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Preliminary Geologic Map of Black Canyon and Surrounding Region, Nevada and Arizona

By Tracey J. Felger, L. Sue Beard, Zachary W. Anderson, Robert J. Fleck, Joseph L. Wooden, and Gustav B. Seixas

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Introduction

This report presents a geologic map compiled for a study of the geologic framework of springs and seeps that discharge in Black Canyon directly south of Lake Mead below Hoover Dam, Nevada and Arizona. The hydrogeologic and geochemical study of the Black Canyon thermal springs by the U.S. Geological Survey was funded by the National Park Service and National Cooperative Geologic Mapping Program of the U.S. Geological Survey. The study consisted of (1) compilation of existing geologic mapping, augmented by new field geologic mapping and geochronology (appendixes 1, 2) and (2) collection and analysis of structural data adjacent to the springs of interest and construction of regional cross sections (Beard and others, 2014, 2011; Anderson and Beard, 2011).

Previous geologic reports pertinent to this study include a body of work by R.E. Anderson, comprising two 15-minute geologic quadrangle maps that include the Black Canyon study area (Anderson, 1977, 1978) and three reports (Anderson, 1969, 1971; Anderson and others, 1972). The study area (map sheet) also includes parts of four previously mapped 7.5-minute quadrangles—Boulder City (Ekren and Anderson, 1996), Hoover Dam (Mills, 1994), Boulder Beach (Smith, 1984), and Henderson (Bell and Smith, 1980). Regional-scale geologic maps include Beard and others (2007) and Felger and Beard (2010). Anderson and others (1972), Gans and Bohrson (1998), and Faulds and others (1999, 2001, 2002) provide geochronologic ages on many of the geologic units important to this study.

Acknowledgments

This map was possible because of the substantial contributions made by the many geologists who worked in the Black Canyon area prior to our study. Peer reviews by Ernie Anderson and Ric Page, digital database and metadata reviews by Sue Priest, and editorial review by Jan Zigler further improved the map.

DESCRIPTION OF MAP UNITS

CENOZOIC SURFICIAL DEPOSITS AND SEDIMENTARY ROCKS

Qdl **Disturbed land (latest Holocene)—**Areas where major excavation or filling has disturbed the land surface to the extent that its geologic character cannot be accurately determined (Felger and Beard, 2010)

Qa **Younger alluvial deposits (Holocene and Pleistocene?)**—Unconsolidated to partly consolidated alluvium, consisting of silt, sand, and gravel in streams, washes, low terraces, alluvial fans, and piedmont slopes. Undissected to moderately dissected (Felger and Beard, 2010). Maximum thickness approximately 20 m

Qc **Colluvium (Holocene and Pleistocene?)**—Talus and hillslope deposits composed of angular to subangular, poorly sorted cobbles and boulders of locally derived material. Mapped on the flanks of Fortification Hill and the north end of the Eldorado Mountains, where deposits obscure bedrock. Includes unit Qc of Ekren and Anderson (1996) and Qt units of Mills (1994). Generally less than 20 m thick

Qp **Playa deposits (Holocene)**—Clay, silt, sand, and evaporate minerals in Dry Lake, Eldorado Valley. Thickness unknown

Qoa **Older alluvial deposits (Pleistocene)**—Moderately to poorly sorted sand, silt, clay, and gravel. Poorly bedded to massive, weakly to moderately consolidated. Surface has slight to well-developed desert pavement and scattered to widespread pedogenic carbonate debris. Mapped on margins of Eldorado Valley. Also occurs on southeast side of Hemenway Wash, north side of Fortification Hill, and east side of River Mountains. Includes unit Qao of Ekren and Anderson (1996) and Mills (1994) and some outcrops of unit Qr of Smith (1984). Exposed thickness 5 to 20 m

QTa **Oldest alluvial deposits (Pleistocene to upper Pliocene)**—Poorly to well cemented conglomerate of angular to subangular cobbles and boulders forming highly dissected alluvial fans. Typically exhibits thick or highly eroded carbonate soil profiles. Found on west side of Eldorado Mountains. Includes unit QTa of Ekren and Anderson (1996). Exposed thickness approximately 10 m

Tsy **Younger sedimentary rocks (Pliocene and upper Miocene)**—Includes fine-grained basinal deposits that filled interior drained basins but are now dissected and exposed because of integration and downcutting by Colorado River and its tributaries. Generally equivalent to Muddy Creek Formation. Deposits are fine-grained sandstone, siltstone, mudstone, gypsum, and halite. Locally includes conglomerate, tuff, and megabreccia deposits. Mostly undeformed. Found on west side of Wilson Ridge, on east side of River Mountains, and in Eldorado Mountains along south edge of map, west of Colorado River. Includes unit Tmu of Anderson (1978). About 5 to 10 Ma (Felger and Beard, 2010). Overlain and intruded by, as well as interlayered with, 5 Ma basalts of unit Tby Maximum exposed thickness approximately 100 m

Tsmy **Younger intermediate-age sedimentary rocks (upper and middle Miocene)**—Mainly clastic strata equivalent in age to unit mapped widely in the Lake Mead area as the informal red sandstone unit (Bohannon, 1983), and in study area as lower Muddy Creek Formation (Anderson, 1978). Dominantly red to tan sandstone and conglomerate, but also includes gypsum, limestone, siltstone and mudstone. Locally includes landslide and megabreccia deposits, with largest mass mapped west of Highway 93 (Tsmm; Anderson, 1978) at top of unit. Deposited in fault-controlled basin between Wilson Ridge and Colorado River. About 10 to 12 Ma. At Malpais Flattop Mesa, unit lies between a basalt flow of the upper part of the Mount Davis Volcanics (Tdmu) with an age of 12.73±0.30 Ma ($^{40}Ar/^{39}Ar$; Faulds and others, 1999) and the Malpais Flattop Mesa basalts (Tbo) with ages of about 11.3 to 11.6 Ma ($^{40}Ar/^{39}Ar$; Faulds and others, 1999). East of Hoover Dam, a tuff near base of unit yielded an $^{40}Ar/^{39}Ar$ age of 11.72±0.06 Ma (Williams, 2003). Maximum exposed thickness approximately 250 m

