldt Formation strata down but eventually ceased. Faults apparently migrated farther west, where rhyolite flows are faulted down to the west, and also the entire Toano Range block subsequently tilted down to the east, probably above a Miocene detachment fault that would daylight east of the range. Strata in the uppermost Humboldt Formation in the northern part of the quadrangle are subhorizontal to gently east dipping, indicating an upward decline in dip of the strata. The uppermost beds are overlain by a conglomerate unit, Thcs, that is derived entirely from strata currently exposed in the northern Toano Range and is tilted 5 to 10 degrees eastward. This sequence of strata with declining eastward dips and westward stepping-out of down-to-the-west faults provides strong support for late Tertiary down-to-the-east tilting of the entire mountain block.

Miocene Strata

Although Eocene volcanic and sedimentary rocks are known in the Loray Pass area (Martindale, 1981; Miller et al., 2011; fig. 2), these rocks do not occur in the Cobre SE quadrangle. The oldest Cenozoic strata are Miocene sandstone, siltstone, limestone, and tuff units of the Humboldt Formation. A ~13.0 to 12.5 Ma (table 2) topaz rhyolite that we informally name the Toano Range rhyolite intervenes within the Humboldt Formation section, and the uppermost section interfingers with angularly overlying

conglomerate (unit Thcs) derived from rocks presently exposed in the northern Toano Range.

Tuffs in the Humboldt Formation are primarily vitric units that range from 1–2 m to over 10 m in thickness and were deposited in varying environments. Lacustrine deposits are laminated to thin-bedded tuff and typically calcareous and show evidence such as ripples for wave reworking. Piedmont deposits are thick, may include pebbles in the lower parts, and have rhizoliths and thick soil development in the upper parts. Eolian tuffs display cross-beds and ripples with characteristic avalanche slopes, and range from 1 to 10 m in thickness. In nearly all cases, the vitric tuff lacks phenocrysts and pumice, but a few beds have small (<1 cm) pumice in basal parts and some of the subaerial tuffs incorporate lithics that include hornblende, sanidine, and quartz as well as fragments of typical rocks of the area such as quartzite, limestone, dolomite, and Eocene andesite. Tuffs of the Humboldt Formation that overlie the Toano Range rhyolite include fragments of that rhyolite. That the tuffs are primarily Snake River Plain-sourced tuffs is evidenced by the scarcity of phenocrysts and high-silica character. Ketner et al. (1998) reported a sanidine K-Ar age of 14.7 Ma for a tuff south of I-80 (table 1). We attempted K-Ar dating a hornblende-bearing tuff, but the resulting 27.4 Ma age probably indicates a large detrital component (table 1). K-Ar dates on glass separates for two tuffs yielded probable non-meaningful results of 7.5 Ma for each (Miller et al., 2026b). The tuffs apparently range from ~15 to 7 Ma in age, similar to other sections of the Humboldt and Salt Lake Formations in the vicinity (Miller et al., 2026b).

The Toano Range rhyolite is an unusual high-U rhyolite that contains small topaz crystals in vugs (Price et al., 1992) and is informally named for the Toano Range where it is exposed. Only two other occurrences of topaz rhyolite in Elko County are known (Coats, 1987). Three fundamental types of deposits are associated with the Toano Range rhyolite, along with several additional variations: near-vent lavas, lithic tuff, and lava flows. Near-vent rocks (Trv) underlie two peaks along the crest of the Toano Range, where they comprise complex masses of foliated and columnar-jointed dense rhyolite in nearly circular outcrop areas. The two vent lavas are compositionally distinct, the northeastern and larger one (Trv₁) having small hexagonal biotite phenocrysts visible by hand lens that the southwestern vent (Trv₂) lacks. In addition, the northern vent has sanidine, quartz, and plagioclase phenocrysts that are mostly medium-grain size but that range from medium to very coarse grained (0.5 to 2.5 mm); quartz is light gray to dark gray and black, evidently darkened by radiation damage in these U-rich rocks (Price et al., 1992).

The southwestern vent (Trv₂) has similar phenocrysts other than a lack of biotite, but the sanidine ranges in size to 5 or 6 mm, and quartz occurs in coarse crystals and in aggregates nearly as large as the sanidine phenocrysts and primarily is very dark gray to black. The southwestern vent area has much float and little outcrop with which its form can be constructed, but both vitrophyre and massive lava are present. In one area, columnar joints are nearly horizontal and perpendicular to the nearby granitic wallrocks. A wide dike or tilted flow extends north from the vent complex.

The northeastern vent area, in contrast, forms a massive outcrop about 1 km in diameter, and with 130 m of relief, exhibiting pervasive foliation that dips ~30–40 degrees east as well as columnar joints that are approximately perpendicular to the foliation, with columns plunging about 50 degrees to the west. The east flank of the lava mass appears to have east-overtaken folds suggesting flow in that direction. Beneath the lava and lying on limestone is a lithic tuff (Tlt) in which layering also dips east. The tuff shows deformed foliation around lithics that indicates flattening, and is progressively lithified upward to vitrophyre at the base of the lava; the lithic tuff is described in a following section. The margin of the lava is frothy breccia in places, reminiscent of carapace breccia. We suggest that the northern near-vent lava represents a flow-dome complex that flowed downhill to the east and west, and was subsequently tilted to the east. Thick vitrophyre and lithic tuff crop out east of the northern vent dome in a complex of interlayered lava and lithic tuff that are petrographically and geochemically similar to lavas of the northern dome. These flows evidently buried a ridge of Prospect Mountain Quartzite, now exposed between east-dipping lava and lithic tuff. A small knoll west of the northern vent, near 114.295443°W, 41.034612°N, is underlain by similar lava, but it is primarily breccia. More brecciated lava (unit Trr) lies west of the northern vent and may indicate lava flow down steep slopes.

