Text and references accompanying Nevada Bureau of Mines and Geology Open-File Report 2023-03

Geologic Map of the Nevada Part of the Boulder Canyon Quadrangle, Clark County, Nevada

by

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INTRODUCTION

The Boulder Canyon 7.5' quadrangle is located east of Las Vegas, NV and almost entirely within the boundary of the Lake Mead National Recreation Area. The south half of the quadrangle overlaps the Nevada-Arizona state line along the north shore of Lake Mead and rugged topography at the northern end of the Black Mountains. The only access to this area is via Northshore Road (Nevada State Road 167), which intersects the north half of the quadrangle, or by boat. New detailed geologic mapping for this report was conducted by the authors between April 2021 and June 2022, and builds on various M.S. theses completed at Northern Arizona University (San Filippo, 2008; Winston, 2016; Demircan, 2019) and the University of Nevada, Las Vegas (Naumann, 1987; Eschner, 1989), as well as detailed geologic mapping in adjacent quadrangles (Anderson, 2003; Duebendorfer, 2003). This report and the accompanying geologic map provide useful insights into the geologic framework of the western Lake Mead structural domain, its complex deformation and magmatic evolution, and the potential for recent Quaternary faulting and seismic hazards proximal to the rapidly expanding Las Vegas urban area and within the Lake Mead National Recreation Area.

STRATIGRAPHIC OVERVIEW

The quadrangle is situated precisely at a major structural and stratigraphic boundary within the central Basin and Range that separates thick Paleozoic, Mesozoic and Cenozoic sedimentary rocks to the north from Proterozoic crystalline rocks and Cenozoic igneous rocks to the south. This boundary corresponds with the northeast-striking, left-lateral Lake Mead fault system, which accommodated at least 20 to 65 km of cumulative displacement mostly between ~13 and 8 Ma in the western Lake Mead area (Anderson, 1973; Bohannon, 1979; Weber and Smith, 1987; Duebendorfer and Wallin, 1991).

In the north half of the quadrangle, the oldest exposed rocks are early Permian and occur in the Echo Hills, a structurally complex transpressional pop-up block within a restraining step-over along the Bitter Spring Valley fault zone (Campagna and Aydin, 1991; San Filippo, 2008). Permian, Triassic, and Jurassic strata are unconformably overlain by Oligocene-Miocene strata of the Rainbow Gardens and Horse Spring Formations, all of which are intensely faulted, tilted, and locally gently folded as a result of Miocene transtension. In the south half of the quadrangle, map units consist of middle to upper Miocene (ca. 16–10 Ma) volcanic and sedimentary rocks and hypabyssal plutonic rocks that represent the northernmost and structurally shallowest part of the ca. 13.5–12.5 Ma Wilson Ridge pluton, which was emplaced during rapid extension across the Lake Mead region.

Along the north shore of Lake Mead, two relatively distinct kilometer-scale screens of sedimentary and volcanic rock at Bearing Peak and Guardian Peak show pervasive hornfels-facies metamorphism and appear to be intruded by, and suspended within, the Wilson Ridge pluton. The Bearing Peak screen (~1.6 km^2) consists of a >1-km-thick, gently to steeply dipping sequence of bedded conglomerate, sandstone, tuff, and angular megabreccia composed entirely of clasts of diverse Precambrian metamorphic rocks that are not exposed in or near the quadrangle; these strata are tentatively correlated with the Thumb Member of the Horse Spring Formation. The Guardian Peak screen (~2.0 km^2) is composed of a >500-m-thick sequence of similar Thumb Member strata underlain by dolomitic breccia and Proterozoic orthogneiss, and overlain by mafic Miocene (?) lavas.

East of the Boulder Wash fault is a >600-m-thick sequence of dacitic lavas, breccias, and tuffs referred to as

the volcanic rocks of Boulder Wash (ca. 14.2–12.5 Ma). Geochemical correlations indicate that the volcanic rocks of Boulder Wash are the extrusive equivalents of the Wilson Ridge pluton (Naumann, 1987). These volcanic rocks are unconformably overlain by mixed gypsum, volcaniclastic sandstone and conglomerate, and tuffs of the red sandstone unit (ca. 12.5–10.0 Ma). Both of these units are interbedded with distal alkaline mafic to intermediate lava flows derived from the Hamblin-Cleopatra stratovolcano (ca. 13.0–10.7 Ma).

STRUCTURE

The dominant structures within the quadrangle include the ENE-striking, left-lateral Hamblin Bay fault and the subsidiary Bitter Spring Valley fault, which together represent the main strands of the Lake Mead fault system. Left-lateral slip is estimated to be at least ~15–20 km on the Hamblin Bay fault (Anderson, 1973) and at least ~5–11 km on the Bitter Spring Valley fault (San Filippo, 2008). While these major faults accommodate the majority of strain in the quadrangle, the structural architecture is expressed as an integrated network of ~NE-striking left-lateral, ~NW-striking right-lateral, and ~N-striking normal faults, and several E- to NNE-trending open folds.

North of the Hamblin Bay fault in Bitter Spring Valley, the onset of regional extension was coeval with deposition of the Horse Spring Formation ca. 16–13 Ma (Beard, 1996; Umhoefer et al., 2010; Demircan, 2019; Lamb et al., 2022). South of this, however, a contemporaneous stratigraphic record is not present, making it difficult to evaluate the onset of extension there. Significant ~E-W extension certainly occurred during and after emplacement of the Wilson Ridge pluton and Boulder Wash volcano between 13.5 and ~10 Ma. Extension was therefore at least partly synchronous with ca. 13–8 Ma left-lateral slip on the Hamblin Bay fault. Post-13-Ma volcanic and sedimentary strata are generally west-tilted in the immediate hanging wall of the major NNW-striking, east-side-down Boulder Wash fault, but stratal dips roll over to become east-tilted toward the eastern map boundary. Total normal displacement on the Boulder Wash fault is at least 1,600 m, and normal slip on the west-dipping Ransome fault is at least 500 m.

