Petrology of Volcanic Rocks Associated with Silver-Gold (Ag-Au) Epithermal Deposits in the Tonopah, Divide, and Goldfield Mining Districts, Nevada

Scientific Investigations Report 2019–5024

U.S. Department of the Interior
U.S. Geological Survey

Cover. Prominent lava flow and volcanic cinder accumulations of the trachyandesite of Red Mountain, at Red Mountain north of Tonopah, Nevada. (Photograph by Edward A. du Bray, U.S. Geological Survey, 2015.)

Petrology of Volcanic Rocks Associated with Silver-Gold (Ag-Au) Epithermal Deposits in the Tonopah, Divide, and Goldfield Mining Districts, Nevada

By Edward A. du Bray, David A. John, Joseph P. Colgan, Peter G. Vikre, Michael A. Cosca, and Leah E. Morgan

Scientific Investigations Report 2019–5024

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia 2019

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Suggested citation:
du Bray, E.A., John, D.A., Colgan, J.P., Vikre, P.G., Cosca, M.A., and Morgan, L.E., 2019, Petrology of volcanic rocks associated with silver-gold (Ag-Au) epithermal deposits in the Tonopah, Divide, and Goldfield mining districts, Nevada: U.S. Geological Survey Scientific Investigations Report 2019–5024, 22 p., https://doi.org/10.3133/sir20195024.

ISSN 2328-0328 (online)

Acknowledgments

Geologic investigations carried out for this study were completed as part of the "Magmatic-tectonic history and component sources of major precious metal deposits at Tonopah and Goldfield, Nevada Project," funded by the U.S. Geological Survey Mineral Resources Program. Constructive reviews by A.K. Gilmer and G.E. Graham (U.S. Geological Survey) are much appreciated and helped clarify data presentation.

Contents

Figures

Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

U.S. customary units to International System of Units

Multiply	By	To obtain
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
	Pressure	
bar	100	kilopascal (kPa)

Ages are expressed in Ma for mega-annum (million years ago), and m.y. for million years

Abbreviations

HFSE High-field-strength element

HREE Heavy rare-earth element

IUGS International Union of Geological Sciences

LREE Light rare-earth element

LILE Large-ion lithophile element

REE Rare-earth element

USGS U.S. Geological Survey

Chemical Compounds

Al_2O_3 Aluminum oxide

CaO Calcium oxide

FeO* Total iron expressed as ferrous oxide

K_2O Potassium oxide

MgO Magnesium oxide

MnO Manganese oxide

Na_2O Sodium oxide

P_2O_5 Phosphorus pentoxide

SiO_2 Silicon dioxide

TiO_2 Titanium dioxide

Elements

Ag	Silver	Ni	Nickel
Ar	Argon	O	Oxygen
As	Arsenic	P	Phosphorous
Au	Gold	Pb	Lead
Ba	Barium	Pr	Praseodymium
Bi	Bismuth	Rb	Rubidium
Ca	Calcium	S	Sulfur
Ce	Cerium	Sb	Antimony
Co	Cobalt	Sc	Scandium
Cr	Chromium	Se	Selenium
Cs	Cesium	Sm	Samarium
Cu	Copper	Sn	Tin
Dy	Dysprosium	Sr	Strontium
Er	Erbium	Ta	Tantalum
Eu	Europium	Tb	Terbium
Fe	Iron	Te	Tellurium
Ga	Gallium	Th	Thorium
Gd	Gadolinium	Tm	Thulium
Hf	Hafnium	U	Uranium
Ho	Holmium	V	Vanadium
La	Lanthanum	W	Tungsten
Lu	Lutetium	Y	Yttrium
Mo	Molybdenum	Yb	Ytterbium
Nb	Niobium	Zn	Zinc
Nd	Neodymium	Zr	Zirconium

Petrology of Volcanic Rocks Associated with Silver-Gold (Ag-Au) Epithermal Deposits in the Tonopah, Divide, and Goldfield Mining Districts, Nevada

By Edward A. du Bray, David A. John, Joseph P. Colgan, Peter G. Vikre, Michael A. Cosca, and Leah E. Morgan

Abstract

Miocene calc-alkaline volcanic rocks, part of the southern segment of the ancestral Cascades magmatic arc, are spatially, temporally, and likely genetically associated with precious metal epithermal deposits in the Tonopah, Divide, and Goldfield Districts of west-central Nevada. In the Tonopah mining district, volcanic rocks include the Mizpah Trachyte, Fraction Tuff, and Oddie Rhyolite; in the Divide mining district, they include the Heller Tuff, Brougher Rhyolite, trachyandesite of Red Mountain, Divide Andesite, and volcanics of Donovan Peak (which includes rhyolite, dacite, and rhyodacite units); in the Goldfield mining district they include the Milltown Andesite, an unnamed porphyritic andesite, and latite. All these rocks are porphyritic and contain phenocryst assemblages that include plagioclase, pyroxene, hornblende, biotite, quartz, alkali feldspar, and olivine. These mostly subalkaline, metaluminous, calc-alkalic, and magnesian rocks range from basaltic trachyandesite to rhyolite and contain 54 to 78 weight percent silicon dioxide.

In the Divide mining district, the Divide Andesite and the volcanics of Donovan Peak are compositionally distinct from volcanic rocks in the other two mining districts. These rocks define a somewhat more restricted range of silicon dioxide content; are more alkalic; have greater titanium dioxide, sodium oxide, barium, hafnium, lanthanum, niobium, tantalum, yttrium, ytterbium, and zirconium abundances; and lower magnesium oxide, strontium, and vanadium abundances. Elevated zirconium contents are particularly characteristic of these rocks, which are also distinctly younger than most of the rocks in the other two mining districts. The alkalic character (principally higher sodium oxide abundances) and elevated zirconium contents characteristic of the Divide Andesite and the volcanics of Donovan Peak suggest that distinctive sources and (or) processes contributed to the petrogenesis of these rocks.

In the Tonopah, Divide, and Goldfield mining districts the geochemistry of Oligocene and Miocene volcanic rocks constrain the processes that contributed to the petrogenesis of these rocks. Specifically, major oxide compositional variation among these rocks is consistent with crystallization and fractionation of the observed phenocryst minerals. In addition, these rocks have negatively sloping rare-earth element patterns consistent with partial melting in a high-pressure, garnet stable regime. Elevated strontium concentrations and small negative europium anomalies are consistent with partial melting in a plagioclase-unstable setting. However, larger negative europium anomalies among the more silica-rich volcanic rocks indicates a progressively greater role for plagioclase fractionation among these rocks. The importance of hornblende in the petrogenesis of these rocks is reflected in subtly U-shaped middle rare-earth element pattern segments. Increasing lead/cerium and decreasing phosphorus pentoxide/potassium oxide with increasing silicon dioxide are characteristic of these volcanic rocks. These characteristics and their distinctive pre-Cenozoic xenolith content suggest a significant role for crustal contamination in their petrogenesis. Diagnostic textural features preserved by phenocrysts, especially plagioclase, constitute additional evidence that open-system behavior, including reservoir-scale mixing, recharge, and assimilation, was critical to the petrogenesis of volcanic rocks in the Tonopah, Divide, and Goldfield mining districts.

Introduction

The Tonopah, Divide, and Goldfield mining districts are currently inactive mining areas in west-central Nevada centered around the town of Tonopah, approximately 380 kilometers (km) southeast of Reno along U.S. Highway 95.

The Tonopah, Divide, and Goldfield mining districts are historic mining areas in west-central Nevada near the towns of Tonopah and Goldfield, approximately 276 and 302 km, respectively, southeast of Reno (fig. 1). Significant amounts of silver (Ag) and gold (Au) were produced from epithermal vein deposits in the Tonopah (Nolan, 1935; Bonham and Garside, 1974; 1979; Ashley, 1990a), Divide (Bonham and Garside, 1979; Erdman and Barabas, 1996), and Goldfield (Ransome, 1909; Ashley, 1974; 1979; 1990b; Ashley and Silberman, 1976) mining districts. These deposits are spatially, temporally, and likely genetically related to Miocene volcanic rocks (approximately 22 to 16 Ma) that are manifestations of magmatism associated with the southern segment of the ancestral Cascades continental magmatic arc (du Bray and others, 2014; John and others, 2015). Although the characteristics of deposits in these mining districts are reasonably well known, the geochemistry and petrographic features of the associated igneous rocks have not been well characterized. Herein, we (1) synthesize and interpret available and new geochemical, geochronological, and petrographic data for unmineralized volcanic rocks in the Tonopah, Divide, and Goldfield mining districts, (2) characterize compositional similarities and differences among these rocks, and (3) use compositional characteristics to interpret the tectonic and petrologic processes responsible for genesis of these rocks.

Only unaltered samples of geologic units that have potential genetic associations with mineralizing processes in the three mining districts are included in this synthesis. Two principal factors identify the igneous rocks most likely to have contributed to mineralizing processes: (1) genetically associated magma reservoirs must have been within 10 km of the deposits of interest and (2) igneous rock ages must be within several million years of deposit ages. In the Tonopah mining district, these units include the Fraction Tuff, Mizpah Trachyte (composed of trachyandesite, andesite, trachydacite, and dacite), and Oddie Rhyolite. In the Divide mining district, these include the Heller Tuff (of Bonham and Garside, 1979), Brougher Rhyolite, trachyandesite of Red Mountain (composed of basaltic trachyandesite and trachyandesite), Divide Andesite (composed of trachydacite and rhyolite), and the volcanics of

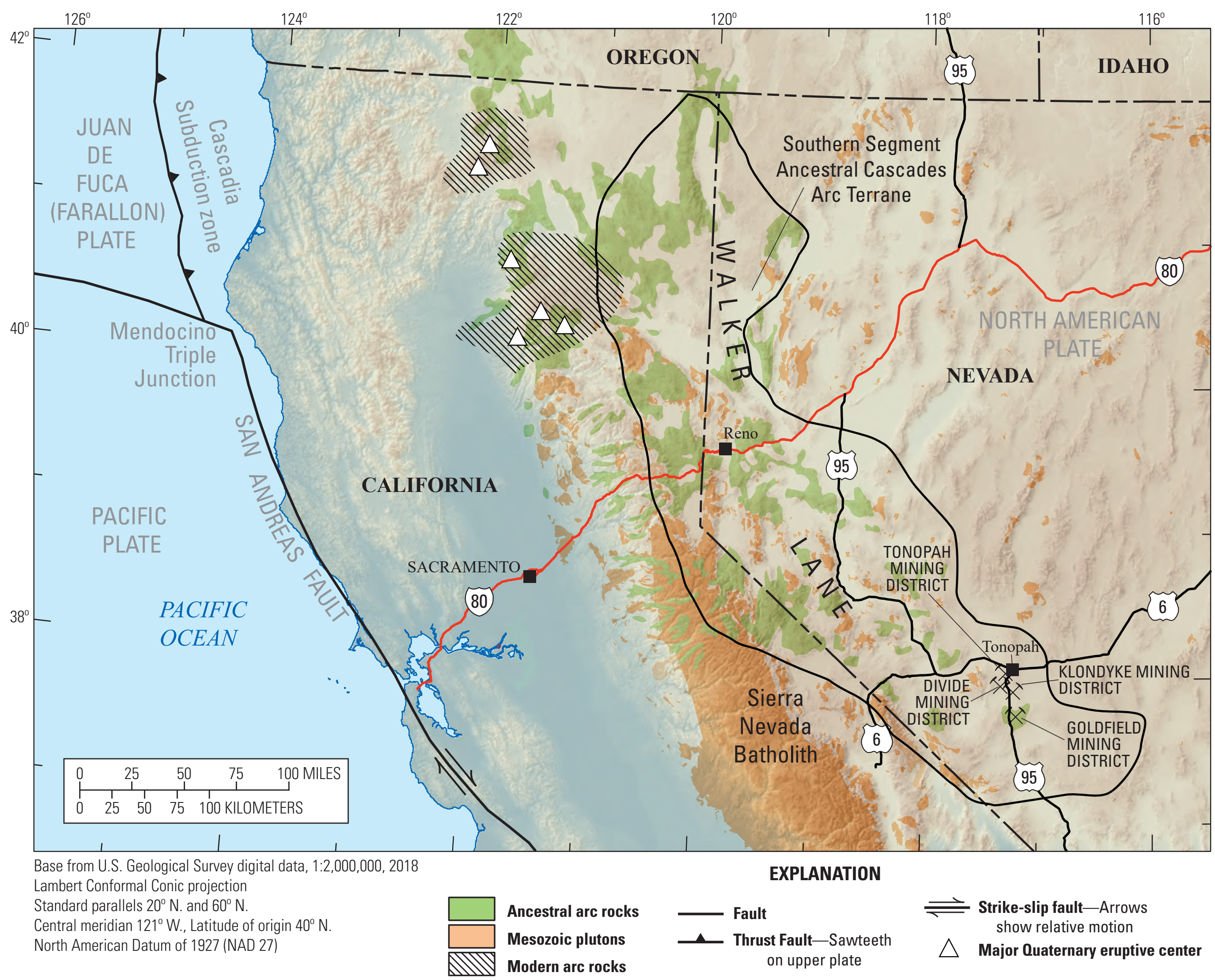

Figure 1. Index map showing the location of the Tonopah, Divide, and Goldfield mining districts, west-central Nevada, relative to the inferred extent of ancestral (green polygons) and modern High Cascades (cross hatched polygons) magmatic arcs in northern California and western Nevada (modified from Colgan and others, 2011; John and others, 2012).

Donovan Peak (Bonham and Garside, 1979). The rhyodacite subunit of the volcanics of Donovan Peak (as subdivided by Bonham and Garside, 1979) is composed of trachydacite and rhyolite, whereas the dacite subunit is composed of trachyandesite and trachydacite. In the Goldfield mining district, rocks that have a potential genetic relation with mineralization include the Milltown Andesite (composed of basaltic trachyandesite, trachyandesite, andesite, trachydacite, and dacite), an unnamed porphyritic andesite (composed of trachyandesite, andesite, and dacite), and latite. Other igneous rocks in the three mining districts are probably either too old or young and (or) their associated reservoirs so distal that they likely did not contribute heat, fluids, or geochemical components required for deposit formation.

Diverse types of volcanic centers are responsible for eruption of volcanic rocks in these three mining districts; characteristics of the associated erupted products are similarly diverse (table 1). Widespread, intermediate composition lava flows and their volcaniclastic equivalents were likely erupted from lava dome complexes, whereas more evolved lavas were emplaced as shallow intrusions, formed extrusive lava domes, or accumulated as lava flows erupted from and arrayed around central vents. Ignimbrite deposits included in the Fraction and Heller Tuffs were erupted from relatively poorly constrained caldera sources, one or more of which may be partly coincident with the Tonopah and (or) Divide mining districts.