Lava flows (Tr) are mapped west and east of the vents and, in many places, have been divided by phenocryst mineralogy into two compositions that correspond to those of the two vents: biotite present with smaller sanidine and quartz for unit Tr₁, and lack of biotite with large sanidine and quartz for unit Tr₂. Lava flows of unit Tr₁ generally crop out relatively close to the vent of that composition, lying east of the vent, in the valley immediately west of the vent area, in limited exposures farther northwest in that western valley, and in one location in the Silver Zone Pass quadrangle to the south. Flows of unit Tr₁ are dense, generally flow-banded, and thin northwestward to wispy, frothy breccia similar to carapace breccia. The flows in several places show abrupt

terminations that may represent former channel walls as well as steep flow margins. In several locations, the lava flows of Tr₁ are brecciated and hydrothermally altered to orange and red masses. Similar orange-altered breccia near northern exposures of this unit are overlain by lava of unit Tr₂. Exposures clearly demonstrating that flows of Tr₁ underlie those of Tr₂ are few but are definitive. Price et al. (1992) reported that lithic tuff with composition similar to Tr₁ lavas underlay the lava flows of Tr₂ in places; lithic tuff also underlies flows of Tr₁. Flows of unit Tr₂ are widespread and as thick as 30 m, and tend to be crystal-rich, vuggy, and massive. Westward from the proximal valley containing flow Tr₁ and lithic tuff, the flows of Tr₂ typically are northeast-tilted by faults that are rarely exposed but are closely located by topographic breaks in the flatiron geometry of the lava-capped ridges. In several places, the Tr₂ lava changes from base to top, and many such outcrops have a topographic break in the middle where rubble is common. We suggest that some of the outcrop area of the Tr₂ unit represent two flows.

A variant of the lava flows is mapped as rhyolite rubble (unit Tr_r). The rubble consists of boulder-size angular fragments of rhyolite lava that form planar masses mimicking flows but are not agglutinated, as are the locally brecciated Tr₁ flows. The rhyolite rubble deposits occur on steep western mountain flanks adjacent to the vents, where they lie on rock-avalanche deposits sourced from the east, and also occur in western fringes of the lava field. Those rubble deposits near the vents may represent primary brecciated flows formed along steep slopes, avalanche deposits, or flows that were subsequently fragmented by colluvial processes. They commonly preserve crude zoning of vitrophyre near the margins. The rubble deposits at the west edge of the field may also represent avalanche derived from fault scarps, but their origins are uncertain.

Lithic tuff (unit Tlt) is exposed both east and northwest of the rhyolite vents and is closely associated with the rhyolite unit Tr₁ as indicated by an identical phenocryst content in an ash matrix, as well as lithics of Tr₁-type rhyolite. Other common lithics include the Paleozoic and Proterozoic rocks, as well as Toano Spring pluton, dacite, and hornblende andesite (probably of Eocene age). A few lenses of rhyolite pebbles that appear to be fluvial in origin based on sorting and roundness are present. Although the lithic tuff typically carries biotite phenocrysts that link it compositionally to lava Tr₁, a few thick tuff sections lack biotite and possibly could have been related to the Tr₂ vent eruption. In many places, the lithic tuff is 10–12 m thick and has three subunits: a lower yellow, orange, or red altered and partly lithified tuff as thick as 5 m, a middle white, bedded

tuff that carries abundant pumice, and an upper thin yellow altered tuff. Humboldt Formation sediment and tuff concordantly underlies the lithic tuff but in a few places is discordant, dipping east more steeply than the tuff; it is commonly altered to reds and oranges similar to the lower lithic tuff. Within these altered intervals silicification is prominent as grain-to-grain cementation as well as subvertical partings and vein-like sheets composed of very fine-grained silica, perhaps modified from opal. Pumice blocks in the lithic tuff range from 50 cm diameter in southern outcrops to less than 5 cm diameter in the northernmost outcrop, and lithic clast size also decreases northward. There are few indications that the tuff represents an ignimbrite, and ash units draping lithics were observed in two places. A few graded fallout tuff beds are evident, and possible fluvial beds were noted. The evidence supports a fallout tuff origin, with energy and grain size decreasing away from the vent area, and both coincident and subsequent reworking by streams. The altered lower part may represent hydrothermal modification after the entire mass was relatively quickly emplaced, and the hot lower rocks self-altered below a cooled cap. The lithic tuff, like unit Tr₁, is limited to outcrops near the vents and shows rapid changes in thickness consistent with topographic control of the deposits. In contrast, the flows of unit Tr₂ are widespread and indicate that any preexisting topographic irregularities may have been smoothed by infilling of tuff and unit Tr₁ flows.

In thin section, the Tr₁ rocks are crystal-rich, containing abundant embayed quartz, sanidine, and minor biotite in a devitrified groundmass that may be flow-banded and generally contains tiny late-phase crystals of uncertain composition. Some flows are finer grained than the majority. Tr₂ rocks are crystal-poor to crystal-rich, with embayed quartz and sanidine making up nearly all of the phenocrysts; both range from subhedral to euhedral. Rare biotite occurs. Broken phenocrysts and pumice are uncommon. The groundmass is complex, consisting of vugs partially to entirely filled with microcrystalline material, and variable textures in devitrified materials. Lithic tuff carries abundant pumice and large quartz and sanidine that are angular to subangular; some quartz is embayed. Lithics include rhyolite, fine-grained quartz sandstone, and siltstone.

A K-Ar age for sanidine, separated from unit Tr₂, of 12.9 ± 0.8 Ma (M81TR-06, table 1) was reported by Miller et al. (1990). The value for K₂O in the sample is lower than that expected for sanidine, which may be because quartz was included in the separate, which should not affect the validity of the result. We also dated a biotite-bearing lithic tuff (M90TR-37), which yielded a K-Ar biotite age of 12.5 ± 0.6

Ma (table 1). The ages for tuff and lava flow are indistinguishable at 95% uncertainty, and along with the outcrop evidence for closely spaced eruptions, such as lack of intervening sediment or soil formation, indicate eruptions between approximately 13.0 and 12.5 Ma.