More regionally, sinistral transtension along the Lake Mead fault system was coeval and kinematically linked with the NW-striking dextral faults of Las Vegas Valley shear zone to the northwest (Anderson, 1973; Longwell, 1974; Duebendorfer and Wallin, 1991; Fryxell and Duebendorfer, 2005), and with E-W extension in the Lower Colorado River Extensional Corridor to the southwest (Anderson, 1971; Weber and Smith, 1987; Faulds et al., 2001).

Quaternary surficial deposits are extensive in the north half of the quadrangle in Pinto Valley and southern Bitter Spring Valley, and comparatively sparse in the south half of the quadrangle in the incised, high-relief terrain of the northern Black Mountains. In Pinto Valley, remnants of older alluvial terraces occur at elevations of no more than ~50 m above modern drainages, suggesting relatively slow post-tectonic erosional denudation and dissection since early(?) Pleistocene time. Although this study did not reveal evidence of Quaternary fault activity within the quadrangle, further investigation with the aid of high-resolution light detection and ranging (LiDAR) elevation data would be an essential step toward a more robust evaluation of seismic hazards for the area.

DESCRIPTION OF MAP UNITS

Quaternary Deposits

Qc Colluvium (Holocene) Poorly sorted, angular, and generally unconsolidated gravelly colluvium. Locally derived and confined to rockfall-prone slopes. Weakly consolidated locally where active drainages have incised through thick accumulations at the base of slopes. Thickness generally less than 3 m.

Qfy Young alluvium and alluvial-fan deposits (Holocene) Locally derived, coarse-grained alluvial deposits in intermittently active alluvial fans and washes; typically sandy pebble- to cobble-sized gravel with boulders. Generally poorly sorted, variably rounded, and unconsolidated. Typically has weak to no soil development. Thickness is generally less than 3 m.

Qfi Intermediate-aged alluvial-fan deposits (early Holocene to middle Pleistocene) Coarse-grained alluvial deposits in mostly inactive alluvial fans and terraces; typically sandy pebble- to cobble-sized gravel with boulders. At range fronts, Qfi commonly includes abandoned, moderately cemented pediment veneers of colluvium. Clasts are subrounded to subangular. Surface morphology is planar with moderately developed gravel pavement and weak to dark varnish on volcanic clasts. Incised drainages have a tributary pattern with channel incision rarely exceeding 3–5 m. Exposed thickness is generally less than 10 m.

Qfo Older alluvial-fan deposits (middle to early Pleistocene) Coarse-grained alluvial deposits on inactive or relict alluvial fans and terraces; typically sandy pebble- to cobble-sized gravel with boulders. At range fronts, Qfo commonly includes abandoned, moderately cemented pediment veneers of colluvium. Generally poorly sorted with subrounded to subangular clasts, and weakly consolidated to well cemented by caliche. Surface morphology varies from planar and smooth with erosionally rounded margins to fully rounded erosional remnants. Planar surfaces commonly display tightly packed gravel pavement, dark to very dark varnish, and some surface litter of pedogenic carbonate clasts. Broader surfaces are commonly highly dissected by tributary channels up to 5–8 m deep. Thickness typically ranges from 1–15 m.

QTf Oldest alluvial-fan deposits (early Pleistocene to Pliocene) Coarse grained, high-standing alluvial deposits in relict alluvial fans abandoned by deep dissection. Grain size is largely comprised of cobble- and boulder-gravels

with subangular to subrounded clasts. Only occurs in the northwestern corner of the map as several isolated and discordant ridge crests or surfaces. Desert pavement is not preserved, and surfaces are commonly characterized by a rubble layer of broken petrocalcic fragments giving the unit a light color in aerial imagery. Pedogenic carbonate forms a continuous 2–5+-m-thick layer with common laminar carbonate structure. Exposed thickness is up to 10 m.

Tertiary Sedimentary Rocks

Trs Red sandstone unit, undivided (late to middle Miocene) Informal rock unit in the Lake Mead area defined by Bohannon (1983) and Duebendorfer and Wallin (1991) that includes basin-fill strata primarily consisting of rhythmically interbedded sandstone, siltstone, conglomerate and gypsum of highly variable lithology and locally containing input from coeval volcanic sources. Interbedding with the volcanic rocks of Callville Mesa (ca. 10.5–8.5 Ma) and geochronologic data from numerous interbedded tuffs tightly constrain the age of the red sandstone unit to ca. 11.7–10.0 Ma west of the quadrangle at Frenchman Mountain and Boulder Basin (Duebendorfer and Wallin, 1991; Castor et al., 2000), and as old as 12.7 Ma just north of the quadrangle in northern Bitter Spring Valley (Lamb et al., 2022). In the Boulder Canyon quadrangle, rocks are mapped as the red sandstone unit if they meet either of these criteria: (1) they unconformably overlie the ~13.5–12.5 Ma volcanic rocks of Boulder Wash (Tbwd, Tbwt) and are interbedded with the ~13.0–10.7 Ma lavas of Hamblin-Cleopatra volcano (Thcb, Thca); or (2) they overlie the 13.8–12 Ma Lovell Wash Member of the Horse Spring Formation (Thl) and are overlain by lavas dated between 11.1 ± 1.1 and 9.4 ± 0.6 Ma in the adjacent Petroglyph Wash quadrangle (Barker et al., 2012).