Geochemical, petrographic, and geochronologic data for volcanic rocks in the Tonopah, Divide, and Goldfield mining districts were systematically compiled by du Bray and others (2019b). Some of the data for volcanic rocks in the Tonopah and Divide mining districts pertain to samples collected during geologic mapping in these areas and analyzed by Bonham and Garside (1979), whereas data pertinent to volcanic rocks in the Goldfield mining district were, in part, derived from samples collected and analyzed by Ashley (1974; 1979; 1990b). In 2013, new petrographic data were derived from systematic re-examination of hundreds of thin sections originally prepared as part of investigations carried out by Bonham and Garside (1979) in the Tonopah and Divide mining districts and by Ashley (1974; 1979; 1990b) in the Goldfield mining district. Additional petrographic, geochemical, and geochronologic data were obtained for samples collected by the authors between 2012–2017, as part of the project titled "Magmatic-tectonic history and component sources of major precious metal deposits in the southern Walker Lane" funded by the U.S. Geological Survey's (USGS) Mineral Resources Program. A small amount of additional geochemical data for samples from each of the mining districts were compiled from other sources. All of the data used to make the interpretations described in this report are presented in du Bray and others (2019a, b).

Geologic Setting of Ag-Au Deposits in the Tonopah, Divide, and Goldfield Mining Districts

Basement rocks in the Tonopah, Divide, and Goldfield mining districts are dominated by lower Paleozoic siliciclastic metasedimentary rocks of the "Nolan belt domain" (Crafford, 2007; 2008) that were deposited on lower Paleozoic to Neoproterozoic siliciclastic rocks of the western North American continental margin. Basement rocks are overlain by Miocene and volumetrically minor Oligocene (approximately 25 to 16 Ma) volcanic rocks that are manifestations of magmatism associated with the southern segment of the ancestral Cascades arc (du Bray and others, 2014). Metasedimentary basement rocks 10 km north of Tonopah, Nevada, were intruded by Triassic granitic rocks (John and McKee, 1987). Similar basement rocks, 15 km south of the Tonopah mining district in the Klondyke mining district, include a distinctive Cretaceous muscovite granite (104.0±2.0 Ma, Bonham and Garside, 1979). Basement rocks in the Goldfield mining district, exposed north and northeast of the main mining district, and in deeper workings in the mining district, are intruded by Jurassic quartz monzonite (164.3±1.8 million years ago [Ma], uranium-lead (U-Pb) zircon age via sensitive high-resolution ion microprobe (SHRIMP), and 159.2±0.8 Ma, U-Pb zircon age via laser ablation mass spectrometry; du Bray and others, 2019b).

Tonopah Mining District

The geologic setting of silver-gold quartz-adularia-muscovite (sericite) veins in the Tonopah mining district is complex and incompletely understood. Arc magmatism in the Tonopah mining district was extinguished by northward migration of the Mendocino triple junction and transition to a transform plate margin in this region at about 12 Ma (Putirka and others, 2012). Prior to this transition, arc magmatism was volumetrically dominated by lava flows and lava dome complexes of the Mizpah Trachyte and ash-flow tuff deposits of the Fraction Tuff. These volcanic rocks contain 8–26 volume percent phenocrysts (table 2), principally plagioclase, pyroxene, and hornblende±biotite; quartz, alkali feldspar, or olivine are present in some samples. New argon ($^{40}Ar/^{39}Ar$) dates suggest that the Mizpah Trachyte was erupted between about 21.4 and 20.9 Ma (du Bray and others, 2019b). Mineralized veins are hosted primarily by poorly characterized silicic eruptive rocks of the Tonopah Formation (Bonham and Garside, 1979) and by intermediate-composition lava flows and breccias of the Mizpah Trachyte near the south end of a presumed dome complex (John and others, 2015).

As mapped by Bonham and Garside (1979) the Mizpah Trachyte in the Tonopah mining district is overlain by multiple cooling units of the rhyolitic Fraction Tuff. They subdivided the Fraction Tuff into a lower unit, the Tonopah Summit Member, and an upper unit, the King Tonopah Member

Table 1. Characteristic features of eruptive centers and volcanic rock units associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada.

[m, meter; km, kilometer; km^2, square kilometer; wt, weight; %, percent; >, greater than; ~, approximately; Ma, million years ago; SiO_2, silicon dioxide; K, potassium; Ar, argon]

Eruptive center/unit	Volcanic landform	Eruptive products	Composition	Average SiO_2 content (wt. %)	Area/dimensions	Age range (Ma)[1]	Notable features
Tonopah mining district							
Mizpah Trachyte	Flow dome complexes	Dominantly lava flows but also minor debris-flow deposits, volcaniclastic sedimentary rocks, and scarce, shallow intrusions	Trachyandesite, trachydacite, andesite, and dacite	62.7	16 km^2 exposed area; ~11×8 km, elongated north-south	21.41 to 20.90	Somewhat compositionally diverse unit. Deposits form flow domes and sequences of lava flows. Debris flow deposits, including lahar deposits, are volumetrically minor.
Fraction Tuff	Ignimbrite sheet	Lithic-rich ash-flow tuff	Rhyolite	74.9	Approximately 50 km^2 exposed in an essentially circular area north of route US 6	20.19 to 19.93	The most widespread, voluminous ash-flow tuff in the in the Tonopah mining district. Tuff commonly contains abundant andesitic flow rock, rhyolitic, and pre-Cenozoic lithic fragments, which inhibited welding. Source caldera may be near Tonopah where a >1,100-m-thick section of Fraction Tuff likely accumulated within its source caldera.
Oddie Rhyolite	Plugs and domes	Hypabyssal intrusions and lava domes	Rhyolite	76.9	2.0 km^2 exposed area; numerous elliptical to irregular masses 0.25 to 0.75 km in diameter	17.29 to 16.60	Steep sided, endogenous to exogenous domes; columnar jointed in some places. Rarely fresh; altered by late stage magmatic and hydrothermal fluids.
Divide mining district							
Heller Tuff	Ignimbrite sheet	Lithic-rich ash-flow tuff	Trachydacite, dacite, and rhyolite	69.8	Approximately 150 km^2 exposed in an essentially circular area south of route US 6	17.43 to 17.28	Moderate volume ash-flow tuff. Probably erupted from a caldera centered just north of Donovan Peak. Contains conspicuous quartz and biotite phenocrysts.
Brougher Rhyolite	Lava flows and domes	Flow domes, lava flows	Rhyolite	74.8	35 km^2 exposed area; largest dome cluster ~5 km across	17.18 to 16.55	Forms topographically prominent outcrops throughout the Tonopah and Divide mining districts. Domes are unaltered and postdate mineralization in Tonopah mining district and most mineralization in the Divide mining district.
Trachyandesite of Red Mountain	Isolated/coalescing stratovolcanoes(?)	Lava flows	Trachyandesite, basaltic trachyandesite, andesite, and basaltic andesite	56.3	98 km^2 exposed area; extensive outcrop area on east flank of central San Antonio Mountains; smaller centers south and west of Tonopah	17.25 to 16.03	Large volume of lava flows likely the products of multiple eruptive centers. Contains distinctive, commonly altered olivine phenocrysts.
Divide Andesite	Flow dome complex	Hypabyssal intrusion and lava flows	Rhyolite and trachydacite	69.1	19 km^2 exposed area; 9×3 km ~east-west elongate area	17.6 to 17.30	Misclassified as andesite by Knopf (1921). Most samples contain distinctive hornblende phenocrysts but are composed of low-silica rhyolite. Probably a resurgent intrusion related to Heller Tuff magmatism.
Rhyolite of Donovan Peak	Plugs, domes, and dikes	Lava domes	Rhyolite	73.3	1.1 km^2 exposed area; several small, 0.5 km-diameter plugs	16.64 to 16.50	Volumetrically minor component of volcanics of Donovan Peak. Relatively crystal-poor rhyolite.
Rhyodacite of Donovan Peak	Plugs, dikes, and domes	Lava domes and flows	Trachydacite, rhyolite, and minor trachyandesite	66.1	5.3 km^2 exposed area; 0.25–0.5 km diameter domes confined to the Divide mining district	16.93 to 16.63	Prominent, dark-weathering lava flows capping peaks and ridges in the Divide mining district.
Dacite of Donovan Peak	Plugs	Hypabyssal intrusions	Trachydacite and trachyandesite	62.7	1.6 km^2 exposed area; two irregularly-shaped masses in the Divide mining district; larger mass is 0.65×2 km	16.70 Ma	Unit is the most crystal-rich component of the volcanics of Donovan Peak and contains relatively abundant plagioclase phenocrysts.

Table 1. Characteristic features of eruptive centers and volcanic rock units associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada.—Continued

[m, meter; km, kilometer; km^2, square kilometer; wt, weight; %, percent; >, greater than; ~, approximately; Ma, million years ago; SiO_2, silicon dioxide; K, potassium; Ar, argon]

Eruptive center/unit	Volcanic landform	Eruptive products	Composition	Average SiO_2 content (wt. %)	Area/dimensions	Age range (Ma)[1]	Notable features
Goldfield mining district							
Milltown Andesite	Stratovolcano(?)	Dominantly lava flows but also debris-flow deposits, volcaniclastic sedimentary rocks, and scarce, shallow intrusions	Trachyandesite, trachydacite, andesite, dacite, and basaltic trachyandesite	61.3	Full extent not delineated; discontinuously covers an area at least 10×14 km throughout the entire Goldfield mining district	22.27 to 21.94	Possibly a geologically composite unit. Characterized by very broad compositional range, including rocks with 54 to 69 wt percent silica.
Porphyritic andesite	Lava flows and domes	Lava flows, lava domes, and carapace breccia deposits	Andesite, dacite, trachydacite, and trachyandesite	62.1	Full extent not delineated; discontinuously covers an area at least 8×14 km and largely coextensive with exposures of the Milltown Andesite	22.36 to 21.8	Contains less, but distinctly coarser grained plagioclase, less clinopyroxene, more hornblende, and occasional quartz phenocrysts, which distinguish this unit from the Milltown Andesite. Includes a distinct marginal breccia facies.
Latite	Lava flows and domes	Lava flows	Latite	61.1	Approximately 10 km^2 exposed area in an approximately rectangular-shaped area several kilometers north-northeast of Goldfield	~22.7	
Rhyolite of Wildhorse Spring	Plugs and lava flows	Lava flows and flow breccia deposits	Rhyolite	76.7	Full extent not delineated; discontinuously covers an area at least 5×5 km in the northeast part of the Goldfield mining district.	21.48 to 20.18	Quartz-rich high silica rhyolite forms a series of lava domes. Relationship to other volcanic rocks in the Goldfield main mining district are not established.

[1]K-Ar and $^{40}Ar/^{39}Ar$ ages (du Bray and others, 2019b)

(itself composed of lower and upper cooling units). Our work suggests that essentially all the Miocene ash-flow tuff in the Tonopah mining district, where it is at least 1,000 meters (m) thick (base not exposed), is a single unit of Fraction Tuff. It is thickest and most widespread north of Tonopah, where it may constitute the eruptive product associated with a caldera whose northern margin is about 9 km north of Tonopah (John and others, 2015). The average (given because ash-flow tuff eruption is an essentially geologically instantaneous event, whereas the eruption of lava flow complexes typically spans considerable time intervals) of new $^{40}Ar/^{39}Ar$ dates of the Fraction Tuff suggest that the ash flows were erupted 20.04 Ma (du Bray and others, 2019b). Geochemical, petrographic, and geochronologic characteristics of all ash-flow tuff exposed north of Tonopah suggest that these rocks represent a single eruptive sequence, referred to hereafter as the Fraction Tuff, and that the Tonopah King and Tonopah Summit Members do not constitute distinct, mappable units.

A diverse group of volcanic rocks overlie or intrude the Fraction Tuff in the area around Tonopah. The Miocene Siebert Formation of Bonham and Garside (1979) includes thick, voluminous volcaniclastic deposits that contain abundant blocks of Mizpah Trachyte and Fraction Tuff, and thinner, less voluminous ash-fall deposits. We tentatively interpret the Siebert Formation to have accumulated in the basin formed during collapse of the caldera that erupted the Fraction Tuff following eruption of the tuff. In the Tonopah mining district, new $^{40}Ar/^{39}Ar$ dates (du Bray and others, 2019b) indicate that the Oddie Rhyolite (erupted between about 17.3 to 16.6 Ma), Brougher Rhyolite (erupted between about 17.2 to 16.6 Ma), trachyandesite of Red Mountain (erupted between about 17.3 to 16.0 Ma), and volcanics of Lime Mountain (erupted between about 16.8 to 12.4 Ma) represent magmatism that is at least 2 million years (m.y.) younger than that associated with the Fraction Tuff and deposition of the Siebert Formation and thus postdate mineralization in the main mining district, and are consequently substantially younger than other volcanic rocks in the Tonopah mining district.

Silver-gold deposits in the Tonopah mining district, from which greater than (>)174 million ounces (Moz) silver and 1.86 Moz gold were produced (mostly from 1910 to 1930; Bonham and Garside, 1979), consist of high- to low-angle quartz-sulfide-adularia-muscovite veins that replaced breccia and gouge in fault zones, and to a lesser extent, filled open-spaces. The principal hydrothermal sulfide minerals include argentite, polybasite, pearcite, sphalerite, galena, chalcopyrite, pyrite, electrum, and pyrargyrite. In addition to adularia and muscovite, the veins contain hydrothermal calcium-magnesium-manganese (Ca-Mg-Mn) carbonate minerals and minor barite. New $^{40}Ar/^{39}Ar$ dates for most adularia from quartz-adularia-muscovite veins in altered Mizpah Trachyte range from approximately (~) 20.5 to 19.9 Ma (du Bray and others, 2019b). Dates of the veins suggest nearly simultaneous eruption of the Fraction Tuff, caldera formation(?), and vein mineralization (John and others, 2015).

Divide Mining District

The geologic setting of the Divide silver-gold mining district, centered about 8 km south of Tonopah, Nev., is similar to the Tonopah mining district with Miocene volcanic rocks overlying Paleozoic basement rocks and Fraction Tuff. Divide mining district volcanic rocks contain 6–21 volume percent phenocrysts (table 2), principally plagioclase, biotite, and hornblende; quartz and alkali feldspar are present in samples of the more silicic units, especially the Heller Tuff and the Oddie and Brougher Rhyolites.

Except for the Heller Tuff, named for prominent exposures at Heller Butte immediately south of Tonopah, most Miocene tuff south of Tonopah (including the Divide mining district) was assigned to the "Tonopah Summit member" of the Fraction Tuff by Bonham and Garside (1979). The Heller Tuff, is megascopically similar to the Fraction Tuff but is distinguished by generally lower silica contents (averages, about 70 and 75 weight percent, respectively) and distinctly greater total phenocryst contents (24 versus 6 percent, respectively), especially quartz (4 percent versus a trace amount, respectively) and biotite (2 percent versus a trace amount, respectively) (du Bray and others, 2019b). The average (given because ash-flow tuff eruption is an essentially geologically instantaneous event) of new $^{40}Ar/^{39}Ar$ dates for the Heller Tuff is 17.34 Ma, excluding one imprecise age (du Bray and others, 2019b), which indicates that the Heller Tuff is also about 3 m.y. younger than the Fraction Tuff. Ash-flow tuff exposures south of Tonopah Summit, a low pass about 4 km southeast of the town of Tonopah, correlated by Bonham and Garside (1979) with the Tonopah Summit Member of the Fraction Tuff, are distinctly different from the Fraction Tuff but indistinguishable in age, petrography, and geochemistry from those of the Heller Tuff. Therefore, we have reassigned those exposures to the Heller Tuff. Exposures of the Heller Tuff ash-flow tuff sheet are most widely distributed and thickest south of Tonopah Summit, which suggests that these deposits may have been erupted from an inferred caldera whose southern margin is about 14 km south of Tonopah, where Bonham and Garside (1979) described voluminous megabreccia deposits and a possible caldera margin in the Klondyke mining district.