The geochemistry of the Toano Range rhyolite is consistent with topaz rhyolites of the eastern Great Basin (Price et al., 1992) in having high values of SiO₂, U, and Th; and somewhat elevated values for rare earth elements (REE). Values of Rb, Th, La, and Lu allow separation of the two lava types of the Toano Range rhyolite. Topaz rhyolites differ from other young rhyolites of the northeastern Great Basin, where two distinct types have been described. Rhyolites of Miocene age in the northeastern Great Basin carry hydrous phases, typically biotite, and are phenocryst-rich. In contrast, rhyolites of the Snake River Plain (SRP) have low phenocryst content and few hydrous phases (Bonnichsen et al., 2008). The Toano Range rhyolite differs from both of these sets of rhyolites in having low Zr and Ba, along with high Rb, U, Th, and heavy REE.

Metamorphism

Greenschist facies metamorphism of the Neoproterozoic and Cambrian rocks in the Cobre SE quadrangle is defined by widespread muscovite, biotite, and chlorite, with less common tremolite, actinolite, phlogopite, and tourmaline. Amphibolite-facies mineral assemblages are recognized at a few localities: muscovite, biotite, staurolite, and garnet that indicate almandine-amphibolite facies, and hornblende-bearing calc-silicate rocks (Glick, 1987). K-Ar analysis of metamorphic biotite and muscovite from greenschist-facies rocks east of the main mass of Toano Spring pluton have yielded Cretaceous and Tertiary ages of: (biotite) 94.5 ± 4.8 Ma and (muscovite) 69.7 ± 3.4 Ma, 61.4 ± 3.0 Ma, 76.1 ± 4.2 Ma, and 73.0 ± 4.0 Ma (table 1). The oldest result is for a sample about 1.2 km from the pluton; other samples were collected near the pluton. Near the pluton, porphyroblasts commonly grow across foliation defined by prograde minerals, evidently indicating sustained temperatures following strain. These data are consistent with the hypothesis that regional metamorphism predated the 95 Ma muscovite cooling age and the Toano Spring pluton emplacement, and that post-deformation mineral growth occurred near the pluton as a result of heating by the magma. Furthermore, K-Ar ages for biotite in the Silver Zone Pass pluton south of the Cobre SE quadrangle are Jurassic in age, and metamorphic grade is greater near the pluton, indicating that the widespread regional metamorphism is probably Jurassic or older (Miller and

Berg, 2022). Pilger (1972) and Miller and Hoisch (1992) argued that fabrics are locally truncated by the Silver Zone Pass pluton (~158 Ma), indicating that initial metamorphism and deformation was Jurassic in age. This is similar to timing in the adjacent Pilot Range, where ductile faults parallel to bedding are early metamorphic (Jurassic) in age, and in the adjacent Pequop Mountains, where ~160 Ma dikes intruded a thrust fault, and metamorphism is considered to be Jurassic in age (Camilleri and McGrew, 1997; Zuza et al., 2020). In all cases, a detachment fault truncates metamorphic rocks; in the Pilot Range this detachment event predates or is synchronous with Eocene dikes (Miller and Hoisch, 1992).

DESCRIPTION OF MAP UNITS

Surficial Deposits

Qal Young alluvium (Holocene) Poorly sorted sand, silt, and gravel in ephemeral stream channels.

Qaf₁ Young alluvial-fan deposits (Holocene) Poorly sorted sand, gravel, and silt deposited in alluvial fans and amalgamated fans of piedmonts. Weak soils generally consist of dark A horizon, stage I calcic horizon. Thickness 1 to 3 m.

Qmc Colluvium (Holocene) Rocky debris on steep slopes, transported by a combination of mass movement and flowing water.

Qaf₂ Old alluvial-fan deposits (Pleistocene) Poorly sorted rocky sand and silt, generally with lenticular beds. Soil development includes stage III calcic horizon. Up to 5 m thick.

QTaf₃ Old alluvial-fan deposits (Pleistocene and Pliocene) Coarse boulder to pebble gravel with clasts of limestone, dolomite, and quartzite, and lesser rhyolite. Locally indurated with thick stage IV calcic horizon. Thickness variable, commonly 5 to 10 m thick.

Bedrock Units

Humboldt Formation (Miocene)

Thcs Conglomerate and sandstone Thick sequence of medium- to thick-bedded conglomerate with sandstone and minor tuff interbeds. Angularly overlies tilted tuff and sandstone (units Tht and Ths) but is itself tilted and contains interbeds typical of those within units Tht and Ths. Clast assemblage similar to nearby exposed bedrock of the northern Toano Range. Thickness about 10 to 30 m.

Ths Sandstone White, yellow, and gray, generally very thin- to medium-bedded, tuffaceous sandstone, with beds of siltstone, limestone, oolite, and conglomerate. Includes dark brown conglomeratic sandstone beds north of the northernmost flows of rhyolite unit Tr₂, that can be traced for several km north; the beds are composed of lithic debris of the rhyolite. In general, lower part of section (in the west) is less tuffaceous than the upper part.

Tht Tuff Light gray vitric tuff. Mapped only where thick tuff units are laterally extensive or where several thin tuffs form a thick section that is predominantly tuff. Many individual tuff units are coarse to fine grained, fining upward in general, and grade upward into brown, heavily burrowed massive tuffaceous material that represents soil development.

Toano Range rhyolite (Miocene)

Dark brown, gray, and maroon flow-banded rhyolite forming thick flows. Basal vitrophyre as thick as 3 m associated with lava flows greater than 10 m thick. Sanidine, plagioclase, biotite, and embayed quartz phenocrysts in microcrystalline matrix. Vugs contain topaz and quartz (Price et al., 1992). Dated by K-Ar at 12.9 ± 0.8 Ma (table 1). Subdivided into:

Tr₂ Upper lava flows bearing large phenocrysts of quartz and sanidine. Forms massive cliffy outcrops with extensive vug development, 10 to 30 m thick.

Trv₂ Vent lava and breccia similar in composition to the upper flows.

Tr₁ Lower lava flows bearing biotite and small phenocrysts of quartz and sanidine. Thickness 1 to 8 m.

Trv₁ Vent lava and breccia similar in composition to the lower flows.

Trr Rubble and breccia of rhyolite similar in composition to the rhyolite flows. Thickness 5 to 10 m.