Trsc Conglomerate lithofacies Reddish-brown, thin- to medium-bedded volcaniclastic conglomerate and subordinate pebbly sandstone. Mostly matrix-supported. Locally displays normal grading and wavy or ripple lamination in sandier beds. Granule- to cobble-sized clasts are typically angular to very angular. The clast assemblage is distinctly monolithologic and composed of porphyritic dacite lava and tuff containing biotite and plagioclase phenocrysts; groundmass colors are variably light gray or pale purple and less commonly cyan, pink, yellow, or red. The monomict clast assemblage suggests that the volcanic rocks of Boulder Wash (Tbwd, Tbwt) are the primary source for this unit in the map area. Outsize clasts up to 50 cm are rare. Maximum thickness is 220 m.

Trss Red sandstone and conglomerate lithofacies In the central part of the map, this unit consists of red to pinkish-red sandstone with interbedded gypsum, pebbly volcaniclastic sandstone and conglomerate, and basalt. Sandstones are generally well sorted, medium- to coarse-grained, thin- to medium-bedded, and composed of mostly quartz with subordinate feldspar and volcanic lithic fragments. Gypsum interbeds reach up to 8 m thick. Pebbly sandstones and conglomerate interbeds are composed entirely of intermediate volcanic clasts associated with the Hamblin-Cleopatra volcano. Near the Boulder Wash fault, this unit consists of red to reddish-brown, unsorted to poorly sorted, matrix-supported volcaniclastic sandstone and pebbly sandstone, with uncommon pebble-cobble conglomerate and rare gypsiferous sandstone. Sandstone is typically well cemented, gray to reddish-purple and composed almost entirely of fine- to medium-grained volcanic lithic fragments. Bedding is generally thin and planar, but locally discontinuous and wavy; normal grading is common. Clasts are distinctly monolithologic dacite identical to that of the conglomerate lithofacies (Trsc). Thickness varies from 10 m to more than 200 m.

Trsg Gypsum and mudstone lithofacies Mostly white to gray, thinly bedded and laminated gypsum with subordinate tan to brown gypsiferous mudstone, sandstone, and tuff. Individual laminae are planar to wavy or crinkly and commonly red, maroon, or dark gray, and less commonly yellowish-gray or pale blue-green. Locally displays 0.5- to 2-m-thick red, oxidized breccia reflecting subaerial exposure and karstification. Intercalated cyan or greenish-blue tuffs 0.5- to 4-m-thick are conspicuous and composed of fine ash with rare sub-mm biotite phenocrysts; the upper parts of some tuffs are reworked and ripple laminated. Basaltic lavas associated with the Boulder Wash volcanic unit (Tbwb) are interbedded with this unit on the north and south sides of Pyramid Peak and Saddle Mountain. Maximum thickness is 280 m.

Trsl Landslide blocks and breccia Pale brown weathered, brecciated limestone blocks and debris flow breccia near the base of this unit. Basal contact is locally a sharp, undulatory slip surface or glide plane. Source of clasts is uncertain. Thickness is up to 10 to 15 m.

Horse Spring Formation (middle Miocene)

The Horse Spring Formation is exposed throughout the Lake Mead domain and consists of a heterolithic assemblage of continental sedimentary rocks that that either conformably overlie the Rainbow Gardens Formation (Trg), or disconformably overlie Paleozoic and Mesozoic rocks with a slight angular discordance locally. In ascending order, it is subdivided in into the Thumb Member, Bitter Ridge Limestone (not exposed in the quadrangle), and Lovell Wash Member. In western Lake Mead, the Horse Spring Formation was deposited between ~17 and 12.7 Ma and records the earliest phase of widespread extension within the Lake Mead domain (Beard, 1996; Castor et al., 2000; Fryxell and Duebendorfer, 2005; Umhoefer et al., 2010; Lamb et al., 2010, 2022). Because of its syn-extensional nature, lateral and vertical facies changes within this unit are complex, and growth strata, and soft sediment deformation are locally common, especially in the Thumb Member (Beard, 1996; Winston, 2016; Demircan, 2019).

Thl Lovell Wash Member Gray pale yellowish-gray and pale orange mudstone, limestone, sandstone, tuffaceous sandstone, and gypsum. Bedding is thin to medium (~3–20 cm thick), even, and laterally continuous. Where mapped between strands of the Hamblin Bay fault, these strata are intruded by hypabyssal igneous rocks of the Hamblin-Cleopatra volcano (Thci). Geochronologic data from northern Bitter Spring Valley indicate an age span of ca. 13.9–12.7 Ma for this unit (Lamb et al., 2022).

Thtu Upper Thumb Member Mostly pale pink to gray gypsiferrous mudstone interbedded with fine-grained sandstone and sparse pebbly sandstone and pale green-gray ash-fall tuffs. The base of this unit is mapped as the top of the last pebble conglomerate bed of the middle Thumb member (Thtm). Exposed thickness is >40 m in the quadrangle.

Thtm Middle Thumb Member Mostly tan to gray, massive, well-bedded pebbly sandstone and sandy pebble-cobble conglomerate with interbedded orange to tan, very fine- to medium-grained sandstone and mudstone, with sparse limestone and tuffs (Demircan, 2019). Conglomerates are predominantly composed of gray Paleozoic carbonate clasts (Pk, Ptb) with variable proportions of red-orange sandstone clasts (Ja, Jkm) locally. The base of this map unit corresponds with a distinctive tuff with an unpublished date of 15.60 ± 0.06 Ma (2σ) from within the quadrangle (P. Umhoefer, pers. comm, 2021; sample LMPU001; 36.232376°N, 114.586495°W). This tuff is ~1 to 2.5 m thick with a reworked upper half, and contains 10–20% euhedral phenocrysts of biotite > feldspar + accessory yellow sphene in a minty green ashy groundmass, with distinctive green pumice up to 4 mm in diameter. The top of this unit is mapped as the top of the youngest pebble conglomerate bed before switching to mudstone- and gypsum-dominated lithofacies (Thtu). Thickness is 150 to 200 m.