The eastern part of the Divide mining district and the large area farther east are dominated by additional Miocene volcanic rocks, including the Divide Andesite (erupted between about 17.6 to 17.4 Ma) and the compositionally diverse volcanics of Donovan Peak (erupted between about 17.3 to 16.5 Ma). These rocks consist of lava flows, lava dome complexes, and hypabyssal plugs. The Divide Andesite, as well as significantly less voluminous rocks included in the volcanics of Donovan Peak, may represent resurgent magmatism associated with the inferred southern caldera. Similarly, the arcuate array of Brougher Rhyolite (erupted between about 17.2 to 16.6 Ma) flow domes east and south of Tonopah Summit may represent ring-fracture hosted, moat intrusions and flows, associated with the inferred southern caldera.

Ages of air-fall tuffs of the Siebert Formation in the Tonopah and Divide mining districts range broadly from about 17.5 to 15.5 Ma (Bonham and Garside, 1979; du Bray and others, 2019b). Ages of the Divide Andesite, erupted between 17.6 to 17.3 Ma, the volcanics of Donovan Peak, erupted between about 17.3 to 16.5 Ma, and the parts of the trachyandesite of Red Mountain erupted between about 17.3 and 16.0 Ma (du Bray and others, 2019b), are commensurate with the age of epithermal precious metal deposits in the Divide mining district. Trachyandesite of Mud Lake lava flows, erupted about 13.7 Ma (du Bray and others, 2019b) southeast of the Divide mining district, are considerably younger than mineralization in the Divide mining district.

Mineralized veins in the Divide mining district are in Miocene volcanic rocks, principally the Oddie Rhyolite, Heller Tuff, and Siebert Formation (Nolan, 1935; Bonham and Garside, 1979). New adularia $^{40}Ar/^{39}Ar$ dates of quartz-adularia veins in the Divide mining district suggest mineralization occurred between about 17.3 and 16.8 Ma (du Bray and others, 2019b). About 3 Moz of silver and 30,000 oz of gold were produced; cerargyrite was the principal ore mineral, although sphalerite, argentiferous galena, chalcopyrite, molybdenite, electrum, acanthite, pyrargyrite, and possible tetrahedrite have been identified in dump samples (Bonham and Garside, 1974; Graney, 1987; Erdman and Barabas, 1996).

Goldfield Mining District

The Goldfield mining district is also dominated by Miocene volcanic rocks, principally lava flows but also breccias and lava domes. These rocks represent the approximate southernmost extent of magmatism related to the ancestral Cascades arc (du Bray and others, 2014), which ended with northward migration of the Mendocino triple junction past the Goldfield mining district at about 13 Ma (Putirka and others, 2012). Volcanic rocks associated with mineralization in the Goldfield mining district contain 17–33 volume percent phenocrysts (table 2), principally plagioclase, pyroxene, hornblende, and biotite. These rocks are cut by a dense network of west-northwest and north- to northeast-striking normal faults. Ashley (1990a) reports that silicic ash-flow tuff and flows (the Vindicator Rhyolite and the Morena and Sandstorm Rhyolites of Ransome, 1909) are associated with eruptions from a 6-km-diameter caldera delineated by a series of poorly defined, presumed ring fractures. However, geophysical data suggest that these fractures are related to pluton emplacement rather than caldera collapse (Blakely and others, 2007).

Milltown Andesite lava flows are volumetrically dominant in the Goldfield mining district and are host rocks for deposits in the southern part of the main mining district near Florence Hill. New $^{40}Ar/^{39}Ar$ ages for the Milltown Andesite indicate eruption about 22.3 to 21.9 Ma (du Bray and others, 2019b). Other important units in the Goldfield mining district include a series of unnamed porphyritic andesite lava flows (dacite of Ransome, 1909 and porphyritic rhyodacite

Table 2. Summary of petrographic characteristics for volcanic rock units associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada. Mineral abundances are averages of microscope-based estimates, relative to total rock, calculated from data presented by du Bray and others (2019b).

[Qtz, quartz; Alk-fspr, alkali feldspar; Plag, plagioclase; Hb, hornblende; Bi, biotite; Pyx, pyroxene; Ol, olivine; Opq, opaque iron-titanium (Fe-Ti) oxides; xtls, crystals. TR, trace. Capitalized entries in the Cpx/Opx column define whether clinopyroxene or orthopyroxene form the dominant pyroxene phenocryst population. Accessory minerals: AP, apatite; TI, titanite; ZR, zircon; AL, allanite; %, percent; mm, millimeter; —, not detected]

Map unit	Average abundances (%)											Estimated average crystal size (mm)								Size of largest crystal (mm)								Accessory minerals
	Qtz	Alk-fspr	Plag	Hb	Bi	Pyx	Cpx/Opx	Ol	Opq	Total xtls	Color index	Qtz	Alk-fspr	Plag	Hb	Bi	Pyx	Ol	Opq	Qtz	Alk-fspr	Plag	Hb	Bi	Pyx	Ol	Opq	
Tonopah mining district																												
Mizpah Trachyte	—	—	16	4	4	TR	C	—	2	26	10	—	—	1.6	0.4	0.7	0.7	—	0.10	—	—	4.7	1.5	1.9	2.0	—	0.40	AP, ZR
Fraction Tuff	TR	2	4	TR	TR	—	—	—	TR	6	TR	0.3	0.6	0.7	0.4	0.4	—	—	0.07	0.8	1.5	1.9	0.5	0.7	—	—	0.31	ZR, AL, TI
Oddie Rhyolite	6	3	1		1	—	—	—	TR	11	1	0.8	0.8	0.7	—	0.4	—	—	0.03	1.8	1.6	1.4	—	1.1	—	—	0.17	AP, ZR
Divide mining district																												
Heller Tuff	4	5	12	TR	2	—	—	—	1	24	3	0.6	0.6	0.7	0.4	0.4	—	—	0.11	1.6	1.6	1.6	0.7	1.0	—	—	0.40	ZR, AL, TI, AP
Brougher Rhyolite	5	4	7	TR	3	—	—	—	1	20	4	0.6	0.7	0.7	0.3	0.4	—	—	0.07	1.4	1.6	1.7	0.6	0.9	—	—	0.26	TI, AL, AP, ZR
Trachyandesite of Red Mountain	—	—	8	TR		3	C	2	2	15	7	—	—	0.5	0.4	—	0.6	0.4	0.03	—	—	1.2	1.4	—	1.4	1.2	0.17	—
Divide Andesite	—	—	11	3	3	—	—	—	1	18	7	—	—	1.1	0.6	0.6	—	—	0.08	—	—	2.9	1.6	1.4	—	—	0.44	AP, ZR
Rhyolite of Donovan Peak	—	TR	4	TR	1	TR	C	—	1	6	2	—	0.3	0.5	0.4	0.3	0.3	—	0.05	—	0.7	1.4	1.2	1.0	0.5	—	0.24	ZR, AP
Rhyodacite of Donovan Peak	—	2	8	1	3	—	—	—	1	15	5	—	0.5	0.8	0.4	0.4	0.4	—	0.07	—	1.1	1.9	1.0	1.1	0.9	—	0.28	AP, ZR
Dacite of Donovan Peak	—	—	12	7	TR	TR	C	—	2	21	9	—	—	1.1	0.5	0.7	0.3	—	0.05	—	—	2.5	2.2	1.1	0.8	—	0.24	AP
Goldfield mining district																												
Milltown Andesite	—	—	19	3	2	5	C	—	3	32	13	—	—	0.8	0.5	0.4	0.4	—	0.08	—	—	2.2	1.6	0.9	1.3	—	0.37	AP
Porphyritic andesite	2	—	20	3	5	1	C	—	2	33	11	0.9	—	1.8	0.4	0.8	0.5	—	0.05	2.6	—	4.4	1.3	2.3	3.1	—	0.31	AP, TI
Latite	TR	—	20	TR	5	—	—	—	2	27	7	1.0	—	1.1	1.0	0.5	—	—	0.13	1.5	—	2.8	1.6	1.2	—	—	0.40	AP, ZR
Rhyolite of Wild-horse Spring	10	3	1	—	2	—	—	—	1	17	3	1.0	1.5	0.8	—	0.7	—	—	0.15	1.8	2.7	2.0	0.8	1.3	—	—	0.50	TI

of Ashley, 1974), latite (Ransome, 1909), and volumetrically minor rhyolites including the Sandstorm and Morena Rhyolites of Ransome (1909) and the rhyolite of Wildhorse Spring (Ashley, 1974) erupted onto an Oligocene erosion surface of Jurassic quartz monzonite and Paleozoic siliciclastic rocks.

Porphyritic andesite, exposed east of the main mining district and in mines in the main mining district, is a second important deposit host and is thought to be temporally coincident with deposit formation (Ransome, 1909). New $^{40}Ar/^{39}Ar$ dates for the porphyritic andesite indicate eruption between about 22.3 to 21.9 Ma (du Bray and others, 2019b). Latite ~22.7 Ma, du Bray and others, 2019b), which partly covers Morena Rhyolite and the erosion surface, is the third principal deposit host rock, especially of Au-Ag deposits in the main mining district immediately northeast of Goldfield (Ransome, 1909; Searls, 1948). North and east of the main mining district, latite consists of gray-purple weathering lava flows and lesser tuffs in which the dull luster of feldspar and mafic phenocrysts reflects partial alteration to very fine-grained clay-mica minerals, quartz, and calcite. In the main mining district, latite has been pervasively altered to quartz, alunite, pyrophyllite, kaolinite, pyrite, illite, montmorillonite and other minerals, rendering distinctions with similarly altered porphyritic andesite and Milltown Andesite problematic. A new $^{40}Ar/^{39}Ar$ date of sanidine indicates eruption of the Morena Rhyolite 25.17±0.03 Ma (du Bray and others, 2019b). New $^{40}Ar/^{39}Ar$ dates of biotite and sanidine in rhyolite of Wildhorse Spring indicate eruption between about 21.5 Ma and 21.2 Ma, respectively, (du Bray and others, 2019b). The rhyolite of Wildhorse Spring is temporally but not spatially associated with mineralized rocks in the Goldfield mining district. A new $^{40}Ar/^{39}Ar$ date of sanidine indicates eruption of the Sandstorm Rhyolite 21.56±0.05 Ma (du Bray and others, 2019b). A series of younger, middle Miocene mafic lava flows, including the Mira Basalt, basalt of Blackcap Mountain, and Malpais Basalt, overlie mineralized, early Miocene rocks in the Goldfield mining district.

Miocene volcanic rocks in parts of the Goldfield mining district are extensively faulted. Breccia fragments and gouge in faults immediately north and northeast of the town of Goldfield (main mining district) have been replaced and encrusted by quartz, alunite, kaolinite and numerous gold-copper-silver-antimony-arsenic-bismuth-tin-tellurium-selenium-sulfur (Au-Cu-Ag-Sb-As-Bi-Sn-Te-Se-S) minerals. Miocene volcanic rocks and pre-Tertiary rocks adjacent to mineralized faults have been extensively altered to quartz, alunite, kaolinite, pyrite, illite and other aluminosilicate and aluminosulfate minerals. The mineralized faults are localized in the southwestern part of a 40 square kilometer (km^2) area of intensely altered rocks (Ransome, 1909; Ashley and Albers, 1975; Ashley, 1990a; Vikre and Henry, 2011). About 4.19 Moz of gold and 1.45 Moz of silver were produced from main mining district fault zones and adjacent wall rocks, mostly from 1903–1940 (Albers and Stewart, 1972). Most new $^{40}Ar/^{39}Ar$ dates of alunite in mineralized fault zones, and in adjacent wall rocks, are between 21.75 and 19.2 Ma (du Bray and others, 2019b).

Analytical Methods

Standard petrographic microscope techniques were employed to identify phenocryst minerals and estimate their abundances in 456 samples of volcanic rocks from the Tonopah, Divide, and Goldfield mining districts. Phenocryst size and crystallinity, rock textures, groundmass characteristics, accessory mineral assemblages, and qualitative relative alteration intensity were also determined for each sample.

New whole-rock compositions for 190 samples analyzed between 2012 and 2018 were carried out in analytical laboratories under contract to the U.S. Geological Survey (du Bray and others, 2019b). Pertinent analytical methods are described by Taggart (2002). Major oxide abundances (recalculated to 100 percent, volatile-free) were determined by wavelength dispersive x-ray fluorescence spectrometry. A 55-element method that employs a combination of inductively coupled plasma-atomic emission spectrometry and inductively coupled plasma-mass spectrometry was used to determine trace element abundances. Compositions for an additional 108 igneous rock samples in the Tonopah, Divide, and Goldfield mining districts are presented by du Bray and others (2019b). Only unaltered samples, unaffected by post-magmatic hydrothermal alteration or weathering, were used in our petrologic investigation of the Oligocene and Miocene volcanic rocks in the Tonopah, Divide and Goldfield mining districts. Du Bray and others (2019b) define the geochemical parameters that were used to identify altered samples and remove them from the interpreted data compilation. Volcanic rock compositions have been classified in accord with the International Union of Geological Sciences (IUGS) nomenclature system (Le Maitre, 2002).

Petrographic Characteristics

Essentially all volcanic rocks associated with mineralization in the Tonopah, Divide, and Goldfield mining districts are porphyritic. Petrographic characteristics of each volcanic rock unit in these mining districts are relatively distinct. As summarized (table 2), most phenocrysts are fine (<1 millimeter [mm]) to medium grained (1–5 mm). Euhedral, albite-twinned plagioclase laths are ubiquitous in these volcanic rocks. Almost all plagioclase phenocrysts are oscillatory zoned and some, especially in intermediate-composition lava flows, are variably sieve textured. Plagioclase in intermediate composition lava flows consists of multiple populations defined by combinations of (1) grain size, (2) presence of distinctive reaction rims, (3) zones that contain mineral and (or) glass inclusions, and (4) resorption textures. Brown to green pleochroic hornblende forms euhedral to subhedral acicular crystals; in weathered or altered samples hornblende is completely replaced by black amorphous material. Clinopyroxene forms pale tan to pale green subhedral to euhedral phenocrysts in intermediate composition lava flows. Biotite is subhedral, tan to deep reddish-brown, and like hornblende, is completely altered to amorphous material in many samples. Olivine, in some samples of the trachyandesite of Red Mountain, forms distinctive but variably altered subhedral phenocrysts. Fine-grained opaque iron-titanium (Fe-Ti) oxide crystals are ubiquitous in all these rocks.