Tlt Lithic tuff unit. Complex unit of altered tuff, lava, and lithic fragments that forms a crudely layered tripartite section: Orange colors in the lowest part, white colors in the middle, and yellow in a thin upper part. In exposures west of the vents, unit is about 12 m thick at greatest; thins northward as lithic clast size decreases. In exposures east of the vents, unit is poorly exposed between lava flows of unit Tr₁, is massive and as thick as 20 m. Dated by K-Ar at 12.5 ± 0.6 Ma (table 1).

Rock avalanche masses (Miocene)

Monolithologic breccia exposed as both large intact blocks and boulder-size jumbles are common west of the vent areas of Toano Range rhyolite and are present in a few other locations. We interpret these masses as rock avalanches. Relations with Humboldt Formation rocks are ambiguous, but landscape position is suggestive of the breccia masses being older than the upper part of the Humboldt Formation. Toano Range rhyolite overlies a few breccia masses. Many avalanche masses lack a source in modern topography, indicating that an ancient steep high escarpment has been modified. Divided by rock unit; source unit given in subscript:

Trad_g Rock avalanche of Guilmette Formation.

Trad_s Rock avalanche of Simonson Dolomite.

Trasole Rock avalanche of Ely Springs and Laketown Dolomites, undivided.

Tra_{opl} Rock avalanche of lower Pogonip Group.

Trao_{enp} Rock avalanche of Notch Peak Formation.

Trac_{ob} Rock avalanche of Big Horse Limestone Member of the Orr Formation.

Trac_c Rock avalanche of Clifside Limestone.

Trac_t Rock avalanche of Toano Limestone.

Trac_{ks} Rock avalanche of Killian Springs Formation.

Trac_{zpm} Rock avalanche of Prospect Mountain Quartzite.

Trazmf Rock avalanche of McCoy Creek Group Unit F.

Cretaceous Intrusive Rocks

Kts Toano Spring pluton (Cretaceous) White to light-gray, subequigranular muscovite-biotite monzogranite, coarse to medium grained. Color index is 6–8, and quartz content is 35–45% (Glick, 1987). Muscovite phenocrysts in 1 cm books; biotite in 0.5 cm books. Also contains accessory garnet. Common aplite and pegmatite dikes contain muscovite and garnet. Foliation defined by flattened quartz and alignment of muscovite and biotite is parallel to margin of pluton. Cretaceous in age, 87 Ma, based on a U-Pb date (White, 2023).

Neoproterozoic and Paleozoic Sedimentary Rocks

Dg Guilmette Formation (Devonian) Pale-colored, cliff-forming, thick-bedded, medium- to dark-gray limestone with minor dolomite, silt partings, and chert more common in lower part. *Amphipora* beds are diagnostic. About 700 m thick.

Ds Simonson Dolomite (Devonian) Banded light- and dark-gray coarse-grained, thick-bedded laminated dolomite, locally cherty; forms ledges of alternating color. Local *Amphipora* beds are diagnostic. About 315 m thick.

DSlm Lone Mountain Dolomite (Devonian and Silurian) Light gray, coarse-grained dolomite forming a homogeneous unit. Round quartz sand grains present in upper part. About 210 m thick.

Srm Roberts Mountains Formation (Silurian) Basal dark gray to black chert beds and dolomite are overlain by distinctive platy, dark-gray, thin-bedded limestone. Limestone is overlain by alternating banded brown sandy dolomite and fossiliferous dark-gray dolomite. Corals are common. About 360 m thick.

SOle Ely Springs Dolomite and Laketown Dolomite, undivided (Silurian and Ordovician) Dark-colored dolomitic rocks that are commonly difficult to separate. The Ely Springs Dolomite is divided into a lower unit of dark- and light-gray sandy dolomite with beds of dark cherty pods, overlain by dark gray to black, fossiliferous dolomite, succeeded by dark gray mottled dolomite with distinctive burrows (Budge and Sheehan, 1980). The overlying Laketown Dolomite consists of bioclastic medium- to dark-gray dolomite, much of it fossiliferous. Combined unit about 240 m thick.

Oe Eureka Quartzite (Ordovician) White, gray, and bluish-gray vitreous quartzite, thin to medium bedded. Distinctly cross-bedded. Quartz grains are well rounded and well to moderately sorted, exhibit suturing, incipient recrystallization as subgrain growth, and pressure solution. Rare conglomerate beds. About 140 m thick.

Ol Lehman Formation (Ordovician) Medium- to dark-gray silty limestone and brown to red mottled siltstone. Commonly dolomitic in upper part, which was referred to as the Crystal Peak Dolomite by Coats (1987). Abundant fossils include gastropods, bryozoans, and ostracods; rare brachiopods are present as well. About 345 m thick.

Ok Kanosh Shale (Ordovician) Brown shale and mottled calcareous siltstone, very thin bedded, forming slopes. Abundant fossils of brachiopods, trilobites, ostracods, and graptolites. About 60 m thick.

Opl Lower Pogonip Group (Ordovician) Silty gray limestone and dark blue-gray limestone forming cliffs and steep slopes. Siltstone occurs as thin wavy beds and as mottles within the limestone. Chert is common; colors are variable. Fossiliferous, with common gastropods, brachiopods, and crinoid debris. Mapped as Garden City Formation with a local subunit of well-rounded, planar- and cross-bedded orthoquartzite by Glick (1987). The lower Pogonip Group in thrust plate I has more quartzite, chert, and dolomite in its lower part, and more chert and dolomite in its upper part, as compared to the unit in the other thrust plates. About 820 m thick.

OEnp Notch Peak Formation (Ordovician and Cambrian) Cliff-forming, massive to bedded dark-gray dolomite, commonly with planar dark chert layers. Stromatolite buildups and abundant light-and-dark 'zebra striped' dolomite in the upper part of the unit are diagnostic, and black dolomite with dark chert pods and stringers are distinctive. Minor limestone with silt partings in the unit. About 325 m thick.