Tsmo **Older intermediate-age sedimentary rocks (middle Miocene)**—Sandstone, mudstone, siltstone, limestone, gypsum, and conglomerate. Deposited in fault-controlled basins and subsequently faulted and folded. Locally includes megabreccia deposits and airfall tuff. Occurs on west side of Malpais Flattop Mesa, on east side of Eldorado Mountains west of Roaring Rapids, and east of Boulder City, where it contains conspicuous manganiferous gypsum in vicinity of Boulder Rifle and Pistol Club. Inferred to be about 12 to 16 Ma in age. At Malpais Flattop Mesa, unit lies between andesite lava and breccia of lower part of Patsy Mine Volcanics (Tpl) with an $^{40}Ar/^{39}Ar$ age of 15.72±0.03 Ma (Faulds and others, 1999) and a basalt flow of upper Mount Davis Volcanics (Tdmu) with an $^{40}Ar/^{39}Ar$ age of 12.73±0.3 Ma (Faulds and others, 1999). To west of river, includes basalt flow dated at 13.68±0.16 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998). Unit is equivalent to sedimentary rocks of Mount Davis Volcanics (Tds). Maximum exposed thickness approximately 75 m

Tsmm **Intermediate-age megabreccia deposits (Miocene)**—Landslide debris of predominantly Precambrian rocks, intercalated in Tsmy and Tsmo. Originally described by Longwell (1951, 1963). Largest mass occurs in Tsmy on west side of Wilson Ridge, west of Highway 93, between Willow Beach and White Rock Canyon, and is Precambrian debris derived from Black Mountains to east. Smaller masses in Tsmo on west side of Malpais Flattop Mesa were probably derived from west and consist of a lens of Precambrian debris overlain by a lens of Tertiary volcanic debris (Anderson, 1978). Other small masses mapped on east side of River Mountains and west flank of Wilson Ridge. Maximum exposed thickness approximately 250 m

CENOZOIC VOLCANIC AND INTRUSIVE ROCKS

Tby **Younger basalts (Pliocene and upper Miocene)**—Dark-gray to black basalt flows and associated pyroclastic deposits. Flows are mostly thin and vesicular. Olivine phenocrysts present in varying amounts. Exposed on Black Island in Lake Mead, at Fortification Hill, and at several locations on west side of Wilson Ridge. Typically intercalated with or overlying Tsy. Ages range from about 4.7 to 5.9 Ma (Reynolds and others, 1986; Feuerbach and others, 1991; Felger and others, 2011). Maximum thickness approximately 150 m

Tbo **Older basalts (upper to middle Miocene)**—Dark-gray to black olivine basalt flows and associated pyroclastic deposits. Interbedded with unit Tsmy. Includes Malpais Flattop Mesa and outcrops northwest of Fortification Hill mapped as basalt of Callville Mesa (Mills, 1994). Basalts at Malpais Flattop Mesa are about 11.3–11.6 Ma ($^{40}Ar/^{39}Ar$; Faulds and others, 1999). Dates on Callville Mesa volcanics north of map area range from 11.41±0.14 Ma ($^{40}Ar/^{39}Ar$; Harlan and others, 1998) to 8.49±0.20 Ma (K/Ar; Feuerbach and others, 1991). Maximum thickness approximately 100 m

Volcanic Rocks of the River Mountains (middle Miocene)—Modified from Beard and others (2007). Complexly faulted volcanic field that includes (1) an andesite stratovolcano complex, surrounded by (2) dacitic domes and flows; (3) an intrusive core to stratovolcano exposed in southern part; and (4) a basalt shield volcano on northern and eastern side of mountains. $^{40}Ar/^{39}Ar$ ages reported by Faulds and others (1999) range from 13.45 Ma on dacite flows to 12.17 Ma on youngest basalt flow. K/Ar ages from 13.2 to 11.8 Ma obtained by Anderson and others (1972) are generally within this range

Trb **Basalt flows**—Basalt flows interbedded with agglomerate and breccia, and minor andesitic flows. Includes: (1) basalt with phenocrysts of augite and plagioclase in a grayish-purple matrix; (2) basalt with porphyritic olivine phenocrysts to 0.5 cm in diameter in an augite and plagioclase-bearing glassy matrix; and (3) aphyric platy basalt. Minor andesite flows contain plagioclase, hornblende, and augite phenocrysts (Bell and Smith, 1980). Faulds and others (1999) report an $^{40}Ar/^{39}Ar$ age of 12.17±0.02 Ma for the uppermost flow in this sequence at north end of River Mountains. Estimated maximum thickness approximately 100 m

Trv **Volcanic flows, domes, breccia, and volcanogenic sedimentary rocks**—Complex unit of dacite, rhyolite and andesite flows and domes, and intercalated tuffs and tuffaceous sedimentary rocks. Unit includes Volcanic rocks of Powerline Road and Volcanic rocks of Bootleg Wash of Smith (1984). Estimated maximum thickness approximately 300 m

Trip **Composite plutons**—Composite plutons formed mostly by plugs and dikes of porphyritic dacite, andesite, and rhyodacite that surround intrusive stock (Tri). Anderson and others (1972) obtained K/Ar ages of 12.5±0.5 Ma, 12.6±0.5 Ma, and 13.1±0.5 Ma on this unit, and Faulds and others (1999) report an $^{40}Ar/^{39}Ar$ age of 13.45±0.02 Ma on a ‘dacite flow’ of unit Trip. Includes numerous zenoliths of highly altered andesite and Paleozoic limestone (Smith, 1984)

Tri **Intrusive stock**—Fine- to medium-grained composite quartz monzonite pluton bearing plagioclase, orthoclase, and biotite. Fine-grained texture near edge of pluton resembles dacite. Faulds and others (1999) obtained an $^{40}Ar/^{39}Ar$ age of 13.23±0.01 Ma