Quartz and alkali feldspar occur only in the most felsic rocks of the Tonopah, Divide, and Goldfield mining districts. Quartz forms variably resorbed and embayed, rounded, anhedral to subhedral phenocrysts and sanidine forms variably and weakly perthitic Carlsbad-twinned, euhedral to subhedral phenocrysts. The groundmass of these volcanic rocks contains microphenocryst (typically 0.05 to 0.2 mm long) assemblages dominated by plagioclase and Fe-Ti oxide minerals but also includes variable combinations of quartz, alkali feldspar, clinopyroxene, hornblende, and biotite. Metastable and variably devitrified volcanic glass is also a major groundmass component. The Fraction and Heller Tuffs also contain abundant, locally derived lithic fragments and much less abundant but distinctive, crustally derived xenoliths, especially fragments of Mesozoic granitic and Paleozoic metasedimentary rocks.

Major Oxide Geochemistry

Compositions of volcanic rocks in the Tonopah, Divide, and Goldfield mining districts vary essentially continuously from about 54 to 78 weight percent silicon dioxide (SiO_2), although rocks with 66 to 71 weight percent SiO_2 are somewhat under-represented (figs. 2–3). Samples from the Divide mining district contain about 61 to 77 weight percent SiO_2, those from the Tonopah mining district contain about 60 to 78 weight percent SiO_2, and those of most samples from Goldfield mining district are restricted to between about 54 and 69 weight percent SiO_2. The volcanic rocks in these mining districts are transitionally alkaline; many of their compositions cluster between the line that separates alkaline and subalkaline compositions on a total alkali-silica diagram (fig. 2) and the alkaline-subalkaline dividing line of Irvine and Baragar (1971). Intermediate composition rocks, with <65 weight percent SiO_2, have Na_2O>K_2O, whereas the more felsic rocks have K_2O>Na_2O (fig. 3).

Relative to standard metrics (in cited sources), compositions (table 3) of most volcanic rocks in the Tonopah, Divide, and Goldfield mining districts are metaluminous to weakly peraluminous (Shand, 1951), calc-alkalic to weakly alkali-calcic (Frost and others, 2001); magnesian (calc-alkaline) to weakly ferroan (tholeiitic) (Frost and others, 2001); and follow a calc-alkaline (Irvine and Baragar, 1971) differentiation trend. However, several aspects of the volcanics of Donovan Peak, and perhaps the Divide Andesite in the Divide mining district, are distinct relative to compositions of rocks in the Tonopah and Goldfield mining districts. At any given silica content, the Divide rocks are more alkalic, contain distinctly greater abundances of TiO_2 and sodium oxide (Na_2O), lower magnesium oxide (MgO) abundances, and have higher ferrous oxide (FeO*, total iron expressed as ferrous oxide)/MgO than the Tonopah and Goldfield rocks. Among volcanic rocks in the Tonopah, Divide, and Goldfield mining districts, concentrations of TiO_2, aluminum oxide (Al_2O_3), FeO*, MgO, calcium oxide (CaO), and phosphorous pentoxide (P_2O_5) decrease relatively systematically with increasing SiO_2 (fig. 3). Na_2O abundances do not vary systematically with changing silica content. Abundances of K_2O increase broadly with increasing SiO_2 content, forming an array coincident with high-K compositions (Gill, 1981). The Heller Tuff contains distinctly lower SiO_2 and characteristically elevated TiO_2, Al_2O_3, FeO*, MgO, and CaO abundances relative to those of the Fraction Tuff.

Trace Element Geochemistry

Volcanic rocks of the Tonopah, Divide, and Goldfield mining districts have trace element abundances similar to those of other convergent-margin, subduction-related igneous rocks. In particular, these rocks are enriched in large-ion lithophile elements (LILE) and depleted in high-field-strength elements (HFSE) (du Bray and others, 2019b). Abundances of niobium, lead, rubidium, tantalum, thorium, (Nb, Pb, Rb, Ta, Th) and U increase, whereas those of cobalt, copper, scandium, strontium, vanadium, yttrium, ytterbium, and zinc (Co, Cu, Sc, Sr, V, Y, Yb, and Zn), and europium/europium* (Eu/Eu*) and total rare-earth element (REE) content, decrease with increasing silica content. Barium and zirconium (Ba and Zr) abundances vary inconsistently in samples with 54 to about 69 weight percent SiO_2 and then decrease dramatically in more silica-rich samples. Abundances of chromium hafnium, lanthanum, molybdenum, and nickel (Cr, Hf, La, Mo, and Ni), and lanthanum/lutetium $(La/Lu)_N$, exhibit no systematic variation with respect to increasing silica content.

Abundances of most trace elements in samples of volcanic rocks from the Tonopah and Goldfield mining districts are essentially indistinguishable. However, at any given silica content, abundances of Sr and V in samples of volcanics of Donovan Peak and the Divide Andesite, in the Divide mining district, are low, whereas abundances of Ba, Hf, La, Nb, Ta, Y, Yb, Zr, and total REEs are high relative to those for Tonopah and Goldfield mining district volcanic rocks. The Heller Tuff contains abundances of Rb and Y that are low and abundances of Ba, Hf, La, Zr, and total REEs that are high relative to those for Tonopah and Goldfield mining district volcanic rocks. Abundances of the metals, including Cu, Mo, Pb, and Zn, in volcanic rocks of the Tonopah, Divide, and Goldfield mining districts are similar to average abundances in basalt and granite (Turekian and Wedepohl, 1961).

Most volcanic rocks in the Tonopah, Divide, and Goldfield mining districts have Ba/Nb>15, similar to values for most subduction-related igneous rocks (Gill, 1981). Similarly, large Ba/Nb and Ba/Ta values reflect negative Nb-Ta anomalies, a recognized characteristic of subduction-related magmatic arc

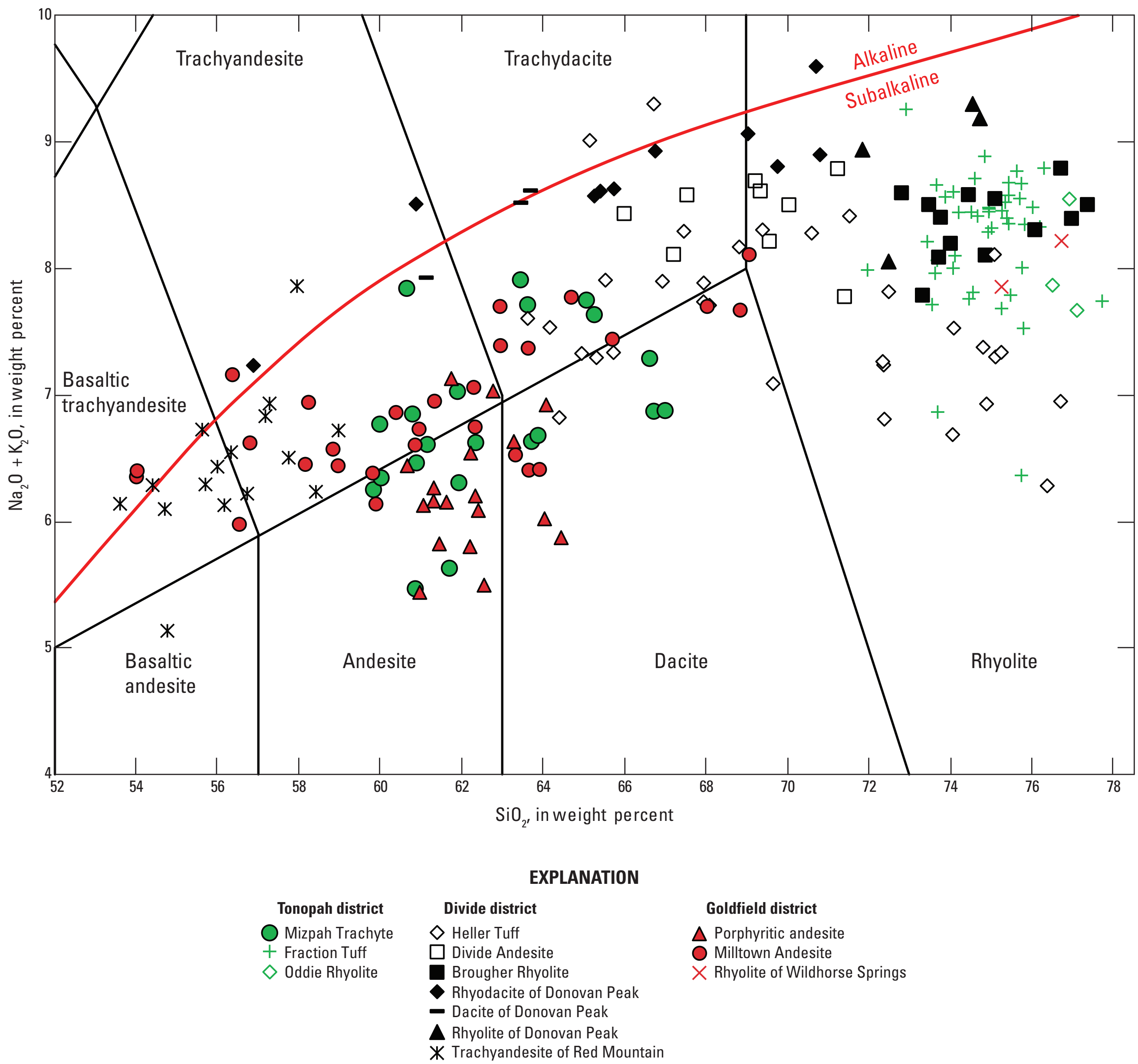

Figure 2. Total alkali-silica variation diagram showing compositions of Miocene volcanic rocks associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada. Field boundaries from Le Maitre (2002). Alkaline-subalkaline dividing line (red) from Irvine and Baragar (1971). (Na_2O, sodium oxide; K_2O, potassium oxide; SiO_2, silicon dioxide).

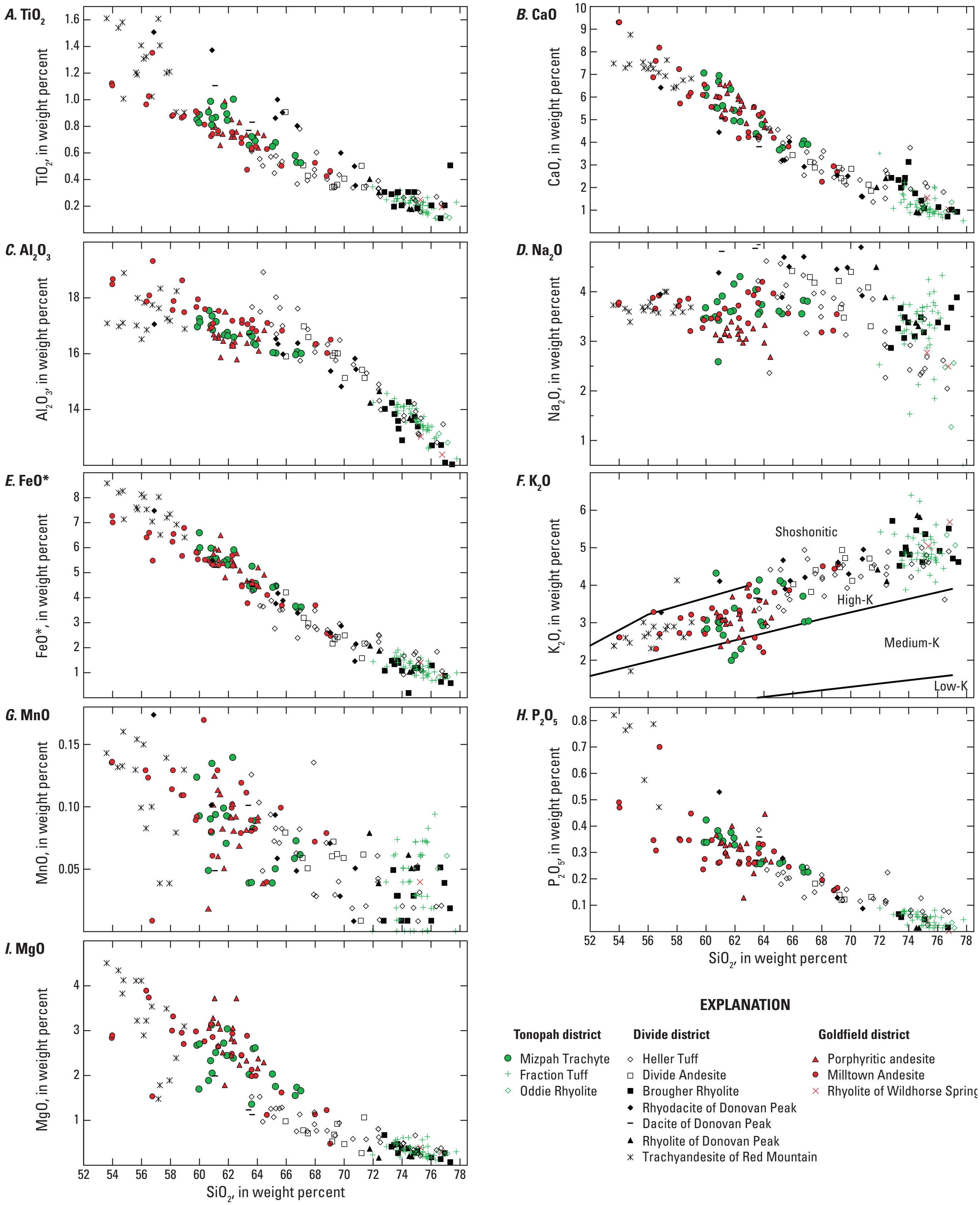

Figure 3. Variation diagrams showing abundances of major oxides (weight percent) in Miocene volcanic rocks associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada. Field boundaries on potassium oxide (K_2O) versus silicon dioxide (SiO_2) diagram from Le Maitre (2002); high K-shoshonitic dividing line from Ewart (1982). (TiO_2, titanium dioxide; Al_2O_3, aluminum oxide; FeO*, total iron expressed as ferrous oxide; MnO, manganese oxide; CaO, calcium oxide; Na_2O, sodium oxide, K_2O, potassium oxide; P_2O_5, phosphorous pentoxide).

Table 3. Representative compositions of volcanic rock units associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada (du Bray and others, 2019b).