Orr Formation (Cambrian)

Ɔosc Corset Spring Shale and Sneakover Limestone Members Two thin members grouped as a single mappable unit. The Corset Spring Shale is dark- to medium-gray limestone with brown and red silt partings. The Sneakover Limestone is cliff-forming, thick-bedded, medium to dark gray, with very thin beds of brown siltstone. The upper part has beds and stringers of dark chert. Locally altered to light-gray dolomite. Combined thickness is about 90 m.

Ɔoj Johns Wash Limestone Member The lower half is light- to medium-gray limestone with silt partings. The upper half is white limestone. Thickness is about 90 m.

Ɔoc Candland Shale Member Medium-gray thin beds of limestone interlayered with very thin beds of siltstone and shale that is red, brown, and green. Forms recessive slopes and benches. Thickness is about 60 m.

Ɔob Big Horse Limestone Member Medium and light blue-gray limestone and coarse-grained dolomite. Parts are silty and rarely have silicified laminae. Contains oncoliths, ooids, and intraclasts along with

rare stromatolites. As mapped, includes in one place a silty lower section mapped as Cambrian limestone by Glick (1987). Thickness about 275 m.

---*North Toano detachment fault near here*---

Emp Morgan Pass Formation (Cambrian) Slope-forming shale and silty limestone exposed only as a thin faulted section. About 125 m thick elsewhere (Glick, 1987).

Ec Clifside Limestone (Cambrian) Medium-gray limestone with brown silty laminae and thin orange siltstone beds. Oolitic grainstone common near base and ooids, oncolites, and pisolites are common near the top. Divided into three units by Glick (1987) and McCollum and Miller (1991): lower, alternating oolitic gray limestone and brown silty limestone; middle, silty limestone and shale; upper, dark-gray limestone with thin undulose silty layers. Metamorphic minerals include tremolite, chlorite, and muscovite. About 500 m thick.

Et Toano Limestone (Cambrian) Interbedded dark-gray limestone and orange and brown calcareous siltstone. Very thin bedded to laminated. Soft-sediment structures are common. Metamorphic minerals in metasiltstone layers commonly include biotite, muscovite, and chlorite. Trilobites indicate a Middle Cambrian age (McCollum and Miller, 1991). About 850 m thick.

Eks Killian Springs Formation (Cambrian) Dark grayish-black graphitic to micaceous phyllite and metasiltstone with minor shale and calcareous phyllite. Thin beds of dark-gray limestone in upper part. Hematite after pyrite is common. Metamorphic minerals commonly include biotite, muscovite, tremolite, and chlorite. About 310 m thick.

EZpm Prospect Mountain Quartzite (Cambrian and Neoproterozoic) Thick sequence of pale gray to off-white, purple, and pink, thick-bedded quartzite with minor siltstone and conglomerate, generally forming cliffs. Generally medium-grained and cross-bedded. Beds commonly have a white quartz-pebble lag on surface. Metamorphic minerals in metasiltstone layers commonly include biotite, muscovite, epidote, and chlorite. Thrust fault at top is parallel to bedding and may remove significant thickness of rock. About 350 m thick, which is much thinner than in the adjacent Pilot Range, where it is 700 to 955 m thick (Miller, 1983).

Neoproterozoic Rocks

McCoy Creek Group of Misch and Hazzard (1962)

Thick sequence of alternating units of quartzite and schistose quartzite. In map area, divided into:

Zmg Unit G Brown metasiltstone interbedded with gray to purple quartzite and arkosic quartzite. Calcareous siltstone is rare. Metamorphic minerals in metasiltstone layers commonly include biotite, muscovite, and chlorite, and locally include staurolite and garnet. Calcsilicate rock contains hornblende, actinolite, and epidote. About 240 m thick.

Zmf Unit F Light colored quartzite in shades of gray, brown and blue-gray; medium grained and well bedded. Local metasiltstone layers and conglomerate beds are common, as is cross-bedding. Metamorphic minerals in metasiltstone layers include biotite, muscovite, and chlorite. About 460 m thick.

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Table 1. Summary of radiometric geochronology data for the Toano Range.