Mount Davis Volcanics (middle Miocene)—Named by Longwell (1963) for outcrops near Mount Davis, Arizona, and further described by Anderson (1971, 1977, 1978) and Anderson and others (1972). Includes volcanic rocks ranging in composition from rhyolite to basalt, interbedded with clastic and volcaniclastic deposits. Ranges in age from about 12.6 to 15.1 Ma. Detailed volcanic stratigraphy for Mount Davis Volcanics in vicinity of Hoover Dam was defined by Mills (1994) and includes (in stratigraphic order) Dam conglomerate (Tdc), Tuff of Hoover Dam (Thd), Switchyard basaltic andesite, Sugarloaf and Black Canyon dacites, and Kingman Wash basaltic andesite; clastic and volcaniclastic rocks (Tds) are interbedded throughout sequence. For this report, we tentatively divided Mount Davis Volcanics into upper, middle, and lower parts and interbedded sedimentary rocks

Tds **Sedimentary rocks**—Clastic and volcaniclastic rocks interbedded with volcanic units of middle and upper Mount Davis Volcanics. Includes red and brown sandstone and conglomerate of fluvial and alluvial origin and white and pale-yellow glassy tuffaceous sedimentary rocks, massive air-fall tuff, and lithic tuffs. Includes units Tdcc, Tdw, Tbr, Tsc, Tts (Mills, 1994) and Tls of Ekren and Anderson (1996) and Tds of Anderson (1977, 1978). Maximum thickness approximately 125 m

Upper part—Upper Mount Davis Volcanics include mafic lava flows (Tdmu) and rhyodacite and dacite flows (Tdru) and intrusions (Tdri) that unconformably overlie or intrude the Boulder City pluton and generally are only gently tilted

Tdmu **Mafic lavas**—Modified from Anderson (1977, 1978). Basalt and basaltic andesite flows that post-date upper Mount Davis rhyodacite and dacite (Tdru). Includes some outcrops of units Tmf and Tdm of Anderson (1977, 1978). Kingman Wash Road basaltic andesite (unit Tkw of Mills, 1994), which makes up bulk of unit, is exposed east of Hoover Dam and has an age of 12.57±0.03 Ma ($^{40}Ar/^{39}Ar$; Faulds and others, 1999). Basalt lavas with an age of 12.73±0.30 Ma ($^{40}Ar/^{39}Ar$; Faulds and others, 1999) are intercalated with fanglomerate (Tsmo and Tsmy) underlying Malpais Flattop Mesa. A small outcrop of basalt exposed along highway 60 in Eldorado Mountains (unit Tmf of Anderson, 1977) is 13.06±0.06 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998). More flows of this unit may exist in outcrops that are currently assigned to mafic lavas of middle part of Mount Davis Volcanics (Tdmm) in northern Eldorado Mountains. Maximum thickness approximately 50 m

Tdru **Rhyodacite and dacite**—Modified from Anderson (1977, 1978). Dacite and rhyodacite lava flows and domes in north part of Black Canyon. Forms prominent brown and tan cliffs, generally with pale-yellow zeolitized slope forming lower part composed of tuffaceous bedded sediments and autoclastic flow breccia. Locally includes a basal vitrophyre visible as a gray zone below brown cliffs, which are formed by dense, interior part of flow. Commonly flow-foliated; gray to pinkish or purplish on fresh surface. Phenocrysts of biotite, hornblende, and plagioclase present in varying amounts and proportions; sparse quartz present in some flows. Erupted from multiple vents. Includes Sugarloaf and Black Canyon dacite (units Tsd and Tbc of Mills, 1994), Lava of No Name Mesa (unit Tl of Ekren and Anderson, 1996), and unnamed flows and domes on east side of Black Canyon south of Palm Tree canyon (unit Tdr of Anderson, 1978). Sugarloaf dacite is 13.11±0.02 Ma ($^{40}Ar/^{39}Ar$; Faulds and others, 1999), and Lava of No Name Mesa is 13.10±0.10 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998). Maximum thickness approximately 100 m

Tdri **Dacite intrusions**—Linear dacite dikes and irregular shaped massive intrusions. Many are intruded along faults, and most are inferred to be feeder systems for vents that produced upper Mount Davis dacite and rhyodacite flows and domes (Tdru). Exposed in vicinity of Goldstrike, Palm Tree, Boy Scout, and Salt Cedar canyons

Middle part—Rocks of middle Mount Davis Volcanics include mafic lava flows (Tdmm), rhyolite and rhyodacite (Tdrm), and Tuff of Hoover Dam (Thd) and Dam conglomerate (Tdc) of Mills (1994). Units of middle Mount Davis are widely exposed on both sides of Black Canyon, unconformably overlie Patsy Mine Volcanics, and may be intruded by or coeval with Boulder City pluton. They range in age from about 14.2 to 13.3 Ma

Tdmm **Mafic lavas**—Modified from Anderson (1977, 1978). Dense to vesicular, dark-gray to black olivine basalt and basaltic andesite. Varies from aphanitic to porphyritic. Comprises bulk of Mount Davis Volcanics and includes Switchyard basaltic andesite (unit Tsb of Mills, 1994), most of unit Tdm of Anderson (1977, 1978), and units Tdm and Tdu of Ekren and Anderson (1996). Outcrops previously mapped as Fortification Basalts west of Colorado River (units Tmf, Tmfc, and Tmfq of Ekren and Anderson, 1996, and unit Tmf of Anderson, 1977, 1978) have been assigned to this unit based on stratigraphic relations and geochronology. A new $^{40}Ar/^{39}Ar$ age of 13.268±0.032 Ma (appendix 1) was obtained from basalt sample collected about 1.5 miles northeast of Boulder City from outcrops that had previously been mapped as Fortification basalt (Anderson and Ekren, 1996; Anderson, 1977). Geochronology suggests that middle mafic lavas have a lower and upper sequence, with Tuff of Hoover Dam (Thd) and felsic lavas of middle Mount Davis (Tdrm) occupying the middle.