[Major oxides (recalculated to 100 percent, volatile free) are in weight percent; FeO* is total iron expressed as ferrous oxide, FeO. Total_I, is prenormalization total; Trace elements are in parts per million; LOI—loss on ignition.Unit names: Fraction, Fraction Tuff; Heller, Heller Tuff; Brougher, Brougher Rhyolite; Red Mtn; trachyandesite of Red Mountain; Mizpah, Mizpah Trachyte; Oddie, Oddie Rhyolite; Divide, Divide Andesite; Rhd Don; volcanics of Donovan Peak-rhyodacite; Dac Don, volcanics of Donovan Peak-dacite; Rhy Don, volcanics of Donovan Peak-rhyolite; Prph and, porphyritic andesite; Milltown, Milltown Andesite; Wildhorse, rhyolite of Wildhorse Spring; Long, longitude; lat, latitude; —, no data; SiO_2, silicon dioxide; TiO_2, titanium dioxide; Al_2O_3, aluminum oxide; FeO*; total iron expressed as ferrous oxide; MnO, manganese oxide; MgO, magnesium oxide; CaO, calcium oxide; Na_2O, sodium oxide; K_2O, potassium oxide; P_2O_5, phosphorus pentoxide; Ba, barium; Cs, cesium; Rb, rubidium; Sr, strontium; Y, yttrium; Zr, zirconium; Hf, hafnium; Nb, niobium; Th, thorium; U, uranium; Ga, gallium; La, lanthanum; Ce, cerium; Pr, praseodymium; Nd, neodymium; Sm, samarium; Eu, europium; Gd, gadolinium; Tb, terbium; Dy, dysprosium; Ho, holmium; Er, erbium; Tm, thulium; Yb, ytterbium; Lu, lutetium; Co, cobalt; Cr, chromium; Ni, nickel; Sc, scandium; V, vanadium; Cu, copper; Mo, molybdenum; Pb, lead; Zn, zinc; Sn, tin; W, tungsten; Ta, tantalum]

Sample	203509	203474	203523	203490	203509	13-T-1	14-T-02	203478	203465	203471	00-T-2	00-T-6	203477	203469	203491	203527	203507	203517	203487	203484	203435	GF93-12	GF87-61A	GF93-17C	203437	GF03-1
Unit	Fraction	Fraction	Fraction	Heller	Heller	Heller	Brougher	Brougher	Red Mtn	Red Mtn	Mizpah	Mizpah	Mizpah	Oddie	Divide	Divide	Rhd Don	Rhd Don	Dac Don	Rhy Don	Prph and	Prph and	Milltown	Milltown	Milltown	Wildhorse
Long	117.1726	117.2230	117.2443	117.2352	117.1726	117.2265	117.2540	117.2133	117.2523	117.2430	117.2213	117.2444	117.2118	117.2234	117.2131	117.1400	117.2038	117.1989	117.1839	117.2037	117.2166	117.1448	117.2186	117.2111	117.2319	117.1294
Lat	37.9715	38.1007	38.0993	37.9646	38.9715	38.0599	38.0533	38.0169	38.0474	38.1269	38.0649	38.1044	38.1038	38.0770	37.9729	37.9748	37.9812	38.0455	37.9840	37.9955	37.7273	37.7360	37.7301	37.7583	37.7487	37.7530
SiO_2	74.80	74.07	74.51	65.52	74.80	70.58	73.46	76.70	54.39	56.32	66.60	63.86	61.91	76.51	69.20	67.52	69.02	56.86	63.67	74.67	61.61	61.44	58.14	63.63	60.94	76.73
TiO_2	0.26	0.24	0.23	0.51	0.26	0.34	0.19	0.11	1.54	1.32	0.58	0.69	0.85	0.11	0.34	0.42	0.45	1.51	0.83	0.18	0.74	0.66	0.88	0.62	0.74	0.19
Al_2O_3	14.30	14.05	13.73	17.70	14.30	15.69	13.93	12.82	17.04	16.92	16.03	16.38	16.70	13.25	15.99	16.65	15.45	17.11	17.01	13.73	16.53	15.94	17.61	16.96	17.13	12.50
FeO*	1.77	1.29	1.40	3.53	1.77	2.02	1.36	0.65	8.20	7.54	3.69	4.59	5.34	0.88	2.18	2.99	2.62	7.48	4.48	1.09	5.39	6.51	6.23	4.64	5.31	1.00
MnO	0.02	0.04	0.04	0.07	0.02	0.02	0.05	0.05	0.13	0.08	0.06	0.09	0.09	0.05	0.06	0.05	0.07	0.17	0.08	0.05	0.08	0.11	0.11	0.08	0.06	—
MgO	0.38	0.37	0.45	1.29	0.38	0.62	0.47	0.17	4.35	3.24	1.58	2.64	3.06	0.35	0.55	0.73	0.65	2.32	1.15	0.23	2.53	3.06	3.01	2.14	2.86	0.32
CaO	0.96	1.26	1.13	3.26	0.96	2.33	1.97	0.68	7.30	7.25	3.91	4.78	5.41	0.94	2.84	2.86	2.53	6.41	3.80	0.88	6.62	6.17	7.21	5.18	5.96	1.03
Na_2O	2.38	3.76	3.59	4.15	2.38	4.05	3.68	3.30	3.68	3.65	3.58	3.76	4.18	2.53	4.22	4.19	4.46	3.97	4.99	3.34	3.16	3.30	3.73	4.07	3.57	2.54
K_2O	5.00	4.84	4.86	3.76	5.00	4.23	4.82	5.50	2.60	2.90	3.71	2.92	2.13	5.34	4.47	4.39	4.60	3.27	3.63	5.81	2.99	2.52	2.72	2.34	3.16	5.68
P_2O_5	0.13	0.07	0.06	0.21	0.13	0.12	0.06	0.02	0.77	0.79	0.25	0.27	0.33	0.03	0.14	0.19	0.13	0.90	0.36	0.02	0.33	0.29	0.35	0.34	0.27	0.01
Total_I	99.94	99.24	99.72	99.17	98.92	100.07	100.26	99.54	100.47	99.06	99.99	99.98	99.33	101.07	99.60	99.58	99.65	99.37	98.17	99.18	99.67	100.58	99.87	101.24	99.33	100.59
LOI	2.75	1.62	2.15	2.18	2.75	1.67	1.01	4.30	1.58	3.09	—	—	2.98	4.38	1.82	2.87	2.58	1.77	1.26	2.90	3.50	1.45	3.23	2.83		1.30
Ba	927	816	712	2470	927	2670	1280	177	1720	1820	1258	1236	1190	379	1980	2028	1847	1931	1670	1330	1100	1590	1200	1900	1160	713
Cs	31.1	4.6	5.4	3.1	31.1	1.8	5.8	5.0	0.3	4.3	1.86	2.83	9.8	5.3	3.7	2.7	2.1	0.9	1.1	3.6	1.4	2.2	0.9	5.5	1.3	—
Rb	177	160	156	85.1	177	105	191	236	34.6	68.7	87	102	206	187	132	125	138	74.8	98.4	211	79.0	92.3	63.5	43.3	80.9	165
Sr	266	226	192	850	266	737	332	65.2	1360	1050	667	804	890	150	594	613	406	1078	723	164	1010	1490	1120	1490	960	255
Y	10.2	13.3	12.1	11.6	10.2	10.8	11	7.4	17.0	27.2	16	15	15.9	9.3	14.4	15.2	22.0	29.7	25.9	14.4	16.4	16.9	15	14.5	15.1	13.0
Zr	139	147	125	328	139	242	154	72.5	244	461	182	150	188	97.8	233	294	348	498	319	170	156	168	144	196	144	—
Hf	5	5	4	7	5	6	4	3	6	10	5.19	4.24	5	4	7	8	9	12	8	5	5	5	4	5	4	—
Nb	20	18	18	13	20	15	17	23	17	30	13	11	13	22	18	18	23	32	20	20	8	11	8.2	11.1	7	14.7
Th	20.1	18.5	20.0	10.5	20.1	12.9	23.4	25.2	3.3	5.0	15.2	11.7	10.4	19.5	14.7	15.2	16.3	6.8	9.8	24.4	9.7	10.4	5.3	9.8	6.7	23.2
U	4.67	5.85	5.93	2.98	4.67	3.20	4.47	8.93	0.95	1.43	3.29	3.28	3.05	3.98	4.03	4.03	4.07	1.92	2.49	5.34	2.34	2.57	1.54	2.91	2.06	3.5
Ga	18	19	19	22	18	18	18	17	16	24	19	20	23	18	21	22	19	24	23	16	20	23	20.1	20	21	13.2
La	32.8	41.2	34.5	57.4	32.8	64.4	39.4	23.0	47.6	74.1	40.3	35.9	36.8	23.8	58.0	60.6	53.9	80.0	49.4	61.9	39.8	48.0	32.3	43.3	33.2	47.4
Ce	57.8	71.9	62.4	94.9	57.8	105	66.7	38.1	99.8	147	71.6	62.7	71.6	40.1	97.0	104	98.2	162	93.3	105	75.4	93.5	61.8	81.3	63.4	75.8
Pr	5.97	7.86	6.77	9.94	5.97	9.91	6.77	3.58	12.0	17.9	7.741	6.810	8.75	4.21	10.2	11.00	10.9	19.6	11.2	10.5	8.68	10.4	7.55	9.42	7.49	—
Nd	18.7	24.6	21.8	32.0	18.7	31.0	21.8	10.0	43.9	65.3	28.8	25.4	32.3	12.5	32.3	35.8	37.4	71.9	40.9	32.9	32.9	38.5	29.8	34.8	28.7	—
Sm	2.7	3.6	3.3	4.3	2.7	4.2	3.3	1.2	7.3	10.3	5.36	4.71	5.3	1.8	4.4	5.1	5.9	11.3	6.9	4.4	5.3	6.7	5.3	5.6	5.0	—

Table 3. Representative compositions of volcanic rock units associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada (du Bray and others, 2019b).—Continued

[Major oxides (recalculated to 100 percent, volatile free) are in weight percent; FeO* is total iron expressed as ferrous oxide, FeO. Total_I, is prenormalization total; Trace elements are in parts per million; LOI—loss on ignition.Unit names: Fraction, Fraction Tuff; Heller, Heller Tuff; Brougher, Brougher Rhyolite; Red Mtn; trachyandesite of Red Mountain; Mizpah, Mizpah Trachyte; Oddie, Oddie Rhyolite; Divide, Divide Andesite; Rhd Don; volcanics of Donovan Peak-rhyodacite; Dac Don, volcanics of Donovan Peak-dacite; Rhy Don, volcanics of Donovan Peak-rhyolite; Prph and, porphyritic andesite; Milltown, Milltown Andesite; Wildhorse, rhyolite of Wildhorse Spring; Long, longitude; lat, latitude; —, no data; SiO_2, silicon dioxide; TiO_2, titanium dioxide; Al_2O_3, aluminum oxide; FeO*; total iron expressed as ferrous oxide; MnO, manganese oxide; MgO, magnesium oxide; CaO, calcium oxide; Na_2O, sodium oxide; K_2O, potassium oxide; P_2O_5, phosphorus pentoxide; Ba, barium; Cs, cesium; Rb, rubidium; Sr, strontium; Y, yttrium; Zr, zirconium; Hf, hafnium; Nb, niobium; Th, thorium; U, uranium; Ga, gallium; La, lanthanum; Ce, cerium; Pr, praseodymium; Nd, neodymium; Sm, samarium; Eu, europium; Gd, gadolinium; Tb, terbium; Dy, dysprosium; Ho, holmium; Er, erbium; Tm, thulium; Yb, ytterbium; Lu, lutetium; Co, cobalt; Cr, chromium; Ni, nickel; Sc, scandium; V, vanadium; Cu, copper; Mo, molybdenum; Pb, lead; Zn, zinc; Sn, tin; W, tungsten; Ta, tantalum]

Sample	203509	203474	203523	203490	203509	13-T-1	14-T-02	203478	203465	203471	00-T-2	00-T-6	203477	203469	203491	203527	203507	203517	203487	203484	203435	GF93-12	GF87-61A	GF93-17C	203437	GF03-1
Unit	Fraction	Fraction	Fraction	Heller	Heller	Heller	Brougher	Brougher	Red Mtn	Red Mtn	Mizpah	Mizpah	Mizpah	Oddie	Divide	Divide	Rhd Don	Rhd Don	Dac Don	Rhy Don	Prph and	Prph and	Milltown	Milltown	Milltown	Wildhorse
Eu	0.59	0.71	0.63	1.20	0.59	1.14	0.57	0.18	1.86	2.41	1.21	1.20	1.29	0.33	1.01	1.29	1.37	2.74	1.78	0.66	1.20	1.58	1.29	1.29	1.10	—
Gd	1.84	2.62	2.31	3.01	1.84	2.78	2.31	0.96	5.64	7.76	3.98	3.60	4.12	1.39	3.19	3.58	4.67	8.37	5.67	3.27	4.30	4.70	3.9	4.01	3.92	—
Tb	0.28	0.37	0.34	0.39	0.28	0.34	0.34	0.12	0.68	1.00	0.557	0.497	0.55	0.24	0.43	0.46	0.69	1.08	0.80	0.46	0.54	0.57	0.53	0.5	0.45	—
Dy	1.69	2.30	2.01	2.23	1.69	1.94	1.82	0.90	3.65	5.09	3.10	2.73	3.08	1.23	2.46	2.65	4.15	5.93	4.59	2.60	3.01	3.28	2.85	2.69	2.66	—
Ho	0.30	0.45	0.38	0.40	0.30	0.38	0.34	0.18	0.67	0.94	0.602	0.529	0.54	0.30	0.47	0.50	0.75	1.06	0.88	0.52	0.54	0.63	0.58	0.53	0.51	—
Er	1.04	1.13	1.19	1.05	1.04	1.04	0.95	0.67	1.72	2.34	1.54	1.40	1.41	0.82	1.30	1.48	2.33	3.03	2.52	1.46	1.51	1.61	1.49	1.39	1.42	—
Tm	0.17	0.21	0.19	0.19	0.17	0.17	0.16	0.14	0.25	0.42	0.237	0.203	0.21	0.20	0.22	0.22	0.35	0.43	0.37	0.25	0.22	0.24	0.22	0.22	0.21	—
Yb	1.2	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.5	2.3	1.45	1.30	1.5	1.2	1.5	1.6	2.4	2.6	2.5	1.7	1.4	1.6	1.5	1.4	1.4	—
Lu	0.20	0.22	0.21	0.20	0.20	0.21	0.19	0.19	0.23	0.38	0.227	0.210	0.21	0.22	0.23	0.25	0.38	0.41	0.37	0.26	0.20	0.24	0.25	0.21	0.2	—
Co	1.8	3.7	2.2	6.4	1.8	3.9	1.5	0.6	15.9	19.8	—	—	15.4	0.9	3.0	3.4	1.8	17.1	5.1	0.7	16.2	16.7	16.3	10.3	12.8	1.2
Cr	—	—	—	10	—	—	—	—	50	80	21	47	40	—	—	—	—	10	—	—	20	210	36	4	40	—
Ni	13	20	11	15	13	—	16	16	29	41	11	11	20	16	14	9	12	17	13	14	15	26	13.3	3.4	15	1.8
Sc	—	—	—		—	—	—	—	14	11	10	10	9	—	—	—	—	14	6	—	9	10	12.9	6.8	12	1.3
V	23	25	21	56	23	35	15	—	145	130	87	97	110	—	27	32	16	141	45	5	116	124	148	83	139	12
Cu	—	—	6	8	—	—	—	—	22	21	9	8	11	—	—	—	—	18	—	—	13	18	9.6	4.1	15	2.7
Mo	3	—	5		3	—	5	4	—	—	—	—	2	2	—	—	6	3	2	3	—	6	1.81	2.09	—	1.35
Pb	30	23	24	16	30	20	25	25	10	30	16	15	11	41	19	21	22	16	17	20	19	22	11.1	15	15	22.0
Zn	42	61	43	73	42	51	35	15	107	125	61	74	75	34	55	63	63	116	96	31	74	83	88	74	79	27
Sn	1	—	—		1	1	2	1	—	5	—	—	—	4	—	—	2	2	—	—	1	3	1.4	1.7	1	1.0
W	3	2	2	1	3	1	1	3	—	—	—	—	1	2	1	1	1	—	—	1	23	1	0.5	0.7	—	1.2
Ta	1.5	1.2	1.4	0.7	1.5	0.9	1.2	1.5	0.7	1.2	1.01	0.871	0.8	1.5	1.1	1.2	1.5	1.5	1.1	1.5	—	0.6	—	0.7	—	—

rocks. Furthermore, almost all volcanic rocks from these mining districts have relative abundances of Rb and Y+Nb consistent with arc magma compositions (fig. 4).