Sample	Collector	Latitude	Longitude	Rock type	Map Unit	Location	7.5' Quadrangle	Material dated	Method	Age(Ma)	2 σ error	Reference
NV21-017TOA	Emily White	40.9146	-114.2935	Granodiorite	Silver Zone Pass pluton	Silver Zone Pass	Silver Zone Pass	zircon	U-Pb in situ	156.01	2.3	White, 2023
NV21-017TOA	Emily White	40.9146	-114.2935	Granodiorite	Silver Zone Pass pluton	Silver Zone Pass	Silver Zone Pass	apatite	U-Pb in situ	153.4	51.8	White, 2023
NV21-016TOA	Emily White	40.982	-114.3193	Granite	Toano Spring pluton		Silver Zone Pass	zircon	U-Pb in situ	86.87	1.8	White, 2023
NV21-016TOA	Emily White	40.982	-114.3193	Granite	Toano Spring pluton		Silver Zone Pass	apatite	U-Pb in situ	74.8	21.8	White, 2023
210719-2	Drew Levy	41.11606	-114.22988	Granodiorite	Castle Park pluton		Pilot Peak SW	zircon	U-Pb in situ	41.1	0.6	Miller et al., 2026b
B85TR-135	Linda Berg	40.969927	-114.305854	Schist	Zmg		Silver Zone Pass	muscovite	K-Ar	61.4	3.0	Miller et al., 1990
M80TR-01	David Miller	41.002704	-114.303909	Granite	Toano Spring pluton	Collar and Elbow Basin	Cobre SE	muscovite	K-Ar	62.9	3.8	Miller et al., 1990
B84TR-112	Linda Berg	40.981609	-114.302334	Metaquartzite	Unit F, McCoy Creek Group		Silver Zone Pass	muscovite	K-Ar	69.7	3.4	Miller et al., 1990
B86TR-111	Linda Berg	40.989933	-114.300247	Granite	Toano Spring pluton	Collar and Elbow Basin	Silver Zone Pass	muscovite	Ar ⁴⁰ /Ar ³⁹ plateau	77.1	0.6	Miller et al., 1990
B84TR-167	Linda Berg	41.020263	-114.278532	Schist	Zmg		Cobre SE	biotite	K-Ar	94.5	4.8	Miller et al., 1990
B85TR-131	Linda Berg	41.118868	-114.231370	Granodiorite	Castle Park pluton		Pilot Peak NW	biotite	K-Ar	36.9	1.8	Miller et al., 1990
M85TR-39	Steve Martindale	41.174786	-114.290607	Andesite	Older andesite		Loray	hornblende	K-Ar	36.8	2.0	Miller et al., 2026b
M85TR-39	Steve Martindale	41.174786	-114.290607	Andesite	Older andesite		Loray	biotite	K-Ar	38.6	2.0	Miller et al., 2026b
M92TR-101	David Miller	41.144496	-114.293414	Dacite vitrophyre	Older dacite		Loray	plagioclase	K-Ar	30.9	7.8	Miller et al., 2026b
M92TR-106	David Miller	41.166940	-114.288129	Rhyolite	Older rhyolite		Loray	Sanidine	K-Ar	37.9	1.8	Miller et al., 2026b
M90TR-37	David Miller	41.070602	-114.336235	Lithic tuff	Lithic tuff		Cobre SE	biotite	K-Ar	12.5	0.6	Miller et al., 2026b
M81TR-06	David Miller	41.085689	-114.346239	Rhyolite	Toano Range rhyolite 2		Cobre SE	Plagioclase + sanidine	K-Ar	12.9	0.8	Miller et al., 2026b
M87TR-77	David Miller	41.066718	-114.324625	Vitric tuff	Humboldt Formation		Cobre SE	hornblende	K-Ar	27.4	1.4	Miller et al., 2026b
415	Donald Lee	41.006870	-114.305020	Granite	Toano Spring pluton	Collar and Elbow Basin	Cobre SE	muscovite	K-Ar	71.7	4.0	Lee and Marvin, 1981
415	Donald Lee	41.006870	-114.305020	Granite	Toano Spring pluton	Collar and Elbow Basin	Cobre SE	Biotite	K-Ar	15.6	1.0	Lee and Marvin, 1981
511	Donald Lee	41.015278	-114.291667	Metaquartzite	Unit F, McCoy Creek Group		Cobre SE	Muscovite	K-Ar	73	4.0	Lee et al., 1980
512	Donald Lee	41.015278	-114.291667	Metaquartzite	Unit F, McCoy Creek Group		Cobre SE	Muscovite	K-Ar	76.1	4.2	Lee et al., 1980

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026).**Volcanic Rocks**

Sample	M81TR-07	B84TR-158	M85TR-39	M87TR-23	M87TR-77	M92TR-99
Collector	Miller, David M.	Berg, Linda L.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.
Latitude	41.010624	41.026290	41.174786	40.951718	41.066718	41.131711
Longitude	-114.326636	-114.274480	-114.290607	-114.371997	-114.324625	-114.285794
Rock Type	topaz rhyolite	topaz rhyolite	andesite	rhyolite	rhyolite	andesite
Map Unit	Toano Range rhyolite 2	Toano Range rhyolite 1	Older andesite	Humboldt Formation tuff	Humboldt Formation tuff	Older andesite
Sample Detail	lava flow	vent rhyolite	hornblende- biotite andesite	vitric tuff	vitric tuff	andesite porphyry
7.5' Quadrangle	Cobre SE	Cobre SE	Loray	Silver Zone Pass	Cobre SE	Loray
Age	Miocene	Miocene	Eocene	Miocene	Miocene	Eocene
SiO ₂	76.5	77.5	65.7	68.8	37.9	60.3
TiO ₂	0.07	0.05	0.47	0.26	0.15	0.53
Al ₂ O ₃	11.3	11.3	15.8	11.9	6.2	15.7
Fe ₂ O ₃	1.28	1.21	3.58	2.33	1.14	4.59
FeO	0.10	0.31	1.43	0.74	0.50	1.82
MnO	0.02	0.02	0.04	0.02	0.02	0.07
MgO	0.15	0.10	1.50	0.67	0.56	3.49
CaO	0.74	0.49	3.91	0.84	27.30	2.94
Na ₂ O	2.69	2.94	3.11	2.20	1.02	3.92
K ₂ O	5.14	4.59	4.08	4.88	2.97	2.76
P ₂ O ₅	<0.05	<0.05	0.17	<0.05	<0.05	0.19
LOI				7.8	23.2	3.9

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).**Volcanic Rocks**

Sample	M92TR-100	M92TR-101	M92TR-103	M92TR-104	M92TR-106	M92TR-108
Collector	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.
Latitude	41.131638	41.144496	41.158220	41.157870	41.166940	41.174238
Longitude	-114.283462	-114.293414	-114.277132	-114.276026	-114.288129	-114.291428
Rock Type	dacite	andesite	andesite	andesite	rhyolite	andesite
Map Unit	Older rhyodacite	Older andesite	Older andesite	Older andesite	Older rhyolite	Older andesite
Sample Detail	rhyodacite lava	andesite vitrophyre	andesite vitrophyre	hornblende- biotite andesite	welded rhyolite tuff	andesite porphyry
7.5' Quadrangle	Loray	Loray	Loray	Loray	Loray	Loray
Age	Eocene	Eocene	Eocene	Eocene	Eocene	Eocene
SiO ₂	67.6	58.9	60.0	58.5	74.6	62.8
TiO ₂	0.48	0.71	0.64	0.75	0.14	0.50
Al ₂ O ₃	15.2	17.5	16.4	16.2	11.1	15.8
Fe ₂ O ₃	3.32	5.99	5.43	6.63	0.97	4.34
FeO	0.36	3.41	2.53	3.43	0.09	1.76
MnO	0.02	0.10	0.08	0.15	0.02	0.07
MgO	0.74	3.14	3.31	4.13	0.14	2.11
CaO	2.19	6.43	5.78	6.64	1.24	3.65
Na ₂ O	3.49	3.46	3.37	3.23	1.30	2.52
K ₂ O	4.16	1.91	2.07	1.93	7.86	5.88
P ₂ O ₅	0.16	0.19	0.17	0.21	0.07	0.21
LOI	1.6	1.1	2.4	1.3	1.3	1.6