Thtl Lower Thumb Member, undivided Heterolithic assemblage of interbedded tan, pinkish-red, and gray conglomerate, sandstone, mudstone, limestone and greenish ash-fall tuffs. In the vicinity of Razorback Ridge, this unit is further divided in ascending order into a gray, clast-supported, basal conglomerate (Thtl-c), sandstone and calcarenite (Thtl-s), and limestone (Thtl-l) lithofacies. The top of this map unit corresponds with a distinctive 15.6 Ma tuff (see Thtm). Thickness is variable and estimated to be 350 to 400 m.

Trg Rainbow Gardens Formation, undivided (early Miocene to late Oligocene) Conglomerate, sandstone, limestone, and mudstone representing the basal Tertiary section that unconformably overlies Mesozoic and Paleozoic units throughout the Lake Mead domain (Lamb et al. 2015, 2018). This unit is only mapped along the Hamblin Bay fault where it unconformably overlies the Aztec Sandstone (Ja). Undivided unit (Trg) only mapped in the west-central part of the map near the Hamblin Bay fault where steep dips and lateral thinning of Trgc and Trgm make it difficult to divide them at the scale of the map.

Trgl Limestone member Pale gray to yellow, resistant, thin- to thick-bedded, algal-laminated limestone with subordinate sandstone, mudstone and gypsum intercalations. Thickness is highly variable due to faulting and ranges from 20 to 120 m.

Trgm Middle member Relatively recessive, heterolithic unit composed of mostly red to tan sandstone, calcarenite, mudstone, limestone and minor gypsum and tuff. Pinkish-red sandy limestones have distinctive rhizoliths, calcareous laminae, and pedogenic textures. Typical thickness is ~70 m, but ranges from 20 to 90 m.

Trgc Basal conglomerate member Resistant, reddish-gray carbonate-cemented, clast-supported conglomerate that weathers to a conspicuous dark brown and is composed exclusively of subrounded to rounded Paleozoic carbonate and Mesozoic sandstone clasts. Mostly massive to indistinctly bedded. Typical thickness is 20 m, but ranges from 10 to 35 m.

Paleozoic and Mesozoic Sedimentary Rocks

Ja Aztec Sandstone (Early Jurassic) Light-tan to pale-pink eolian sandstone with characteristic large-scale trough cross-bedding. Weathers tan to reddish-orange. Composed of fine- to medium-grained, well-rounded and well-sorted quartz arenite. Moderately indurated with minor hematitic cement, although locally friable and uncemented. Thickness is uncertain due to faulting, but is at least 600–800 m.

Jkm Kayenta and Moenave Formations, undivided (Early Jurassic) Red to reddish brown or orange sandstone and siltstone. Sandstones are very fine- to medium-grained, very thin or thin bedded with common ripple cross-stratification, and form lenses within siltstone. Thin beds of limestone and silty limestone are uncommon. Locally displays conspicuous white or pale minty green, cm-scale and circular reduction spots. The base of this unit consists of up to a few meters of brown, cross-stratified, pebbly sandstone with mostly subangular and less commonly rounded clasts of chert. The absence of interbedded tuffs in this unit helps to distinguish it from the upper red member of the Moenkopi Formation (Ꞧmu). Thickness is 150 to 175 m.

Chinle Formation (Late Triassic)

Ꞧcu Upper part Mostly poorly exposed, variegated mudstone and gypsiferrous mudstone with subordinate sandstone and limestone. Colors range from reddish-brown to lavender, tan, pinkish-gray, and green, with mudstones typically having lighter shades. Sandstones are typically darker shades of brown and purple and composed of fine- to coarse-grained,

subangular to well-rounded, moderate- to well-sorted quartz-rich sand with subordinate feldspar and chert and weak calcite cement. White to red fragments of petrified wood are distinctive and diagnostic. Coarser sandstone, pebbly sandstone and rare conglomerate beds display trough cross-bedding; pebbles are well-rounded chert and less quartzite, similar to the underlying Shinarump Member (Ꞧcs). Finer sandstones show subtle ripple laminations and conspicuous burrow textures occur along some bedding planes. Bedding is very thin to thin, typically wavy and discontinuous, and only expressed by sandstone and limestone interbeds. Mostly equivalent to Petrified Forest Member. Thickness is 80–150 m.

Ꞧcs Shinarump Member Pale yellowish-gray to white or tan sandstone, pebbly sandstone and conglomerate that weathers gray to pale brown. Sandstone consists of well sorted, subrounded, medium- to very-coarse-grained quartz arenite with minor feldspar and sparse chert fragments. Pebbles up to 3 cm wide occur as thin stringers or are normally graded and concentrated at the base of sandstone beds. The base of the unit is typically marked by a resistant 40- to 50-cm-thick, calcite cemented, dark-gray to black weathered, sandy pebbly conglomerate containing very well-rounded clasts of orange, brown, dark gray and maroon chert with subordinate quartzite and white vein quartz. Generally medium to thick bedded, commonly displays trough or planar tabular cross-bedding. Thickness is typically 5 to 10 m, but ranges to a maximum of 50 m.

Ꞧm Moenkopi Formation, undivided (Early Triassic) Divided into four members after Anderson (2003) and following subdivisions of Stewart et al. (1972). Undivided unit (Ꞧm) only mapped in a small fault block in north-central part of map where exposure is limited.