Chondrite normalized REE patterns for volcanic rocks of the Tonopah, Divide, and Goldfield mining districts are negatively sloping and include variably developed negative Eu anomalies (fig. 5). $(La/Yb)_N$ values, and therefore chondrite normalized pattern slopes, are not correlated with silica content; these values span a limited range from about 15 to 25. Light REE (LREE) pattern segments are distinctly more steeply sloped than heavy REE (HREE) pattern segments (fig. 5). HREE pattern segments for volcanic rocks in all three mining districts, especially those for the felsic units, are distinctly U-shaped. Chondrite-normalized REE patterns for intermediate composition rocks from the Tonopah, Divide, and Goldfield mining districts are completely overlapping and indistinguishable.

Chondrite-normalized REE patterns for felsic rocks from the Tonopah and Divide mining districts are also essentially indistinguishable. Samples of the Oddie Rhyolite, and to a lesser extent the Fraction Tuff, from the Tonopah mining district have well-developed negative Eu anomalies (Eu/Eu* as small as 0.31) and samples with the lowest Eu/Eu* values have the highest silica contents. REE abundances for the felsic volcanic rocks from the Divide mining district vary over a broad range. As a group, REE patterns for the Divide Andesite and volcanics of Donovan Peak define a relatively broad REE abundance array. However, patterns, and therefore REE abundances, for each of the four units define relatively limited and distinct compositional ranges. Among volcanic rocks in the Divide mining district, the Brougher Rhyolite and the rhyolite of Donovan Peak have the largest negative Eu anomalies (Eu/Eu* values of 0.55 and 0.53, respectively). Diagnostically, most samples

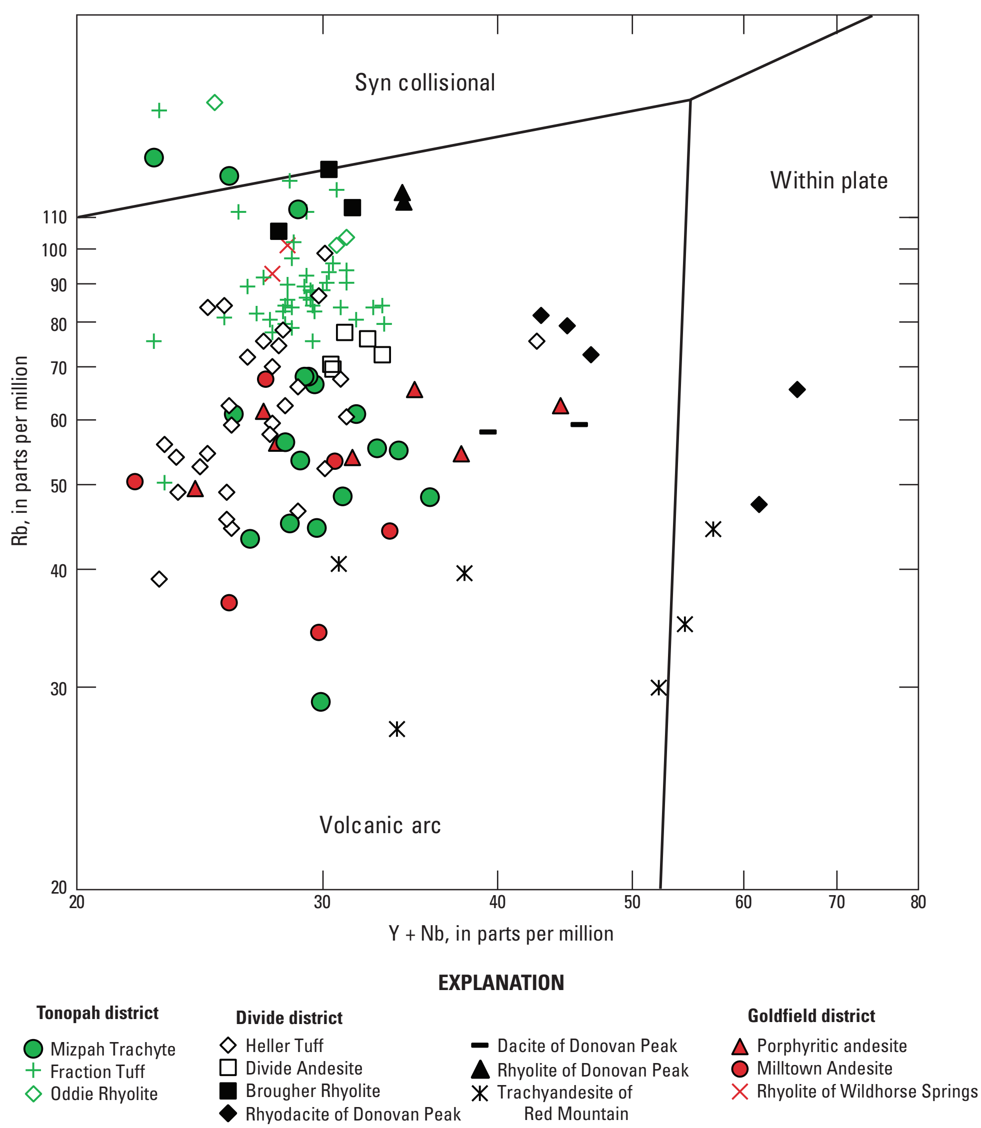

Figure 4. Trace-element, tectonic-setting-discrimination variation diagram showing the composition of volcanic rock units associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada. Tectonic setting-composition boundaries from Pearce and others (1984). (Rb, rubidium; Y, yttrium; Nb, niobium).

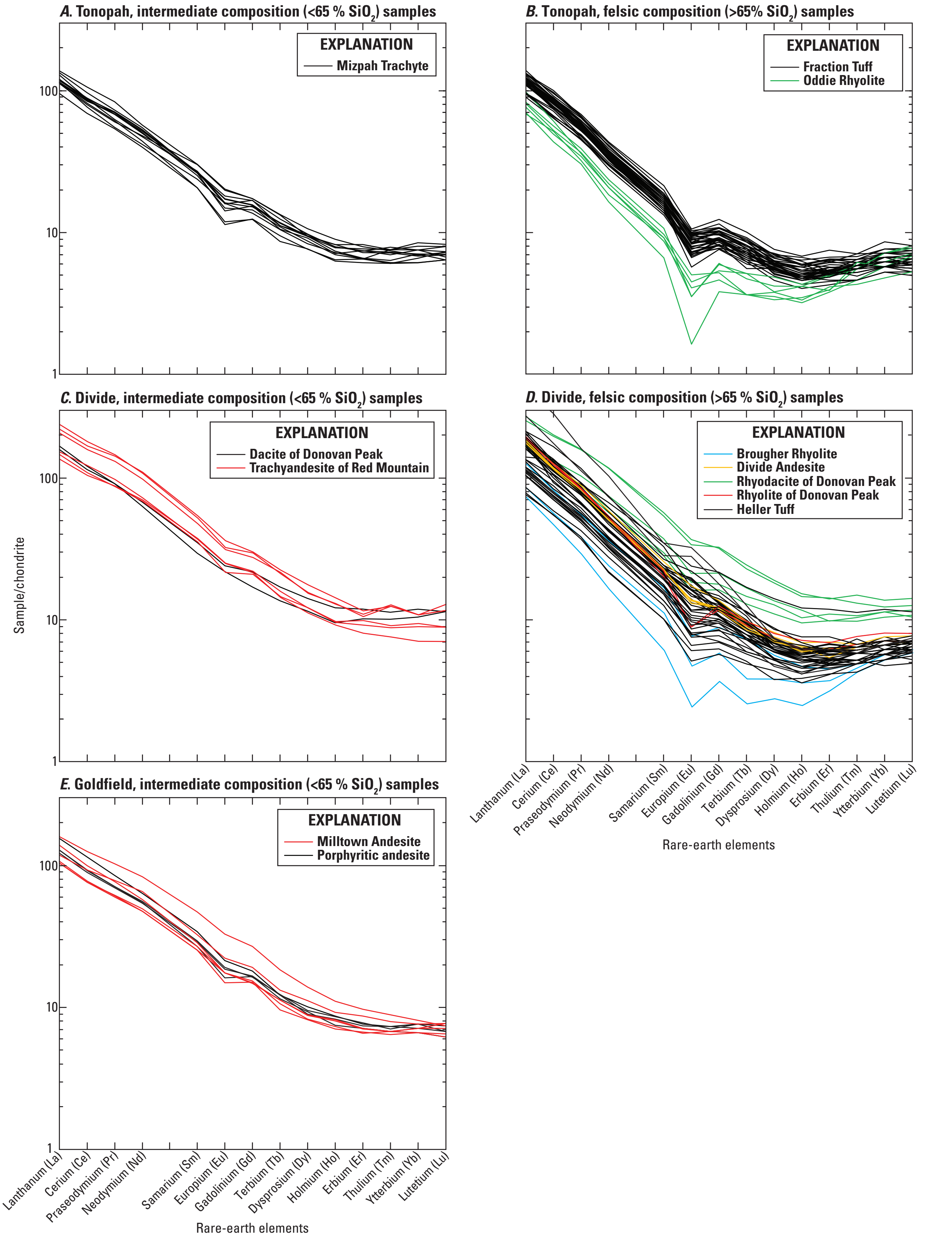

Figure 5. Chondrite normalized rare-earth element diagrams for volcanic rocks associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada. Chondrite abundances from Anders and Ebihara (1982). (SiO_2, silicon dioxide; >, greater than; <, less than). The unlabeled tick between Neodymium and Samarium corresponds to Promethium which does not occur in nature, and therefore this tick is never labelled.

of the Heller Tuff have negative Eu anomalies that are much smaller than those that are characteristic of the Fraction Tuff. Limited REE data for volcanic rocks in the Goldfield mining district yield relatively consistently negatively sloped patterns with small negative Eu anomalies (Eu/Eu* ranges from 0.73 to 0.88).

Volcanic rocks in the Tonopah, Divide, and Goldfield mining districts have primitive mantle-normalized patterns that are also similar to rocks characteristic of other continental margin, subduction-related magmatic arc complexes (fig. 6). These patterns are gently negatively sloping and have well developed negative Nb-Ta anomalies similar to those characteristic of subduction-related arc magmas (Wood and others, 1979; Gill, 1981; Pearce and others, 1984). Primitive mantle-normalized patterns for these rocks also have distinctly positive Pb and variably developed negative P and Ti anomalies. Most of the volcanic rocks in the Tonopah, Divide, and Goldfield mining districts have similar primitive mantle-normalized trace element patterns. Only the rhyolitic rocks in each of these three mining districts have somewhat distinctive patterns. Larger negative Ba, P, and Ti anomalies and previously described middle REE depletions are especially noteworthy features of patterns for these rhyolitic rocks.

Petrogenesis of Volcanic Rocks in the Tonopah, Divide, and Goldfield Mining Districts

The subalkaline, metaluminous, and magnesian character of intermediate composition volcanic rocks that dominate the Tonopah, Divide, and Goldfield mining districts is consistent with their genesis in a subduction related magmatic setting within the southern segment of the ancestral Cascades arc. Putirka and others (2012) suggest that the Mendocino triple junction passed north of the Goldfield and Tonopah regions about 13 and 12 Ma, respectively. Subsequently, subduction of the Farallon Plate beneath North America in this region ceased and additional subduction-related inputs to ongoing magmatism ended.

Volcanologic processes that contributed to development of volcanic centers in the Tonopah, Divide, and Goldfield mining districts are constrained by their petrographic and geochemical characteristics. Plagioclase in many of the constituent volcanic rocks is oscillatory zoned, partly resorbed, sieve textured, and includes variable, within-sample size populations; these features suggest that evolution of the associated magma reservoirs involved open-system behavior, especially periodic recharge. Similarly, the geochemistry of these volcanic rocks, especially those that are part of the stratovolcano represented by the Milltown Andesite, and the petrologically diverse, dome-forming rocks included in the Mizpah Trachyte, vary broadly, also indicative of recharge and incomplete homogenization of reservoir contents.

Major oxide compositional variations among these rocks are in accord with crystallization and fractionation of the observed phenocryst assemblages. Consistent linear decreases, especially of CaO, but also Al_2O_3, with increasing silica content suggests that plagioclase crystallization and fractionation contributed significantly to the compositional evolution displayed by this suite of rocks. Importantly, Sr abundances that decrease linearly from about 1,600 parts per million (ppm) in rocks with about 54 weight percent SiO_2 to 150 ppm in rocks with about 77 weight percent SiO_2 and Eu/Eu* that decreases from about 0.85 to about 0.50 in these same rocks indicate significant plagioclase fractionation from their parental magmas. Decreasing TiO_2, FeO*, and MgO abundances with increasing silica content (fig. 4) are consistent with clinopyroxene, hornblende, biotite, and lesser Fe-Ti oxide crystallization and fractionation. Concomitant K_2O abundance increases with increasing SiO_2 content signal its incompatibility and concentration in evolving, residual magma. The importance of accessory minerals (especially apatite and Fe-Ti oxides) in the petrogenesis of volcanic rocks in the Tonopah, Divide, and Goldfield mining districts is demonstrated by increasingly well-developed negative P and Ti anomalies among rocks with higher silica contents (fig. 6). Relatively elevated Na_2O and TiO_2 abundances characteristic of the volcanics of Donovan Peak and, to a lesser extent, the Divide Andesite, in the Divide mining district, are off trend from compositional arrays defined by Tonopah and Goldfield mining district volcanic rocks. Together with the off trend MgO depletion characteristic of the volcanics of Donovan Peak, these variations suggest a compositionally distinct source for most magmas erupted in the Divide mining district.

The preponderance of volcanic rocks in the Tonopah and Goldfield mining districts have Zr abundances that vary from about 140 to 190 ppm, a range commensurate with Zr abundances buffered by zircon saturation in calc-alkaline magmas, as per relations described by Watson (1979). Among these rocks, those with >72 weight percent silica have markedly lower Zr abundances, which probably represents accessory zircon crystallization and fractionation from their parental magmas. Importantly, at any given SiO_2 content, volcanic rocks in the Divide mining district have significantly higher Zr abundances (as much as 562 ppm) than Tonopah and Goldfield volcanic rocks, which reflect increased Zr solubility in alkaline silicate melts (Watson, 1979).