Ages for lower sequence are 14.2 to 14.1 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998; Faulds and others, 1999). Ages for upper sequence are 13.77 to 13.27 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998; this paper). Maximum thickness approximately 125 m

Tdrm **Rhyolite and rhyodacite**—Modified from Anderson (1977, 1978). Mostly quartz-free rhyolite, rhyodacite, and dacite. Weathered outcrops are reddish brown and tan. Fresh surfaces are pale red, gray, and yellowish-gray. Phenocrysts are dominantly plagioclase and biotite; sanidine is conspicuous in some flows, and quartz and hornblende are present in trace amounts in some flows. Includes dacite outcrops on north and south sides of Bighorn Sheep canyon and outcrops in Eldorado Mountains between south end of No Name Mesa and Forlorn Hope Spring. Includes unit Tdr of Anderson (1977, 1978) and Ekren and Anderson (1996). A flow about 2.5 miles (4 km) north of Forlorn Hope Spring yielded an age of 14.06±0.04 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998). Maximum thickness approximately 250 m

Thd **Tuff of Hoover Dam**—Gray-brown to white, poorly to moderately welded lithic ash-flow tuff. Lithic fragments include Patsy Mine Volcanics and Wilson Ridge pluton(?). Dacitic, with phenocrysts of plagioclase, biotite, and hornblende. About 180 m thick in vicinity of Hoover Dam. Thickness decreases dramatically south of Sugarloaf canyon, and tuff is interbedded with clastic and volcaniclastic deposits. Traceable to Arizona Hot Spring canyon; unit has not been identified on west side of Black Canyon. $^{40}Ar/^{39}Ar$ age of 13.88±0.1 Ma obtained from base of tuff (Mills, 1994; Faulds and others, 1999). Originally named Latite Flow Breccia by Ransome (U.S. Bureau of Reclamation, 1950). Mapped and described in detail by Smith (1984) and Mills (1985, 1994). Herein included with middle part of Mount Davis Volcanics based on stratigraphic position and age

Tdc **Dam conglomerate**—Dam Breccia of Ransome (U.S. Bureau of Reclamation, 1950). Dark red and reddish-brown conglomerate and sandstone. Conglomerate typically clast supported and poorly sorted, with angular, gravel- to boulder-sized clasts of Patsy Mine Volcanics, Boulder City(?) pluton, and sparse Proterozoic lithologies. Crudely to moderately stratified. Locally grades into red volcaniclastic sandstone that in places has well-sorted, well-rounded grains and well-developed planar bedding and cross-bedding. Marks unconformity between underlying Patsy Mine Volcanics and overlying middle Mount Davis Volcanics between Hoover Dam and Palm Canyon. A red, well-sorted, well-bedded sandstone observed (but not mapped) in Bighorn Sheep and Arizona Hot Spring canyons at unconformity between Patsy Mine and middle Mount Davis Volcanics may be equivalent. Maximum thickness approximately 100 m

Lower part—Rocks of lower Mount Davis Volcanics include rhyolite and rhyodacite (Tdrl) and mafic lava flows (Tdml) that range in age from about 15.1 to 14.9 Ma (Gans and Bohrson, 1998) and are moderately to steeply tilted. Units are only exposed along highway 60 in southwest corner of map area

Tdrl **Rhyolite and rhyodacite**—Modified from Anderson (1977). Massive cliff-forming, mostly quartz-free rhyolite and rhyodacite with phenocrysts of plagioclase, sanidine, and biotite in varying amounts and proportions. Includes some outcrops of Tdr of Anderson (1977). Ages range from 15.04 to 14.93 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998). Maximum thickness approximately 150 m

Tdml **Mafic lavas**—Modified from Anderson (1977). Dark-gray and dark-grayish, red-purple andesite flows below rhyolite and rhyodacite unit (Tdrl) and above Tuff of Bridge Spring (Tb). Includes as many as 16 andesite flows with a total thickness of as much as 275 m. Distinctly porphyritic varieties contain about 25 percent phenocrysts of plagioclase, augite, and altered olivine with minor altered orthopyroxene as individual grains and as cores surrounded by augite. Principal accessory minerals are iron oxides and apatite. Pyroxene to olivine ratio is typically about 3:1. Includes some outcrops of Tdm of Anderson (1977). Ages range from 15.1 to 15.00 Ma ($^{40}Ar/^{39}Ar$; Gans and Bohrson, 1998)

Tiw **Wilson Ridge pluton (middle Miocene)**—Modified from Beard and others (2007). Texturally diverse, fine- to coarse-grained quartz diorite intrusion. Cut by abundant dikes, locally in dike-on-dike array, of granite, granitic porphyry, aplite, basalt, and biotite lamprophyre. Pervasively fractured and faulted, with many fractures coated with riebeckite and less commonly actinolite (Mills, 1994). Larsen and Smith (1990) define two plutonic suites, the older Horsethief Canyon diorite, and the more voluminous Teakettle Pass suite (not mapped separately). Interpreted as a sub-volcanic intrusion by Anderson (1973) and later geochemically correlated by Feuerbach and Smith (1986) to volcanic rocks of River Mountains. They proposed that the volcanic rocks were originally adjacent to or above Wilson Ridge pluton but tectonically transported westward to their present location in the River Mountains (Weber and Smith, 1987) along the Saddle Island detachment fault system. Dated at 15.1±0.6 and 13.6±0.6 Ma by Anderson and others (1972, K/Ar). Subsequent K/Ar ages by Larsen and Smith (1990) reported as 13.34±0.4 Ma for dioritic Horsethief Canyon suite and 13.5±0.4 Ma on Teakettle Pass rocks, but intrusive relations clearly show that diorite is the older phase. In general, accepted age is about 13.5 Ma. Northern end of pluton, exposed in Boulder Canyon reach of Lake Mead, yielded younger $^{40}Ar/^{39}Ar$ ages of 12.57±0.05, 12.62±0.03, and 12.65±0.04 Ma (Anderson and others, 1994). These younger ages were interpreted to reflect cooling of the north end through about 300°C, whereas older ages were presumed to reflect emplacement age