Ꞧmu Upper red member Poorly exposed pale reddish-brown to orange or tan ripple-laminated siltstone interbedded with subordinate yellowish-gray sandstone and gypsiferrous mudstone and rare pebbly sandstone. Bedding is typically very thin to thin and continuous, but can be discontinuous or lenticular. Locally displays circular, grayish-green reduction spots up to 10 cm wide. Numerous distinctive minty greenish-gray tuffs and tuffaceous sandstones occur as very thin, platy interbeds that are unique to this red bed unit and help to divide it from the lower red bed member of the Moenkopi Formation (Ꞧml) and the Kayenta and Moenave Formations (Jkm), which seem to lack interbedded tuffs. The base of Ꞧmu is defined here as the first thick (>2 m) red mudstone above the Shnabkaib Member (Ꞧms). Thickness is 200 to 250 m.

Ꞧms Shnabkaib Member Recessive, interbedded white and gray dolomite and gypsum with minor mudstone and limestone; distinctive yellow beds occur near base of unit. Bedding is generally very thin to thin, and mixed lithologies including gypsiferrous or calcareous mudstone and sandy siltstone are common. Dolomite is bright white and locally contains ripple lamination; some limestone interbeds are oolitic. Base of unit is defined by a prominent recessive yellow bed of gypsiferrous mudstone. Thickness is 80 m.

Ꞧmv Virgin Limestone Member Resistant, ledgy yellowish-gray to tan limestone with minor interbedded sandy limestone, calcareous siltstone, and sparse recessive, white dolomite and gypsum. Rare bioclastic beds contain abundant gastropods, crinoids and/or pelecypods. Common sedimentary structures in limestone beds include ripple lamination, low-angle and hummocky cross-stratification, and wavy bedding; less common are ooids, light gray to yellow limestone rip-up clasts, and gray chert nodular that weathers brown. Thickness is 100 to 120 m.

Ꞧml Lower red bed member Mostly recessive red mudstone with minor laminated to thin-bedded gray gypsum, gypsiferrous mudstone, and rare greenish-gray very fine-grained sandstone. The absence of interbedded tuffs distinguishes this unit from the upper red member of the Moenkopi Formation (Ꞧmu). In some locations, this unit displays a pale grayish-orange basal conglomerate that is up to 7 m thick and composed of gray limestone and chert clasts of the Kaibab Formation (Pk). Thickness is typically up to 100 m.

Pk Kaibab Formation, undivided (middle to early Permian) Divided into Harrisburg and Fossil Mountain Members following Anderson (2003) and based on subdivisions of Cheevers and Rawson (1979) and Nielson (1981). Undivided unit (Pk) only mapped in a fault-bounded block in the Echo Hills along the northeastern edge of the map.

Pkh Harrisburg Member Mostly light gray, medium- to thick-bedded limestone and cherty limestone interbedded with minor thin, yellowish-gray dolomite and rare gypsum. Fossils are sparse and mostly consist of crinoids, brachiopods, and bryozoans. More distinctly bedded and lightly colored than the underlying Fossil Mountain Member (Pkf). Upper part of unit is commonly brecciated and composed of angular limestone and chert fragments in a tan, sandy matrix, likely reflecting subaerial exposure, karstification, and erosional reworking of the Permian-Triassic unconformity surface. Thickness is up to 35 m.

Pkf Fossil Mountain Member Light to medium gray, massive to evenly bedded, cherty, fossiliferous limestone. Bedding is well defined by trains of chert nodules, lenses, or bands that weather dark brown. Fossils include crinoids, rugose coral, bryozoans, brachiopods, and echinoderms. This unit forms resistant brown-weathering cliffs that are distinctly thicker and darker than the overlying Harrisburg Member (Pkh) and the underlying Brady Canyon Member of the Toroweap Formation (Ptb). Thickness is 100 to 150 m.

Pt Toroweap Formation, undivided (early Permian) Divided into Woods Ranch and Brady Canyon Members following Anderson (2003) and based on subdivisions of Cheevers and Rawson (1979) and Nielson (1981). Undivided unit (Pt) only mapped in the Echo Hills in northeast corner of the quadrangle, where it appears to overlie the Permian red beds unit (Pr). Total thickness including the unexposed Seligman Member is estimated to be up to 120 m (Anderson, 2003).

Ptw Woods Ranch Member Poorly exposed, recessive, thin- to medium bedded, red to gray or white mudstone and gypsum interbedded with resistant, thick-bedded, grayish-orange limestone and tan dolomite that weathers light gray. Forms conspicuous recessive slope between resistant limestone cliffs of the underlying Brady Canyon Member (Ptb) and the overlying Fossil Mountain Member of the Kaibab Formation (Pkf). Thickness is about 20 to 30 m.

Ptb Brady Canyon Member Light- to medium-gray or blueish gray, medium- to very thick-bedded, evenly bedded, medium-grained cherty limestone. Dark-brown-weathering, spherical to irregular-shaped chert nodules are up to 20 cm in diameter are sparse to absent, but locally concentrated in single layers up to 40 cm thick. Indistinct fossils include crinoid fragments, brachiopods, and rugose coral. Only about 40 m exposed; base not exposed.

Pr Red beds (early Permian) Mostly pale red, reddish-pink, or yellowish-tan, fine- to medium-grained, cross-bedded sandstone with sparse interbedded reddish-brown mudstone and gypsum. Sandstones are thin- to thick-bedded and shows indistinct crossbedding in most exposures. Conspicuous yellow, very well-sorted quartz-rich sandstone with large-scale trough cross-bedding may correlate with the Permian Coconino Sandstone or Esplanade Sandstone. Thickness estimated to be >100 m; base not exposed.