Like most other Miocene volcanic rocks associated with the southern segment of the ancestral Cascades arc, Sr abundances (1,100 and 750 ppm at 57 and 63 weight percent SiO_2, respectively) of volcanic rocks in the Tonopah, Divide, and Goldfield mining districts are significantly elevated relative to those characteristic of Andean arc andesites, which contain 600–900 ppm Sr (Hildreth and Moorbath, 1988). Partial melting at the base of the crust-subcontinental mantle section, at plagioclase-unstable pressures (Green, 1982) greater than about 20 kilobars (kb) (70 km depth) and relatively hydrous conditions (Moore and Carmichael, 1998), yields high-Sr magmas. Otherwise, conditions that favor plagioclase stability promote preferential Sr retention in plagioclase, its principal

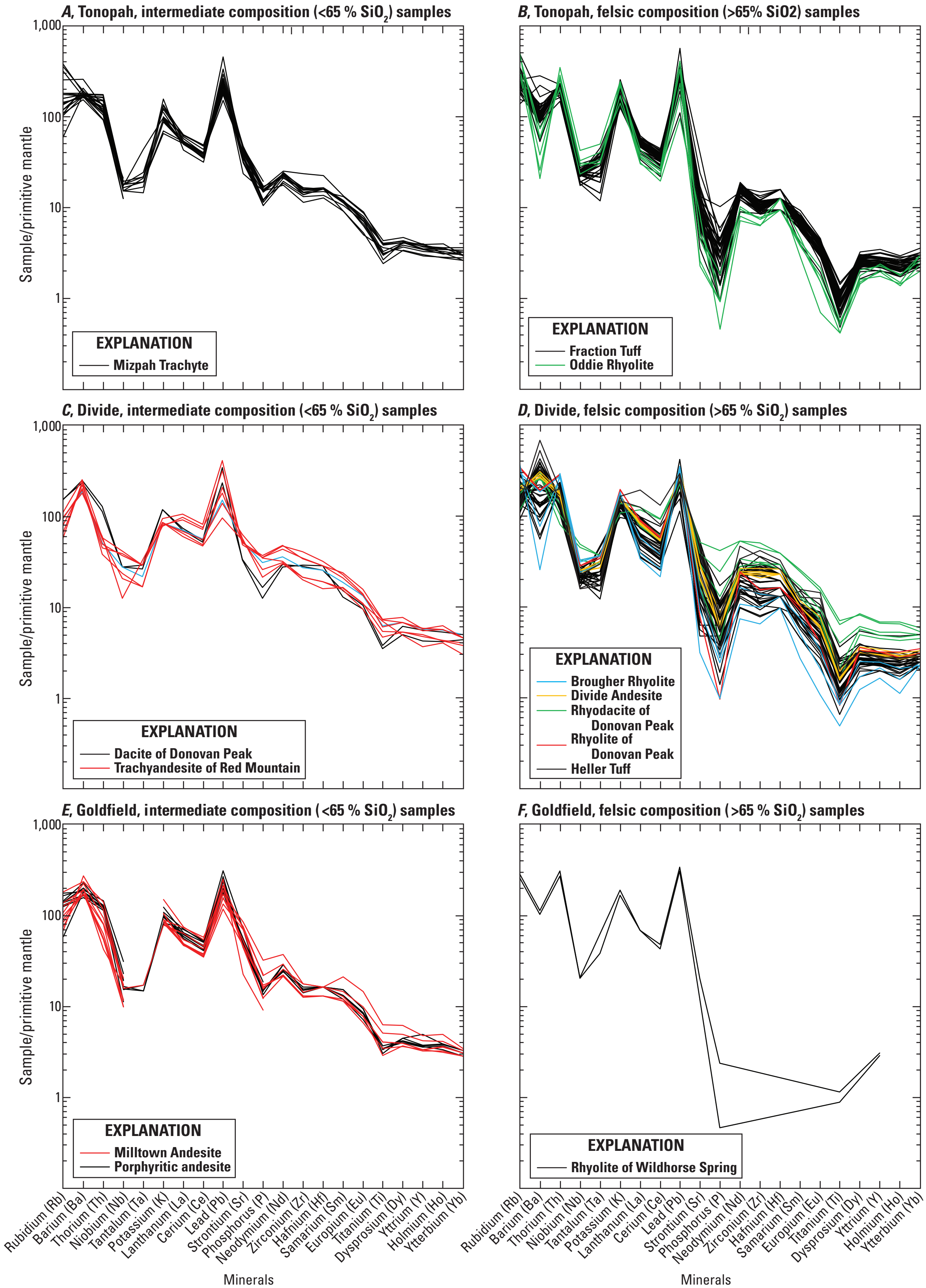

Figure 6. Primitive mantle-normalized (Sun and McDonough, 1989) trace element diagrams for volcanic rock units associated with mineralization in the Tonopah, Divide, and Goldfield mining districts, Nevada. (SiO_2, silicon dioxide; >, greater than; <, less than).

mineralogic residence, and consequent Sr-poor magmas. Accordingly, volcanic rocks from all three mining districts probably reflect partial melting in a relatively hydrous, high-pressure regime beneath a thick section composed of continental crust and subcontinental mantle.

Volcanic rocks in the Tonopah, Divide, and Goldfield mining districts have relative abundances of Rb and Y+Nb consistent with their genesis in a volcanic arc setting (fig. 4). Negative Nb-Ta anomalies (fig. 6) are similarly in accord with genesis of the associated magmas in a subduction-related magmatic arc setting. The amplitude of these anomalies appears minimally correlated with host rock composition, which suggests that these anomalies are not fractionation-related phenomenon.

The values of Ba/Nb further corroborate a volcanic arc setting for genesis of volcanic rocks in the Tonopah, Divide, and Goldfield mining districts. Gill (1981) suggests that most magmatic arc rocks have Ba/Nb>15. Volcanic rocks in these three mining districts with 54 to 68 weight percent SiO_2 have Ba/Nb that range from 50–150 and cluster around 100. Ba/Nb values for these rocks do not covary systematically with respect to either host rock age or composition, although values generally decrease among rocks with greater than 72 weight percent SiO_2, probably because of feldspar and biotite crystallization and fractionation.

REE abundance variations further constrain the petrogenesis of volcanic rocks in the Tonopah, Divide and Goldfield mining districts. Moderately steep, negatively sloped chondrite-normalized REE patterns such as those characteristic of these volcanic rocks (fig. 5) are similar to those of Andean magmatic arc rocks and are likely additional manifestations of high-pressure partial melting in a garnet-stable regime (Hildreth and Moorbath, 1988), because garnet is a HREE reservoir. MREE to HREE depletion, as defined by subtly U-shaped MREE to HREE pattern segments, is characteristic of the volcanic rocks, especially the more evolved rhyolitic rocks, in the Tonopah, Divide, and Goldfield mining districts (fig. 5). Amphibole fractionation has been inferred in the genesis of MREE depletion and development of U-shaped REE patterns because mineral/melt partition coefficients for amphibole are greatest among the MREE, especially dysprosium (Dy) (Davidson and others, 2007). Consequently, U-shaped MREE to HREE pattern segments for volcanic rocks in the three mining districts probably reflect varying degrees of amphibole fractionation. Weak negative Eu anomaly development characteristic of intermediate composition rocks reflects relatively high pressure melting conditions in a relatively hydrous regime (Moore and Carmichael, 1998) that favored garnet rather than plagioclase (a principal Eu reservoir) stability. Consequently, small negative Eu anomalies that typify the intermediate composition rocks in the three mining districts (fig. 5) are consistent with source-region plagioclase instability and consequent Eu partitioning into partial melts rather than into residuum. In contrast, significantly larger negative Eu anomalies among the more evolved, mostly rhyolitic rocks in these three mining districts suggests that plagioclase fractionation contributed significantly to the compositional evolution of these rocks.

Lead/cerium (Pb/Ce) increases from ~0.1 to ~0.4 with increasing SiO_2 content among volcanic rocks of the Tonopah, Divide, and Goldfield mining districts. Increasing Pb/Ce values may result from (1) greater subducted slab contributions to mantle-derived melts or (2) increased assimilation of Pb-rich crustal rocks during reservoir melting, assimilation, and homogenization processes. Similarly, elevated Ba/Nb may reflect contributions of subducted slab components, by slab dehydration, to mantle wedge-derived magmas (Hawkesworth and others, 1995; Pearce and Peate, 1995; Cousens and others, 2008; Schmidt and others, 2008). Consequently, the observed positive and negative correlations between Pb/Ce and Ba/Nb, respectively, with SiO_2 content suggest that the most SiO_2-rich rocks in these areas represent magmas that assimilated relatively greater amounts of crustal material, an inference that could be evaluated using, presently scant, radiogenic isotope data.

Farmer and others (2002), Cousens and others (2008), and du Bray and others (2014) suggest that magmatism represented by the southern segment of the ancestral Cascades arc involved significant crustal contamination; an array of geochemical parameters indicate that magmas represented by Miocene volcanic rocks in the Tonopah, Divide, and Goldfield mining districts were affected by similar, variable crustal contamination. Progressively lower P_2O_5/K_2O among increasingly silicic compositions and higher values with increasing MgO abundances are consistent with primary, mafic magmas having assimilated crustal contaminants, because crustal materials generally have $P_2O_5/K_2O < 0.1$ (Farmer and others, 2002). P_2O_5/K_2O decreases with increasing SiO_2 and increases with higher MgO contents among rocks of the three mining districts, which suggests that the associated magmas evolved to intermediate or silicic compositions by variable contamination of primary mafic partial melts by crustally derived inputs. Decreasing CaO/Al_2O_3 and increasing lanthanum/samarium (La/Sm) and Zr/Sm with increasing SiO_2 are additional measures reflective of crustal contamination (Cousens and others, 2008). Correspondingly, CaO/Al_2O_3 decreases, and La/Sm and Zr/Sm increases with increasing SiO_2 among rocks of the Tonopah, Divide, and Goldfield mining districts further corroborate the role of progressive crustal contamination in the petrogenesis of intermediate- to felsic-composition rocks in these areas.

Conclusions

Precious metal epithermal deposits in the Tonopah, Divide, and Goldfield mining districts of west-central Nevada are spatially, temporally, and likely genetically associated with Miocene calc-alkaline volcanic rocks that are part of the southern segment of the ancestral Cascades magmatic arc. Geochemical characteristics of these volcanic rocks constrain the tectonic setting in which they evolved and corroborate their relations with ancestral Cascades arc magmatism. Specifically, relative abundances of Rb, Y, and Nb in these rocks are commensurate with compositions typical of arc magmas, as are their elevated Ba/Nb and negative Nb-Ta anomalies. Arc-related magmatism in each of these mining districts was extinguished by northward passage of the Mendocino triple junction between about 13 and 12 Ma.

Specific Miocene volcanic rock units are essentially unique to each of the three mining districts. Although the probable source of mineralizing fluids in the Tonopah mining district is not well established, its mineral deposits are principally hosted by the Mizpah Trachyte, which forms a small field of coalesced lava domes, and the Fraction Tuff, likely erupted from a caldera whose northern margin is about 9 km north of Tonopah. Mineral deposits in the Divide mining district are spatially and temporally associated with (1) the Heller Tuff, likely erupted from a caldera whose southern margin is preserved about 14 km south of Tonopah, and (2) the Divide Andesite and volcanics of Donovan Peak, both likely manifestations of post caldera resurgent magmatism. At Goldfield, mineral deposits are principally associated with the Milltown Andesite, an unnamed porphyritic andesite, and latite.

All these volcanic rocks have petrographic and geochemical characteristics consistent with their genesis in a magmatic arc setting. Almost all are porphyritic, containing 5 to 35 percent phenocrysts, principally composed of plagioclase, pyroxene, and hornblende±biotite; quartz, alkali feldspar, or olivine form phenocrysts in some of these rocks. Geochemical compositions of these rocks range essentially continuously from basaltic trachyandesite and basaltic andesite to rhyolite, with SiO_2 contents that range from 54 to 78 weight percent. Most have compositions that are transitional from alkaline to subalkaline, metaluminous, calc-alkalic to alkali-calcic, and magnesian (calc-alkaline) to weakly ferroan (tholeiitic). Compositions of the Divide Andesite and the volcanics of Donovan Peak in the Divide mining district are somewhat distinct relative to volcanic rocks in the Tonopah and Goldfield mining districts. Specifically, they are more alkalic; have greater TiO_2, Na_2O, Ba, Hf, La, Nb, Ta, Y, Yb, and Zr abundances; and lower MgO, Sr, and V abundances than their Tonopah and Goldfield mining district analogs. None of the unaltered volcanic rocks in the Tonopah, Divide, and Goldfield are particularly metal enriched.

Significantly elevated Zr contents characteristic of volcanic rocks from the Divide mining district, including the Heller Tuff, are particularly noteworthy and indicate equilibration with relatively alkaline magma. The Divide mining district rocks have Na_2O contents that are distinctly greater and K_2O contents at the high end of the range defined by rocks from the Tonopah and Goldfield mining districts. These alkalinity characteristics suggest that the petrogenetic evolution of the Miocene volcanic rocks in the Divide mining district involved a source and (or) processes dissimilar to those that controlled the magmatic evolution of volcanic rocks in the other two mining districts.

Numerous geochemical characteristics similarly constrain the petrogenetic processes that contributed to compositional evolution among Miocene volcanic rocks in the Tonopah, Divide, and Goldfield mining districts. For example, negatively sloping, relatively HREE depleted REE patterns are consistent with high-pressure, garnet stable, plagioclase unstable partial melting. Elevated Sr concentrations and generally small negative Eu anomalies characteristic of these volcanic rocks are additional manifestations of partial melting in a plagioclase unstable regime. Progressively larger negative Eu anomalies among the more silica rich volcanic rocks in the three mining districts reflect the increased importance of plagioclase fractionation from magmas represented by those rocks. Subtly U-shaped middle chondrite-normalized REE patterns reflect the importance of amphibole crystallization and fractionation from the associated magmas. Major oxide compositional variation among these rocks is consistent with crystallization and fractionation of the other observed phenocryst minerals, including clinopyroxene, biotite, and Fe-Ti oxides. Well-developed negative P and Ti anomalies on extended trace element diagrams substantiate the importance of accessory minerals, especially apatite and Fe-Ti oxides, to the compositional evolution of magma reservoirs represented by volcanic rocks in the three mining districts. Other geochemical parameters suggest that magmas represented by volcanic rocks in these three mining districts underwent variable amounts of crustal contamination during ascent and storage in shallow crustal reservoirs. Specifically, increasing Pb/Ce and decreasing P_2O5/K_2O with increasing SiO_2 abundances are well known manifestations of crustal contamination. Diagnostic textural features preserved by phenocrysts, especially plagioclase, constitute additional evidence that open-system behavior, including reservoir-scale mixing, recharge, and assimilation, were critical to the petrogenesis of volcanic rocks in the Tonopah, Divide, and Goldfield mining districts.

References Cited

Albers, J.P., and Stewart, J.H., 1972, Geology and mineral deposits of Esmeralda County, Nevada: Nevada Bureau of Mines and Geology Bulletin 78, 80 p. [Also available at http://pubs.nbmg.unr.edu/Geol-mineral-Esmeralda-Co-p/b078.htm.]