Tip **Paint Pots pluton of Mills (1994) (middle Miocene)**—Modified from Beard and others (2007). White with bright red and yellow hues, medium-grained to hypabyssal monzonite with highly altered plagioclase phenocrysts. Hematitically altered, fractured, and sheared. Some fractures cutting hematitically altered rocks are filled with gypsum. Exposed west of Fortification Hill and informally called Paint Pots because of brightly colored appearance due to hematitic alteration. Age unknown, but locally intrudes 13.9 Ma Tuff of Hoover Dam (Thd; Mills, 1994). Contains roof pendants of Cambrian limestone and shale just (Pz) west of Fortification Hill. Metcalf and others (1993) suggest that Paint Pots may be subjacent plutonic source for Tuff of Hoover Dam that intruded its own volcanic cover

Tibu **Boulder City pluton, undifferentiated (middle Miocene)**—Large composite epizonal batholith exposed mostly northeast and east of Boulder City. Bulk of pluton is quartz monzonite with lesser amounts of granite, monzonite, and syenodiorite (Ekren and Anderson, 1996). Quartz monzonite is mostly light gray, fine to medium grained, faintly to distinctly porphyritic, nonfoliated pyroxene bearing, with biotite and hornblende as important mafic constituents. Rocks either more mafic or more siliceous than quartz monzonite occur mostly as fine-grained to aphanitic dikes and border facies in Boy Scout Canyon area and in outcrops east and southeast of Boulder City. Contacts between various lithologies are obscure and appear to be gradational in most areas. Fractures and breccia are pervasive, and are host to hematite, barite, and manganese mineralization. Sub-horizontal bands at about 700 m elevation, interpreted by Anderson (1969) to represent a paleohydrologic feature, are formed by strong concentrations of hematite

Tib **Unaltered quartz monzonite**—Unmineralized parts of Boulder City pluton, exposed mostly northeast of Boulder City above paleohydrologic feature of Anderson (1969). Includes masses of light-gray, fine- to medium-grained plutonic rock that grades from near granite in composition to syenodiorite. The rock is faintly to distinctly porphyritic, non-foliated, and highly fractured in most areas. Considerable accessory sphene present in some outcrops (Ekren and Anderson, 1996). A new U-Pb age of 13.96±0.25 Ma (appendix 2) was obtained from this unit; previous K/Ar analyses of biotite yielded ages of 14.17±0.6 Ma (recalculated; Anderson and others, 1972) and 14.65±0.47 Ma (recalculated; R. Fleck, U.S. Geological Survey, written commun., 2008)

Tibb **Border facies**—Modified from Ekren and Anderson (1996). Brecciated dioritic and andesitic rocks and aplite. Unit may include some volcanic rocks, although no depositional contacts or cooling breaks indicative of volcanism were observed. Rocks locally include basaltic dikes that may be related to Mount Davis Volcanics. Includes unit Tqbf of Ekren and Anderson (1996)

Ti **Intrusive rocks, undifferentiated (middle Miocene)**—Modified from Anderson (1977). Unit is mostly quartz monzonite similar to Boulder City pluton; outcrops are jointed, but generally not brecciated. Largest outcrops are Railroad Pass pluton in McCullough Range. In southern River Mountains, sheared and brecciated outcrops of quartz monzonite might be a faulted part of Boulder City pluton. In Eldorado Mountains southwest of State Highway 60, rocks are mostly greenish-gray propylitized dacite

Tid **Dikes, undifferentiated (middle Miocene)**—Closely-spaced fine-grained quartz monzonite to pyroxene-bearing basalt dikes (unit Td of Smith, 1984) that intrude Boulder City pluton (Tibu) along its northern edge

Tif **Felsic dikes (middle Miocene)**—Dacite dikes (unit Tdd of Smith, 1984) in River Mountains. Aphyric to porphyritic with plagioclase and biotite as dominant phenocrysts. Dikes range in width from 1 to 150 m and in length from 200 m to 3.2 km

Tim **Mafic dikes (middle Miocene)**—Includes basalt and basaltic andesite dikes (unit Tid of Mills, 1994) that intrude Wilson Ridge pluton, Paint Pots pluton, and volcanic rocks near Hoover Dam and basalt and andesite dikes (unit Tdb of Smith, 1984) in River Mountains

Til **Lamprophyre dikes (middle Miocene)**—Dikes and flows(?) of highly alkalic biotite, pyroxene, and plagioclase-bearing lamprophyre (kersantite) exposed in River Mountains (unit Tdl of Smith, 1984). Dark-green to purplish-gray with biotite phenocrysts to 1.2 cm in diameter

Tb **Tuff of Bridge Spring (middle Miocene)**—Modified from Anderson (1977). Welded to non-welded, gray to pale-red, quartz-free rhyolitic ash-flow tuff; purplish-gray andesitic lithic inclusions are common. Phenocrysts of sanidine, plagioclase, biotite, augite, and hornblende are present in varying amounts and proportions. Sphene is principal accessory mineral present in variable amounts. Where exposed in vicinity of highway 60, consists of two cooling units that total up to about 180 m thick. Also occurs in isolated outcrops south of Malpais Flattop Mesa and east of Indian Rapids (north of Willow Beach). Originally mapped and described by Anderson (1971), tuff is inferred to have erupted from a caldera in northern Eldorado Mountains (Gans and others, 1994). $^{40}Ar/^{39}Ar$ ages from outcrops near type section along highway 60 in Eldorado Mountains range from 15.03±0.06 to 15.34±0.06 Ma (Gans and Bohrson, 1998)

Tcr **Chaos rocks (middle Miocene)**—Area of structural chaos between highways 95 and 60 consisting of numerous faulted and folded blocks of Tertiary volcanic and sedimentary rocks in a complex mosaic (Anderson, 1977). Possibly related to southern ring fracture of Boulder City

Cauldron of Gans and others (1994), which was the source for Tuff of Bridge Spring (Tb)