Pp Pakoon Limestone (earliest Permian) Light gray, thick- to very thick-bedded, fine-grained crystalline cherty limestone and dolomite. Some beds contain brown-weathering chert nodules as isolated nodules or in semi-continuous layers or trains. This unit is only exposed in the Echo Hills in the northeast corner of the quadrangle, where it is in fault contact with other units, making its stratigraphic correlation uncertain. Thickness uncertain, but is at least 50 m; base not exposed.

Tertiary Volcanic and Intrusive Rocks

Hamblin-Cleopatra volcano (late to middle Miocene)

Dissected stratovolcano emplaced during, and offset by, middle to late Miocene sinistral slip along the Hamblin Bay fault (Anderson, 1973; Weber and Smith, 1987). Mafic and intermediate lavas and autobreccias dominate, while tuffs and other pyroclastic rocks are conspicuously sparse. Lavas are subalkaline and geochemically classified as basalt, hawaiite, trachybasalt, shoshonite, and trachyte (Barker et al., 2012). Eruptive activity occurred from ~13.0 to 10.7 Ma (Thompson, 1985; Barker et al., 2012) and overlapped in time and in space with deposition of the Lovell Wash Member of the Horse Spring Formation (Thl), the Wilson Ridge pluton (Tw) and volcanic units of Boulder Wash (Tbwd, Tbwt, Tbwb), and the red sandstone unit (Trs).

Thc-bx Fault breccia Cataclastic to pervasively brecciated and fractured intermediate volcanic rocks of the lower (Thcl) and middle (Thcm) volcanic sequences of Hamblin-Cleopatra volcano. Only mapped in narrow, fault-bounded slivers along of strands of the left-lateral Hamblin Bay fault. Shear bands, veinlets, and hydrothermal alteration increase in abundance in proximity to mapped faults.

Thcu Upper volcanic sequence Mostly basaltic andesite to shoshonite lava flows and breccias occurring in the east part of the map area and generally correlated with the Cleopatra lobe of the Hamblin-Cleopatra volcano. Weathers reddish-brown, brown, burgundy, or grayish-purple. Textures vary between flows from aphanitic to porphyritic. Most lavas are finely porphyritic with minor (2–4%) plagioclase, clinopyroxene and/or olivine (as iddingsite) phenocrysts in a dense, microlitic, gray groundmass. Less common lavas have a distinctive porphyritic texture consisting of ~5–10% euhedral plagioclase crystals up to 12 mm long with accessory olivine and pyroxene in a medium-gray groundmass. Lavas commonly display a reddish-gray basal autobreccia consisting of slightly vesicular basalt clasts. Thickness of individual flows varies from ~2 to 15 m. This unit appears to be interbedded, and at least partly coeval, with the upper dacitic lavas and tuffs of the Boulder Wash volcanic unit (Tbwd, Tbwt) and gypsum facies of the red sandstone unit (Trsg). Thickness is uncertain, but is at least 250 m including interbedded gypsum beds of Trsg.

Thcd Hornblende-dacite lava flows Pinkish-gray porphyritic dacite lava flow with hornblende, plagioclase, and biotite. Subrounded xenoliths of purple, microvesicular, porphyritic basaltic andesite with megacrystic plagioclase and less common and smaller clinopyroxene and olivine-phyric andesite are common and locally abundant; less common xenoliths are fine-grained, aphanitic gray basalt. Xenoliths are likely derived from underlying Thcl and Thcm. Interbedded with volcaniclastic conglomerate of Hamblin-Cleopatra volcano (Thcc) and eponymous facies of the red sandstone unit (Trss). Though correlated with the Hamblin-Cleopatra volcanic sequence, the composition of Thcd is more similar to dacite lavas of Boulder Wash (Tbwd). Thickness is up to 60 m.

Thcc Volcaniclastic conglomerate Mostly massive, unsorted, clast-supported, volcaniclastic cobble-boulder conglomerate, volcanic breccia, and

sandy pebble-cobble conglomerate. Clast compositions vary from basalt to andesite. Monomict basaltic-clast conglomerates are gray to blueish-gray, while polymict andesite-basalt-bearing deposits are generally weathered tan to brown. Thickness is at least 250 m.

Thcm Middle volcanic sequence Porphyritic basaltic andesite, andesite, and trachyte lava flows and interbedded massive tuff breccias and volcanic breccias. Highly weathered to reddish-purple or brown. Andesites are porphyritic with ~8- to 12%-mm-scale phenocrysts of plagioclase and clinopyroxene and accessory hornblende set in a very fine-grained gray groundmass. Basaltic andesites generally have 10–30% phenocrysts of plagioclase >> clinopyroxene > olivine. Thcm has a greater proportion of lava flows than underlying Thcl. Thickness is ~500 m.

Thcl Lower volcanic sequence Typically poorly exposed intermediate volcanic breccias and tuff breccias with less common porphyritic plagioclase-hornblende-phyric lava flows. Crosscutting dikes form the majority of outcrops in this unit. Compositions are mafic to intermediate with common plagioclase, hornblende, and minor pyroxene as mm-scale phenocrysts up to 15% by volume in a fine-grained, dense gray to purple groundmass. Some flows contain megacrystic hornblende up to 15 mm long. Thickness uncertain but estimated to be at least 400–500 m.

Thci Hypabyssal rocks Homogenous, light gray to pinkish-gray porphyritic andesite to granite porphyry with abundant euhedral plagioclase up to 8 mm long and less euhedral biotite and hornblende in a microcrystalline feldspar groundmass. Angular xenoliths composed of porphyritic basaltic andesite or andesite are locally abundant. Rocks show variable hydrothermal alteration, locally chloritic or graphitic. The conspicuous absence of autobreccias and flow foliation and more phaneritic texture suggest they are shallow intrusive equivalents of the Hamblin-Cleopatra volcano (Thcl, Thcm, Thcu). Commonly intruded by late-stage andesite and dacite dikes. This unit is interpreted as the hypabyssal intrusions representing the subvolcanic plumbing system of the Hamblin-Cleopatra volcano.