Anders, E., and Ebihara, M., 1982, Solar-system abundances of the elements: Geochimica et Cosmochimica Acta, v. 46, p. 2363–2380. [Also available at https://doi.org/10.1016/0016-7037(82)90208-3.]

Ashley, R.P., 1974, Goldfield mining district, *in* Guidebook to the geology of the four Tertiary volcanic centers in central Nevada, Cordilleran Section Meeting, Las Vegas, Nev., March 1974, road log to Austin-Northumberland caldera—Carver Station: Nevada Bureau of Mines and Geology Report 19, p. 49–66. [Also available at http://pubs.nbmg.unr.edu/Four-Tertiary-volcanic-centers-p/r019.htm.]

Ashley, R.P., 1979, Relation between volcanism and ore deposition at Goldfield, Nevada, *in* Papers on mineral deposits of western North America: Nevada Bureau of Mines and Geology Report 33, p. 77–86. [Also available at http://pubs.nbmg.unr.edu/Mineral-W-North-America-p/r033.htm.]

Ashley, R.P., 1990a, The Tonopah precious-metal district, Esmeralda and Nye Counties, Nevada, *in* Shawe, D.R., and Ashley, R.P., eds., Epithermal gold deposits—Part 1: U.S. Geological Survey Bulletin 1857–H, p. H8–H13. [Also available at https://doi.org/10.3133/b1857H.]

Ashley, R.P., 1990b, The Goldfield gold district, Esmeralda and Nye Counties, Nevada, *in* Shawe, D.R., and Ashley, R.P., eds., Epithermal gold deposits—Part 1: U.S. Geological Survey Bulletin 1857–H, p. H1–H7. [Also available at https://doi.org/10.3133/b1857H.]

Ashley, R.P., and Albers, J.P., 1975, Distribution of gold and other ore-related elements near ore bodies in the oxidized zone at Goldfield, Nevada: U.S. Geological Survey Professional Paper 843–A, 48 p. [Also available at https://doi.org/10.3133/pp843A.]

Ashley, R.P., and Silberman, M.L., 1976, Direct dating of mineralization at Goldfield, Nevada by potassium-argon and fission-track methods: Economic Geology, v. 71, p. 904–924. [Also available at https://doi.org/10.2113/gsecongeo.71.5.904.]

Blakely, R.J., John, D.A., Box, S.E., Berger, B.R., Fleck, R.J., Ashley, R.P., and Heinemeyer, G.R., 2007, Crustal controls on magmatic-hydrothermal systems—A geophysical comparison of White River, Washington, with Goldfield, Nevada: Geosphere, v. 3, p. 91–107. [Also available at https://doi.org/10.1130/GES00071.1.]

Bonham, H.F., Jr., and Garside, L.J., 1974, Tonopah mining district and vicinity, *in* Guidebook to the geology of the four Tertiary volcanic centers in central Nevada, Cordilleran Section Meeting, Las Vegas, Nev., March 1974, road log to Austin-Northumberland caldera—Carver Station: Nevada Bureau of Mines and Geology Report 19, p. 42–48. [Also available at http://pubs.nbmg.unr.edu/Mineral-W-North-America-p/r033.htm.]

Bonham, H.F., and Garside, L.J., 1979, Geology of the Tonopah, Lone Mountain, Klondike, and northern Mud Lake quadrangles, Nevada: Nevada Bureau of Mines and Geology Bulletin 92, 142 p. [Also available at http://pubs.nbmg.unr.edu/Bulletins-s/1852.htm.]

Colgan, J.P., Egger, A.E., John, D.A., Cousens, B., Fleck, R.J., and Henry, C.D., 2011, Oligocene and Miocene arc volcanism in northeastern California—Evidence for post-Eocene segmentation of the subducting Farallon plate: Geosphere, v. 7, p. 733–755. [Also available at https://doi.org/10.1130/GES00650.1.]

Cousens, B.L., Prytulak, J., Henry, C.D., Alcazar, A., and Brownrigg, T., 2008, Geology, geochronology, and geochemistry of the Miocene-Pliocene ancestral Cascades arc, northern Sierra Nevada, California and Nevada—The roles of the upper mantle, subducting slab, and the Sierra Nevada lithosphere: Geosphere, v. 4, p. 814–828. [Also available at https://doi.org/10.1130/GES00166.1.]

Crafford, A.E.J., 2007, Geologic map of Nevada: U.S. Geological Survey Data Series 249, 46 p., 1 pl., accessed 2015, at http://pubs.usgs.gov/ds/2007/249/. [Also available on CD-ROM.]

Crafford, A.E.J., 2008, Paleozoic tectonic domains of Nevada—An interpretive discussion to accompany the geologic map of Nevada: Geosphere, v. 4, p. 260–291. [Also available at https://doi.org/10.1130/GES00108.1.]

Davidson, J., Turner, S., Handley, H., Macpherson, C., and Dosseto, A., 2007, Amphibole “sponge” in arc crust?: Geology, v. 35, p. 787–790. [Also available at https://doi.org/10.1130/G23637A.1.]

du Bray, E.A., Cosca, M.A., Morgan, L.E., Heizler, M., Fleck, R.J., Holm-Denoma, C.S., and John, D.A., 2019a, Petrographic, geochemical and geochronologic data for Cenozoic volcanic rocks of the Tonopah, Divide, and Goldfield Mining Districts, Nevada: U.S, Geological Survey data release, https://doi.org/10.5066/P9HZCRGV.

du Bray, E.A., John, D.A., and Cousens, B.L., 2014, Petrologic, tectonic, and metallogenic evolution of the southern segment of the ancestral Cascades magmatic arc, California and Nevada: Geosphere, v. 10, p. 1–39; accessed 2016 at https://doi.org/10.1130/GES00944.1.

du Bray, E.A., John, D.A., Vikre, P.G., Colgan, J.P., Cosca, M.A., Morgan, L.E., Fleck, R.J., Premo, W.R., and Holm-Denoma, C.S., 2019b, Petrographic, geochemical, and geochronologic data for Cenozoic volcanic rocks of the Tonopah, Divide, and Goldfield mining districts, Nevada: U.S. Geological Survey Data Series 1099, https://doi.org/10.3133/ds1099.

Erdman, C.P., and Barabas, A.H., 1996, Precious metal mineralization at Gold Mountain, Tonopah Divide district, Esmeralda County, Nevada, *in* Coyner, A.R, and Fahey, P.L., eds., Geology and ore Deposits of the American Cordillera, Symposium Proceedings, April 10–13, 1996: Reno, Geological Society of Nevada, Symposium Proceedings no. 95–1, p. 329–351. [Also available at https://gsnv.org/publications/?itemid=95-1.]

Ewart, A., 1982, The mineralogy and petrology of Tertiary—Recent orogenic volcanic rocks with special reference to the andesitic-basaltic compositional range, *in* Thorpe, R.S., ed., Andesites: New York, John Wiley and Sons, p. 25–87.

Farmer, G.L., Glazner, A.F., and Manley, C.R., 2002, Did lithospheric delamination trigger late Cenozoic potassic volcanism in the southern Sierra Nevada, California?: Geological Society of America Bulletin, v. 114, p. 754–768. [Also available at https://doi.org/10.1130/0016-7606(2002)114<0754:DLDTLC>2.0.CO;2.]

Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., and Frost, C.D., 2001, A geochemical classification for granitic rocks: Journal of Petrology, v. 42, p. 2033–2048. [Also available at https://doi.org/10.1093/petrology/42.11.2033.]

Gill, J., 1981, Orogenic andesites and plate tectonics: New York, Springer-Verlag, 390 p.

Graney, J.R., 1987, Hasbrouck Mountain, Nevada, precious-metal mineralization in a fossil hot springs environment, *in* Johnson, J.L., and Abbott, E., eds., Bulk mineable precious metal deposits of the western United States April 6–8, 1987, Guidebook for Field Trips, 1987 Symposium: Reno, Geological Society of Nevada, p. 120–125. [Also available from the Nevada Bureau of Mines and Geology, Open-File Report 10–8, at http://ronhess.info/MD/scans/1490/14900273.pdf.]

Green, T.H., 1982, Anatexis of mafic crust and high pressure crystallization of andesite, *in* Thorpe, R.S., ed., Andesites—Orogenic andesites and related rocks: New York, John Wiley and Sons, p. 465–487.

Hawkesworth, C., Turner, S., Gallagher, K., Hunter, A., Bradshaw, T., and Rogers, N., 1995, Calc-alkaline magmatism, lithospheric thinning and extension in the Basin and Range: Journal of Geophysical Research, Solid Earth, v. 100, p. 10,271–10,286. [Also available at https://doi.org/10.1029/94JB02508.]

Hildreth, W., and Moorbath, S., 1988, Crustal contributions to arc magmatism in the Andes of central Chile: Contributions to Mineralogy and Petrology, v. 98, p. 455–489. [Also available at https://link.springer.com/content/pdf/10.1007%2FBF00372365.pdf.]

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548. [Also available at https://doi.org/10.1139/e71-055.]

John, D.A., du Bray, E.A., Blakely, R.J., Fleck, R.J., Vikre, P.G., Box, S.E., and Moring, B.C., 2012, Miocene magmatism in the Bodie Hills volcanic field, California and Nevada: A long-lived eruptive center in the southern segment of the ancestral Cascades arc: Geosphere, v. 8, p. 44–97, accessed 2015, at https://doi.org/10.1130/GES00674.1.

John, D.A., du Bray, E.A., Henry, C.D., and Vikre, P.G., 2015, Cenozoic magmatism and epithermal gold-silver deposits of the southern ancestral Cascade arc, western Nevada and eastern California, *in* Pennell, W.M., and Garside, L.J., eds., New concepts and discoveries, Sparks, Nev., May 14–23, 2015, Symposium Proceedings: Geological Society of Nevada Symposium Proceedings, no. 15–CD, p. 611–645, 1 CD-ROM. [Also available at https://gsnv.org/publications/?itemid=15-CD.]

John, D.A., and McKee, E.H.,1987, K-Ar ages of granitic plutonism and hydrothermal alteration in western part of the Tonopah 1°×2° quadrangle, Nevada: Isochron/West, no. 48, p. 16–18.

Knopf, A., 1921, Contributions to economic geology, 1920, Part I, Metals and Nonmetals except fuels—The Divide silver district, Nevada,: U.S. Geological Survey Bulletin 715–K, p. 147–170. [Also available at https://doi.org/10.3133/b715K.]

Le Maitre, R.W., 2002, Igneous rocks—A classification and glossary of terms, 2d ed.: Cambridge University Press, 236 p. [Also available at https://doi.org/10.1017/CBO9780511535581.]

Moore, G., and Carmichael, I.S.E., 1998, The hydrous phase equilibria (to 3 kbar) of an andesite and basaltic andesite from western Mexico—Constraints on water content and conditions of phenocryst growth: Contributions to Mineralogy and Petrology, v. 130, p. 304–319. [Also available at https://doi.org/10.1007/s004100050367.]

Nolan, T.B., 1935, Underground geology of the Tonopah mining district, Nevada: Nevada University Bulletin 23, no. 5, 49 p. [Also available at http://pubs.nbmg.unr.edu/Underground-geol-Tonopah-mining-p/b023.htm.]

Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 956–983. [Also available at https://doi.org/10.1093/petrology/25.4.956.]

Pearce, J.A., and Peate, D.W., 1995, Tectonic implications of the composition of volcanic arc magmas: Annual Review of Earth and Planetary Sciences, v. 23, p. 251–285. [Also available at https://www.annualreviews.org/doi/pdf/10.1146/annurev.ea.23.050195.001343.]

Putirka, K., Jean, M., Cousens, B., Sharma, R., Torrez, G., and Carlson, C., 2012, Cenozoic volcanism in the Sierra Nevada and Walker Lane, California, and a new model for lithosphere degradation: Geosphere, v. 8, p. 265–291, accessed 2015, at https://doi.org/10.1130/GES00728.1.

Ransome, F.L., 1909, The geology and ore deposits of Goldfield, Nevada: U.S. Geological Survey Professional Paper 66, 258 p. [Also available at https://doi.org/10.3133/pp66.]

Schmidt, M.E., Grunder, A.L., and Rowe, M.C., 2008, Segmentation of the Cascade arc as indicated by Sr and Nd isotopic variation among diverse primitive basalts: Earth and Planetary Science Letters, v. 266, p. 166–181. [Also available at https://doi.org/10.1016/j.epsl.2007.11.013.]

Shand, S.J., 1951, Eruptive rocks: New York, John Wiley, 488 p.

Searls, F., 1948, A contribution to the published information on the geology and ore deposits of Goldfield, Nevada: Nevada Bureau of Mines and Geology Bulletin 48, 24 p. [Also available at http://pubs.nbmg.unr.edu/Geol-ore-deposits-Goldfield-p/b048.htm.]

Sun, S.-S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts—Implications for mantle composition and processes, *in* Saunders, A.D., and Norry, M.J., eds., Magmatism in the Ocean Basins: Geological Society of London Special Publication 42, p. 313–345. [Also available at https://sp.lyellcollection.org/content/specpubgsl/42/1/313.full.pdf.]

Taggart, J.E., Jr., 2002, Analytical methods for chemical analysis of geologic and other materials, U.S. Geological Survey: U.S. Geological Survey Open-File Report 02–0223. [Also available at https://doi.org/10.3133/ofr02223.]

Turekian, K.K., and Wedepohl, K.H., 1961, Distribution of the elements in some major units of the Earth’s crust: Geological Society of America Bulletin, v. 72, p. 175–192. [Also available at https://pubs.geoscienceworld.org/gsa/gsabulletin/article/72/2/175/5262/distribution-of-the-elements-in-some-major-units.]

Vikre, P.G., and Henry, C.D., 2011, Quartz-alunite alteration cells in the ancestral southern Cascades magmatic arc, *in* Steininger, R., and Pennell, B., eds., Great Basin Evolution and Metallogeny, 2010 Symposium, May 14–22, Symposium Proceedings: Reno, Nev., Geological Society of Nevada, Symposium Proceedings, no. 10–1, v. I, p. 701–745. [Also available at https://gsnv.org/publications/?itemid=10-1.]

Watson, E.B., 1979, Zircon saturation in felsic liquids; experimental results and applications to trace element geochemistry: Contributions to Mineralogy and Petrology, v. 70, p. 407–419. [Also available at https://link.springer.com/content/pdf/10.1007%2FBF00371047.pdf.]

Wood, D.A., Joron, J.L., and Treuil, M., 1979, A re-appraisal of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings: Earth and Planetary Science Letters, v. 45, p. 326–336. [Also available at https://doi.org/10.1016/0012-821X(79)90133-X.]

For more information concerning the research in this report, contact the
Center Director, USGS Geology, Geophysics, and Geochemistry Science Center
Box 25046, Mail Stop 973
Denver, CO 80225
(303) 236-1800
Or visit Geology, Geophysics, and Geochemistry Science Center website at https://www.usgs.gov/centers/gggsc

du Bray and others—**Volcanic Rocks Associated with Silver-Gold Epithermal Deposits in Nevada**—Scientific Investigations Report 2019–5024

ISSN 2331-1258 (online)
https://doi.org/10.3133/sir20195024