Patsy Mine Volcanics (middle and lower Miocene)—Type section of Patsy Mine Volcanics was defined by Longwell (1963) for a thick section of lava flows, flow breccias, and subordinate tuffaceous sedimentary rocks exposed in Eldorado Mountains, about 3 mi northwest of Nelson, NV (3 mi south of map boundary). Anderson (1971, 1977, 1978) divided Patsy Mine Volcanics into upper, middle, and lower informal parts. Upper and lower parts are predominantly andesite and middle part is mostly rhyolite. Patsy Mine Volcanics are bracketed by Peach Springs Tuff with an age of about 18.5 Ma (Nielson and others, 1990) and Tuff of Bridge Spring (Tb) with an age of about 15.2 Ma (Gans and Bohrson, 1998). Total thickness as much as 4,000 m

Tpv **Volcanic rocks, undivided**—Modified from Anderson (1977, 1978). Andesite and basaltic andesite lavas and associated breccia and tuffaceous sedimentary rocks. Inferrred to be mostly correlative with upper (Tpu) and lower (Tpl) parts of Patsy Mine, but not subdivided due to stratigraphic and structural complexities. Outcrops southeast of Malpais Flattop Mesa are mostly andesitic lava and breccia that may be correlative with rocks of lower part (Tpl). Here, basal contact is generally complicated by faults but is locally marked by a few tens of meters of prevolcanic clastic rocks, similar to lower part (Tpl). Outcrops may represent parts of a single lava pile separated by faults; although mostly andesitic, rocks are lighter colored, more siliceous (biotite- and hornblende-bearing rocks are common), contain fewer breccias, and are more varied texturally and mineralogically than typical rocks of coeval lower part (Tpl) to west.

Outcrops west of highway 60 are a poorly exposed, steeply tilted section of interbedded basaltic andesite flows and sparse whitish-gray tuffaceous sedimentary rocks. This section is probably equivalent to upper part (Tpu) but has been displaced westward on faults so that it lies along the strike of older Patsy Mine strata. East of highway 60, several hundred meters of basaltic andesite lava is underlain by as much as 120 m of coarse volcaniclastic conglomerate which, in turn, is underlain by numerous thin andesite lavas totaling as much as several thousand meters in thickness. These strata are probably correlative with lower part (Tpl), but their lesser thickness and occurrence of clastic rocks suggests that they are "flank" deposits that have been displaced adjacent to "core" deposits (Tpl) by faulting

Tpu **Upper part**—Modified from Anderson (1977, 1978). Dark-purplish-gray, massive, porphyritic pyroxene-olivine andesite and basaltic andesite flows locally interstratified with thin beds of whitish-gray tuffaceous sedimentary rocks. Includes at least one flow of hornblende-biotite rhyodacite near base; rhyodacite contains sparse quartz and sanidine and common accessory sphene. Exposed in southern part of map area along State Highway 60 and southwest of Malpais Flattop Mesa. Maximum thickness approximately 500 m

Tpm **Middle part, undivided**—Rhyolite lavas and interbedded tuffaceous sedimentary rocks exposed south of Malpais Flattop Mesa and west of State Highway 60 (Anderson, 1977, 1978). Outcrops of dacite and interbedded flow breccias and volcaniclastic sedimentary rocks west of Hoover Dam (unit Ted of Smith (1984)) have been tentatively assigned to this unit. Maximum thickness approximately 800 m□

Tpma **Altered dacite**—Modified from Smith (1984). Highly altered and locally mineralized dacite flows exposed northwest of Hoover Dam. Unit Teda of Smith (1984). Maximum exposed thickness approximately 100 m

Tpmr **Rhyolite lava**—Modified from Anderson (1978). Lobate and lenticular bodies of rhyolite lava that form brown to dark-brown cliffs and bold knobs. Core zones are massive, resistant, gray to reddish-gray, devitrified or crystalline porphyritic rock that grades outward to highly weathered, crumbly, yellowish-gray zeolitized rhyolite that is commonly brecciated. Gray to dark-gray vitrophyre commonly separates the crystalline core zone from the zeolitized base. Entire mass is zeolitized at thin distal ends. Most rock is crystal-poor, quartz-free two-feldspar rhyolite. Only mapped south and southwest of Malpais Flattop Mesa. Maximum thickness approximately 225 m

Tpms **Sedimentary rocks**—Modified from Anderson (1978). Predominantly pale-yellow, highly lithified, zeolitized, tuffaceous sedimentary rocks that contain sparse to abundant pumice lapilli and volcanic lithic clasts, probably mostly of rhyolitic composition. Unit includes minor tuffaceous sandstone and pebble- and cobble-conglomerate. Light-gray to white vitric tuffs are very sparse. Only mapped south and southwest of Malpais Flattop Mesa. Maximum thickness approximately 150 m

Tpl **Lower part**—Modified from Anderson (1977, 1978). Dark-purplish-gray andesite lava and breccia. Mafic phenocryst assemblages vary widely but most rocks are two-pyroxene andesites, with or without olivine; rocks with orthopyroxene in excess of clinopyroxene are sparse, as are hornblende- and biotite-bearing rocks. Unit contains some strata that are probably laharic or mudflow breccia. Tuffaceous interbeds are sparse to absent in most sections. Most rocks are weakly to moderately altered and highly fractured. Basal contact with Proterozoic metamorphic rocks (Xgn) generally complicated by faults, but in some outcrops in southern part of map area, a thin rhyolitic ash-flow tuff (possibly the Peach Springs Tuff) and a few tens of meters of prevolcanic clastic rocks separate the volcanic and metamorphic rocks. Two major areas of outcrop in southern part of map area were probably a single volcanic pile that has been separated by faulting. Outcrops in Black Canyon between Hoover Dam and Willow Beach, which were mapped as Tpv by Anderson (1978), are herein tentatively assigned to the lower part of Patsy Mine Volcanics and are inferred to be core and flanking flows of an andesite dome complex. Maximum thickness approximately 2,700 m

Volcanic rocks of the McCullough Range (Miocene)—Andesite (Ta) and altered andestite (Taa) exposed in McCullough Range in northwest corner of map area