Volcanic rocks of Boulder Wash (middle Miocene)

Interbedded dacite lavas, tuffs, breccias and rare basalts referred to as the "Boulder Wash volcanics" by Naumann (1987). Subdivision of these units is done for the purpose of showing structure and dividing lava-dominant (Tbwd) from pyroclastic-dominant facies (Tbwt), which are interstratified throughout the map area. Barker et al. (2012) reported a K-Ar age of 14.2 ± 0.5 Ma on plagioclase from a dacite lava within Tbwt, and Beard et al. (2007) reported a whole rock $^{40}Ar/^{39}Ar$ age of 12.52 ± 0.04 Ma [$^{40}Ar/^{39}Ar$] from a dacite lava in Tbwd. Here we report a new preliminary $^{40}Ar/^{39}Ar$ age of 12.99 ± 0.04 Ma (2σ) on biotite from a dacite lava in this unit (sample MD21bcs-40; 36.16660°N, 114.51972°W). Naumann (1987) interpreted the Boulder Wash lavas to represent a structurally disrupted stratovolcano and noted that geochemical and textural data indicate they are volcanic equivalents of the Wilson Ridge pluton (Tw). Total thickness is probably >700 m, although variable and uncertain due to faulting.

Tbwb Basaltic lavas Aphanitic to weakly porphyritic basaltic lava flows with up to 5% microphenocrysts of olivine, plagioclase, and pyroxene in variable proportions. Geochemical data indicates a phonotephrite composition with elevated alkalis and low silica, very similar to that of late-stage basaltic dikes that crosscut the Wilson Ridge pluton (Tw). Individual lava flows are typically no more than 5–7 m thick and occur as isolated interbeds within the upper part of the Boulder Wash volcanic sequence and in the overlying red sandstone unit (Trs).

Tbwt Dacitic tuffs and breccias Pale greenish-blue to cyan or white tuffs and tuff breccias with subordinate dacite lava flows (Tbwd). Pumice-lithic tuffs commonly contain white, biotite-phyric pumice and/or angular biotite-plagioclase dacite clasts that are generally <5 cm wide. Tuffs vary from homogeneous ash to pumice- and/or lithic-rich with small dark gray to purple angular volcanic-lithic fragments. Tuff breccias are matrix-supported. Mostly recessive, slope-forming unit, although may form relatively resistant cliffs locally.

Tbwd Dacitic lavas and domes Variably colored pale pink, purple, gray, or grayish-green dacite lava flows with subordinate dacitic tuffs and breccias (Tbwt). Weathered tan-orange, brown, or black. Lavas are porphyritic (10–15% phenocrysts) and contain a disequilibrium assemblage of biotite >= rounded sodic plagioclase >> embayed quartz and rare olivine in a dense pink or gray groundmass. Basal and carapace autobreccias are common and reach up ~40 m thick. Lava flow interiors typically display well-developed and tightly spaced (1–3 cm) pink-gray flow foliations. Uncommon flows also contain dark purple, subrounded to subangular porphyritic plagioclase-biotite dacite or aphanitic basalt(?) inclusions typically up to 8–10 cm wide, which may represent chilled enclaves of mafic magma (Naumann, 1987).

Wilson Ridge pluton (middle Miocene)

Compositionally and texturally diverse composite pluton composed of fine-grained quartz monzonite to quartz diorite (Eschner, 1989; Larsen and Smith, 1990; Anderson et al., 1994); however, in the Boulder Canyon quadrangle it mostly consists of abundant light to dark-gray dikes of granite porphyry, basalt, and rhyodacite commonly arranged in parallel or dike-on-dike array (Naumann, 1987; Anderson, 2003). Pervasive fractures are commonly coated with riebeckite, and secondary hematite and barite are common. The unusual chemical and textural diversity in both the Wilson Ridge pluton and correlative volcanic units

of Boulder Wash (Tbwd, Tbwb) probably record intimate mixing and comingling of mafic and granite magmas (Naumann, 1987). Age is accepted to be ~13.5–12.5 Ma based on K-Ar ages of 13.4–13.5 Ma south of the quadrangle (Larsen and Smith, 1990) and $^{40}Ar/^{39}Ar$ ages of ~12.5–12.6 Ma at the northern end of the pluton just west of the map boundary in the Callville Bay quadrangle (Anderson et al., 1994; Anderson, 2003); the younger ages are thought to reflect alteration history and/or cooling to <300°C, rather than emplacement age.

Twa Hydrothermally altered quartz monzonite Reddish-orange to brown or yellow, fine-grained, hypabyssal quartz monzonite or rhyolite showing extensive hydrothermal alteration. Mineralized by hematite, malachite, manganese, barite, and gypsum.

Tw Hypabyssal quartz monzonite Mostly medium to dark gray, fine-grained, hypabyssal quartz monzonite and rhyodacite containing abundant (up to 25%) and large (up to 5 mm) euhedral plagioclase, with less common and smaller biotite and embayed quartz in a dense aphanitic groundmass. Weathers black to reddish-brown. Extensively fractured and typically showing minor to moderate deuteric or hematitic alteration. Aphanitic to weakly porphyritic basalt dikes are subordinate, and share a similarly alkaline, low-silica (phonotephrite) composition as late-stage basaltic lava flows (Tbwb) intercalated with the Boulder Wash volcanics (Tbwd) and the red sandstone unit (Trs). Although only several prominent dikes are depicted on the map, the entire unit is composed of hundreds, if not thousands, of dikes.