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).**Volcanic Rocks**

Sample	M22TR-1408	M23TR-899	M23TR-913	M23TR-994	M23TR-1132	M81TR-06
Collector	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.
Latitude	41.079933	41.106774	41.053299	41.150815	41.025847	41.085689
Longitude	-114.345833	-114.354503	-114.3335	-114.274086	-114.27554	-114.346239
Rock Type	topaz rhyolite	topaz rhyolite	topaz rhyolite	rhyolite	topaz rhyolite	topaz rhyolite
Map Unit	Toano Range rhyolite 2	Toano Range rhyolite 2	Toano Range rhyolite 2	Older rhyolite	Toano Range rhyolite 1	Toano Range rhyolite 2
Sample Detail	lava flow	boulder in alluvium	lava flow	rhyolite tuff	lava flow	lava flow
7.5' Quadrangle	Cobre SE	Cobre SE	Cobre SE	Loray	Cobre SE	Cobre SE
Age	Miocene	Miocene	Miocene	Miocene	Miocene	Miocene
SiO ₂	73.8	76.8	76.6	75.8	76.7	74.0
TiO ₂	0.07	0.06	0.05	0.16	0.07	0.07
Al ₂ O ₃	12.3	11.1	12.4	12.8	11.9	12.2
Fe ₂ O ₃	1.27	1.25	1.12	1.49	1.34	1.06
FeO	NA	NA	NA	NA	NA	NA
MnO	0.03	0.02	0.01	0.03	0.02	0.03
MgO	0.09	0.19	0.03	0.43	0.06	0.09
CaO	0.65	1.20	0.26	1.38	0.63	0.59
Na ₂ O	3.00	3.12	2.84	3.26	3.33	3.01
K ₂ O	5.50	4.47	6.03	3.65	4.93	5.25
P ₂ O ₅	0.01	0.03	0.02	0.08	0.02	<0.01
LOI	3.4	1.9	1.0	1.1	1.2	3.5

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).**Volcanic Rocks**

Sample	M24TR-2186	M24TR-2214	M24TR-2221	M24TR-2239	M24TR-2247	M24TR-2249
Collector	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.
Latitude	41.105286	41.051008	41.053158	41.03464	41.031202	41.030544
Longitude	-114.347316	-114.333351	-114.332308	-114.297448	-114.29268	-114.29151
Rock Type	topaz rhyolite	topaz rhyolite	topaz rhyolite	topaz rhyolite	topaz rhyolite	topaz rhyolite
Map Unit	Toano Range rhyolite 2	Toano Range rhyolite 1	Toano Range rhyolite 2	Toano Range rhyolite 1	Toano Range rhyolite 1	Toano Range rhyolite 1
Sample Detail	lava flow	lava flow	lava flow	lava flow	lava flow	vent rhyolite
7.5' Quadrangle	Cobre SE	Cobre SE	Cobre SE	Cobre SE	Cobre SE	Cobre SE
Age	Miocene	Miocene	Miocene	Miocene	Miocene	Miocene
SiO ₂	74.9	75.6	77.2	75.4	76.0	77.6
TiO ₂	0.06	0.05	0.06	0.06	0.03	0.07
Al ₂ O ₃	11.9	11.8	11.6	11.9	12.4	11.6
Fe ₂ O ₃	1.08	0.90	0.39	1.20	1.11	1.23
FeO	0.50	0.30	0.20	<0.2	0.80	0.80
MnO	0.02	0.01	<0.01	0.03	0.04	0.02
MgO	0.08	0.21	0.16	0.17	0.05	0.06
CaO	0.59	0.77	0.46	1.34	0.28	0.20
Na ₂ O	2.69	2.54	2.45	3.33	2.73	2.03
K ₂ O	5.54	5.45	5.74	4.77	6.20	6.90
P ₂ O ₅	<0.01	0.02	0.04	0.01	<0.01	<0.01
LOI	3.1	2.7	1.7	1.1	1.1	0.5

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).**Volcanic Rocks**

Sample	M24TR-2272	M24TR-2332	M24TR-2333	M24TR-2340	M24TR-2405
Collector	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.
Latitude	40.995987	41.033197	41.03311	41.029607	41.154564
Longitude	-114.382093	-114.284176	-114.284642	-114.285746	-114.281805
Rock Type	topaz rhyolite	topaz rhyolite	topaz rhyolite	topaz rhyolite	dacite
Map Unit	Toano Range rhyolite 2	Toano Range rhyolite 1	Toano Range rhyolite 1	Toano Range rhyolite 1	Older dacite
Sample Detail	lava flow	vent rhyolite	vent rhyolite	lava flow	feldspar rich dacite lava
7.5' Quadrangle	Hardy Creek	Cobre SE	Cobre SE	Cobre SE	Loray
Age	Miocene	Miocene	Miocene	Miocene	Eocene
SiO ₂	76.2	76.5	76.8	76.8	64.4
TiO ₂	0.08	0.06	0.03	0.06	0.60
Al ₂ O ₃	12.1	12.1	12.6	12.2	16.1
Fe ₂ O ₃	1.24	1.26	1.10	1.33	4.55
FeO	0.60	0.90	0.90	0.70	1.00
MnO	0.03	0.03	0.03	0.03	0.03
MgO	0.06	0.06	0.08	0.07	1.66
CaO	0.74	0.20	0.20	0.51	4.47
Na ₂ O	3.31	2.54	2.54	3.34	3.52
K ₂ O	5.05	6.47	6.86	4.87	2.61
P ₂ O ₅	0.04	0.02	0.02	0.01	0.15
LOI	0.8	0.6	0.8	0.9	2.2