Ta **Andesite**—Modified from Anderson (1977). Numerous west-dipping, mostly thin flows of porphyritic andesite that are medium gray, grayish purple, and pale red in their stoney interiors and have red or yellowish-brown vesiculated to scoriaceous rinds. Flow breccia and vitrophyre are uncommon. Plagioclase and augite are principal phenocrysts, and pseudomorphs of orthopyroxene (?) and olivine are present in most flows. Sparse biotite occurs in at least two flows low in sequence. Uppermost flows are medium- to dark-gray, massive to vesicular, augite-olivine basalt or basaltic andesite. Probably the down-faulted equivalents of lavas exposed in main part of McCullough Range to west. Unit Ta of Anderson (1977). Maximum exposed thickness approximately 150 m

Taa **Altered andesite**—Modified from Anderson (1977). Mostly pale-olive and greenish-gray massive propylitized flow breccias and lavas that were probably predominantly andesite prior to alteration. Includes very minor altered volcanigenic clastic rocks. Volcanic rocks are massive, partly as a result of alteration process that tends to homogenize by concealing or obliterating original rock structure, texture, and lithologic contrast. Flow breccias contain impressive blocks of andesite approximately 0.3 m or so in diameter that tend to be darker than enclosing matrix. Effects of silicic and argillic alteration are evident adjacent to plutons (Ti), in areas of high dike population, and along faults. Fault zones contain secondary quartz, barite, hematite, and calcite and have been extensively prospected. Unit contains numerous, small, unmapped intrusive masses and, locally, contacts with larger intrusive masses (Ti) are vague and approximately located. Unit Taa of Anderson (1977). Maximum exposed thickness approximately 150 m

MESOZOIC AND PALEOZOIC ROCKS

Ki **Intrusive rocks (Upper Cretaceous)**—Muscovite-biotite granite in Black Mountains south of Wilson Ridge

Pz **Sedimentary Rocks (Paleozoic)**—Small outcrops of limestone, shale, sandstone, and quartzite on Saddle Island, eastern River Mountains, and west flank of Fortification Hill. Interpreted as exotic blocks in River Mountains stock and Paint Pots pluton by Smith (1984) and

Mills (1994). In southern River Mountains, rocks interpreted as in situ exposures of Cambrian strata, intruded and overlain by River Mountains volcanic complex (Timm, 1985)

PALEOPROTEROZOIC ROCKS

Xgn **Metamorphic and plutonic rocks, undifferentiated (Paleoproterozoic)**—Gneiss, schist, granite, and metavolcanic rocks exposed on Saddle Island and Wilson Ridge, in Black Canyon, and on west side of Eldorado Mountains between highways 95 and 60

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Appendix 1. Basalt flow $^{40}Ar/^{39}Ar$ data

An age of 13.268+/-0.032 Ma was determined by the $^{40}Ar/^{39}Ar$ (or Ar-Ar) technique on a sample of basalt (BCP-2) from outcrops east of Boulder City, NV (lat 35.98753 W., long 114.79255 N.). The sample was prepared as a groundmass separate by crushing to 60–80 mesh, removing the most highly magnetic grains, and then removing olivine and (or) coarse plagioclase in a non-magnetic fraction with the Frantz isodynamic separator. The sample was irradiated in the core of the U.S. Geological Survey TRIGA reactor in Denver, CO, at approximately 1-MW power. Measurements were made in the USGS laboratory in Menlo Park, CA (table 1), utilizing incremental heating with a tantalum, resistance-heated furnace and molybdenum crucible to extract argon. Reactive gases were removed from the argon and other rare gases using a Zr-Al getter. Argon isotopic ratios were measured on a MAP216, 15.5-cm radius, 90°-sector mass spectrometer. The reactor neutron flux constant, J, was calculated from measurements of Taylor Creek Rhyolite (TCR-2) sanidine, with an age of 27.87 Ma, but ages were also calculated to yield an age of 28.02 Ma on sanidine from the Fish Canyon Tuff (Renne and others, 1998) by adjusting the flux constant. Corrections for neutron-induced interferences were made using correction factors determined by analyzing argon from irradiated fluorite and potassium glass. Potassium and argon isotopic abundances and the decay constants for ^{40}K that were used are those recommended by Steiger and Jager (1977). The plateau age determined from the Ar-Ar age spectrum is defined as the weighted mean age of contiguous gas fractions representing more than 50 percent of the ^{39}Ar released, for which no difference can be detected between the ages of any two fractions at the 95 percent level of confidence (Fleck and others, 1977). Ar-Ar plateau and isochron ages were calculated using the ISOPLOT program of Ludwig (2003).

Table 1. Results of $^{40}Ar/^{39}Ar$ incremental-heating analysis of BCP-2.

BCP-2 Basalt Groundmass IRR271-85 J = 0.001470528

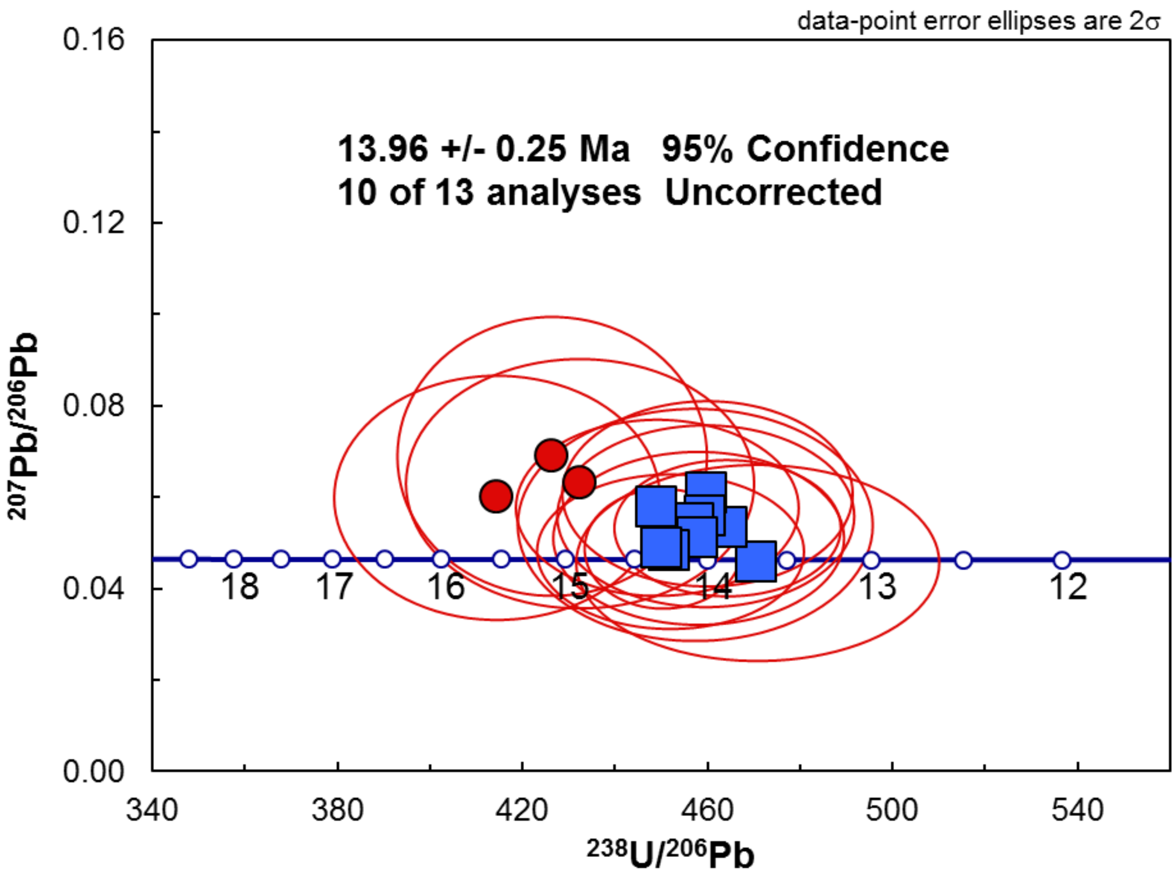
Step (°C)	% $^{39}Ar_K$	% $^{40}Ar^*$	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	K/Ca	Cl/K	Age (Ma)
550	2.86	62.59	8.1769	1.5392	0.0107	0.341	0.00155	13.541±0.232
625	10.59	72.38	7.0996	1.2880	0.0070	0.407	0.00073	13.593±0.079
700	13.82	78.49	6.4911	0.9384	0.0050	0.559	0.00050	13.474±0.066
775	16.40	89.92	5.5989	0.9370	0.0021	0.560	0.00043	13.316±0.051
850	17.73	96.72	5.1960	0.8123	0.0008	0.646	0.00033	13.291±0.046
925	13.92	96.68	5.1852	0.6724	0.0007	0.780	0.00058	13.256±0.046
1000	13.17	93.11	5.3714	0.6412	0.0014	0.818	0.01057	13.225±0.047
1075	4.90	82.08	6.0647	1.6630	0.0041	0.315	0.00412	13.172±0.106
1200	4.58	67.08	7.4027	18.7377	0.0134	0.028	0.00249	13.291±0.079
1400	2.03	92.32	5.9129	7.3129	0.0035	0.071	0.00219	14.494±0.071

		Wtd Mean Plateau age (Ma)	MSWD = 0.58	**13.268±0.032**
Intercept =	296.2±6.9	Isochron age (Ma)	MSWD = 0.90	13.265±0.068
		Integrated age (Ma)		13.365±0.067

Note: TCR-2 flux monitor with age of 28.87 Ma compares to an age of 27.62 Ma for Fish Canyon Tuff sanidine.

Appendix 2. Boulder City pluton zircon data

Sample no. 08222A: Latitude - 35.98753, Longitude - 114.79255



Spot Name	% common ^{206}Pb	ppm U	ppm Th	^{232}Th/^{238}U	Uncorrected ^{238}U/^{206}Pb	% error 1 sigma	Uncorrected ^{207}Pb/^{206}Pb	% error 1 sigma	^{207}corr. ^{206}Pb/^{238}U	1 sigma error	^{207}corr ^{206}Pb/^{238}U age Ma	1 sigma error
08222A-11.1	0.95	135	165	1.26	472.02	2.6	.0538	19.8	.00210	.00006	13.5	0.4
08222A-13.1	-0.09	79	149	1.95	470.83	3.4	.0456	19.2	.00213	.00008	13.7	0.5
08222A-5.1	0.87	215	470	2.26	464.29	2.2	.0532	11.4	.00213	.00005	13.7	0.3
08222A-10.1	1.83	113	210	1.92	459.96	2.8	.0607	13.6	.00213	.00006	13.7	0.4
08222A-6.1	1.21	112	187	1.73	459.59	2.9	.0558	14.6	.00215	.00007	13.8	0.4
08222A-1.1	0.96	75	139	1.92	457.31	3.4	.0539	19.2	.00217	.00008	13.9	0.5
08222A-3.1	0.59	109	199	1.88	458.05	2.8	.0510	15.2	.00217	.00006	14.0	0.4
08222A-7.1	1.44	124	240	2.00	449.11	2.8	.0577	13.6	.00219	.00006	14.1	0.4
08222A-12.1	0.22	134	218	1.69	451.96	2.6	.0481	14.4	.00221	.00006	14.2	0.4
08222A-9.1	0.30	356	828	2.40	450.38	1.5	.0487	11.0	.00221	.00004	14.3	0.2
08222A-8.1	2.10	68	94	1.43	432.41	3.6	.0629	17.7	.00226	.00009	14.6	0.6
08222A-2.1	2.86	89	179	2.07	426.39	3.2	.0689	18.1	.00228	.00008	14.7	0.5
08222A-4.1	1.71	71	81	1.19	414.45	3.5	.0599	18.2	.00237	.00009	15.3	0.6