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).**Intrusive Rocks**

Sample	M83TR-37	M83TR-36	M80TR-01	M83TR-39	M83TR-60A	M84TR-62
Collector	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.
Latitude	40.992522	40.908564	41.002704	40.90405	40.930023	40.903047
Longitude	-114.315065	-114.307131	-114.303909	-114.297829	-114.271342	-114.289274
Rock Type	granite	granodiorite	aplite	granodiorite	granodiorite	granodiorite
Map Unit	Toano Spring pluton	Silver Zone Pass pluton	Toano Spring pluton	Silver Zone Pass pluton	Silver Zone Pass pluton	Silver Zone Pass pluton
Sample Detail	pluton	pluton	dike	pluton	dike	pluton
7.5' Quadrangle	Silver Zone Pass	Silver Zone Pass	Cobre SE	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass
Age	Cretaceous	Jurassic	Cretaceous	Jurassic	Jurassic	Jurassic
SiO ₂	73.8	67.8	77.0	68.6	71.4	69.5
TiO ₂	0.03	0.44	0.02	0.45	0.29	0.43
Al ₂ O ₃	14.6	15.5	13.3	15.3	14.8	14.7
Fe ₂ O ₃	0.76	2.97	0.63	3.22	2.17	3.20
FeO	0.22	1.51	0.42	1.68	1.07	1.67
MnO	0.04	0.04	0.23	0.05	0.04	0.05
MgO	0.14	1.34	0.10	1.49	0.88	1.39
CaO	0.73	4.01	0.29	3.19	2.67	3.45
Na ₂ O	4.11	3.77	4.28	3.53	3.87	3.70
K ₂ O	4.11	2.51	3.44	3.14	2.90	2.36
P ₂ O ₅	0.09	0.18	0.06	0.18	0.11	0.15
LOI	0.7	0.8	0.5	NA	NA	NA

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).**Intrusive Rocks**

Sample	M84TR-63	M84TR-81	M84TR-82	M84TR-83A	M84TR-83B	B85TR-131
Collector	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Berg, Linda L.
Latitude	40.903172	40.989669	40.989939	40.929611	40.929611	41.118868
Longitude	-114.292665	-114.300548	-114.274148	-114.271454	-114.271454	-114.231370
Rock Type	granodiorite	granite	granite	amphibolite	amphibolite	granodiorite
Map Unit	Silver Zone Pass pluton	Toano Spring pluton	Toano Spring pluton	Silver Zone Pass pluton	Silver Zone Pass pluton	Castle Park pluton
Sample Detail	pluton	pluton	float block	dike	dike	pluton
7.5' Quadrangle	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass	Pilot Peak SW
Age	Jurassic	Cretaceous	Cretaceous	Jurassic	Jurassic	Jurassic
SiO ₂	68.4	74.4	74.6	50.6	41.1	65.2
TiO ₂	0.44	0.04	0.03	1.18	2.47	0.40
Al ₂ O ₃	15.4	14.6	14.2	11.7	11.2	17.0
Fe ₂ O ₃	3.23	0.79	0.74	10.20	15.70	2.75
FeO	1.70	0.26	0.36	6.99	9.04	1.30
MnO	0.06	0.03	0.02	0.20	0.16	0.08
MgO	1.46	0.12	0.16	10.10	11.10	0.95
CaO	3.37	0.87	0.83	9.06	11.60	3.15
Na ₂ O	3.75	3.81	3.75	2.10	1.46	4.00
K ₂ O	2.69	4.17	4.20	2.31	1.24	3.90
P ₂ O ₅	0.15	0.10	0.08	0.28	1.19	0.30
LOI	NA	NA	NA	NA	NA	NA

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).**Intrusive Rocks**

Sample	B86TR-53	M87TR-39	M89TR-87	M89TR-87A	M89TR-87B	M90TR-181
Collector	Berg, Linda L.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.	Miller, David M.
Latitude	40.97117	40.898209	40.908433	40.908433	40.908433	40.908254
Longitude	-114.334316	-114.270907	-114.304883	-114.304883	-114.304883	-114.307198
Rock Type	aplite	granodiorite	diabase	Monzodiorite	monzodiorite	granodiorite
Map Unit	Toano Spring pluton		Silver Zone Pass pluton	Silver Zone Pass pluton	Silver Zone Pass pluton	Silver Zone Pass pluton
Sample Detail	dike	dike	xenolith	xenolith	xenolith	pluton
7.5' Quadrangle	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass	Silver Zone Pass
Age	Mesozoic	Eocene?	Jurassic	Jurassic	Jurassic	Jurassic
SiO ₂	74.2	69.9	50.2	51.9	55.9	66.5
TiO ₂	0.10	0.31	1.41	1.08	1.05	0.47
Al ₂ O ₃	15.1	14.9	13.7	16.6	16.4	15.4
Fe ₂ O ₃	1.04	2.32	10.50	9.94	8.16	3.09
FeO	0.31	1.65	6.68	5.98	5.22	1.49
MnO	0.07	0.07	0.18	0.24	0.17	0.05
MgO	0.20	0.78	6.90	5.16	4.39	1.47
CaO	0.28	2.49	9.76	7.33	5.87	4.26
Na ₂ O	4.20	3.65	2.32	3.70	3.88	3.80
K ₂ O	3.20	3.10	1.88	2.49	2.44	2.46
P ₂ O ₅	0.08	0.13	0.40	0.41	0.38	0.27
LOI	1.0	1.7	2.2	0.8	0.9	1.3

Table 2. Summary of U.S Geological Survey geochemistry data for samples collected in the Toano Range; concentrations are given in wt.%, LOI=loss on ignition. Complete data are available in Miller et al. (2026a) and Felger et al. (2026) (continued).

Intrusive Rocks

Sample	M91TR-51
Collector	Miller, David M.
Latitude	41.128149
Longitude	-114.220343
Rock Type	granodiorite
Map Unit	Castle Park pluton
Sample Detail	pluton
7.5' Quadrangle	Pilot Peak NW
Age	Eocene
SiO₂	69.5
TiO₂	0.35
Al₂O₃	15.4
Fe₂O₃	2.83
FeO	1.52
MnO	0.04
MgO	1.31
CaO	3.06
Na₂O	4.02
K₂O	2.48
P₂O₅	0.11
LOI	0.6