Metamorphic Rocks

Hornfelsed sedimentary rocks as intruded screens; tentatively correlated with the Thumb Member of the Horse Spring Formation (middle Miocene)

Blocks and screens >1 km long composed of stratified rocks displaying common hornfels and deuteric alteration and mapped entirely within the Wilson Ridge pluton (Tw) and subvolcanic intrusions of the Hamblin-Cleopatra volcano (Thci). These screens are tentatively correlated with sedimentary strata of the Thumb Member of the Horse Spring Formation based on (1) similar lithofacies consisting of interbedded conglomerate, sandstone, mudstone, tuff, angular breccia and megabreccia composed of crystalline-basement clasts, and mafic lavas (Castor et al., 2000; Duebendorfer, 2003; Fryxell and Duebendorfer, 2005), and (2) the requirement that these were deposited prior to emplacement of Tw (i.e., pre–13.5 Ma), which is compatible with deposition of the Thumb Member from 17.2 to 14.5 Ma (Castor et al., 2000; Beard et al., 2007).

Tht-v Mafic lavas Weathered grayish-purple to green porphyritic mafic lava with abundant plagioclase and variable amounts of clinopyroxene and Fe-Ti oxides as phenocrysts up to 5 mm long. Pervasively fractured with spatially variable deuteric or propyllitic alteration. Only occurs in the south-central map area within the Guardian Peak screen, where it displays a sharp, intrusive contact with the overlying Wilson Ridge pluton (Tw) as evinced by dikes of hypabyssal quartz monzonite that originate at the contact and intrude downward into Tht-v. Thickness is up to 120 m.

Tht-s Sandstone, shale, and tuff Mostly tan to reddish-brown, well-sorted sandstone with lesser-gray limestone, weathered brownish-yellow, thinly laminated greenish-gray shale, and uncommon conglomerate and tuff. Beds are medium thickness, planar, laterally extensive, and well indurated. Sandstones display plane bed and subtle low-angle and trough cross-stratification. Many are normally graded and contain a basal layer of granules or small pebbles composed predominantly of gneiss or granite, although chert and limestone clasts are locally abundant as well. Pale cyan tuffs are aphanitic, weathered light tan, and mostly occur near the base of the unit near the contact with underlying Tht-c. Thickness varies from ~80–350 m in the Guardian Peak and Bearing Peak screens within the Wilson Ridge pluton (Tw), and to >800 m along the Hamblin Bay fault where it is intruded by Thci.

Tht-c Granite- and gneiss-clast conglomerate, breccia, and megabreccia Mapped in two locations at Bearing Peak and Guardian Peak. Poorly sorted, matrix-supported conglomerate, breccia and megabreccia consisting of angular clasts of crystalline basement including primarily megacrystic granite and gneiss, with less common garnet-biotite gneiss, amphibolite, and schist. Clasts are mostly pebbles and cobbles and uncommonly include blocks up to 3 m wide. Where discernible, beds are amalgamated and massive or thick to very thick. In the Guardian Peak screen, this unit contains beds with up to 70% clasts of rusty-brown dolomite (Tht-d). This unit was previously interpreted by Naumann (1987) as a hydro-magmatic breccia formed either by hydrofracturing or decompression-driven volatile exsolution during emplacement of the Wilson Ridge pluton (Tw). However, compelling evidence supports a sedimentary origin for this unit that is unrelated to pluton emplacement, including: (1) preserved bedding and bed-perpendicular grading in many outcrops; (2) polymict clast assemblages of diverse crystalline basement lithologies not exposed in or near the map area; and (3) the conspicuous absence of hypabyssal quartz monzonite clasts that characterize Tw. Thickness varies from 350–400 m in the Guardian Peak screen to as much as 900 m in the Bearing Peak screen.

Tht-d Brecciated dolomite Cliff-forming, rusty yellow-orange to tan weathering, medium-grained crystalline dolomite. Varies from brecciated dolomite to massive, in-tact blocks(?) of dolomite. On the southeast side of Guardian Peak, this unit is brecciated and interbedded with conglomerate and breccia composed

of angular crystalline basement and similar yellow dolomite clasts (Tht-c). This lithology bears a strong resemblance to the Cambrian Muav Limestone and Bonanza King Formations (Beard et al., 2007) which is exposed throughout the eastern Lake Mead domain. However, the absence of adjacent Paleozoic strata and the presence of dolomite-clast breccias in the overlying unit (Tht-c) lead us to interpret this unit as a landslide block of Cambrian origin that was deposited during early deposition of the basal Thumb Member of the Horse Spring Formation in middle Miocene time. The basal contact of this unit was previously interpreted as a low-angle detachment fault separating Precambrian crystalline basement in the lower plate from Cambrian and younger strata in the upper plate (Naumann, 1987; Eschner, 1989; Duebendorfer et al., 1990). In Flamingo Cove, however, the basal contact with Tw is clearly intrusive as indicated by its undulatory, nonplanar geometry and the occurrence of dolomite blocks up to 2 m wide that are entrained within Tw along the contact. Thickness is up to 60 m.

Ꝑg Orthogneiss (Proterozoic) Banded to strongly foliated quartzofeldspathic and amphibolitic gneiss. Commonly migmatitic and showing irregular ptygmatic folding of quartz-rich leucosome. Crosscutting quartz veins of variable orientations are locally abundant. Exposed only on the southeast side of Guardian Peak, where it appears to be nonconformably(?) overlain by dolomitic breccia (Tht-d) and conglomerate (Tht-c) correlated with the Thumb Member of the Horse Spring Formation, and all of which are intruded by the Wilson Ridge pluton (Tw). This unit likely correlates with similar Paleoproterozoic crystalline basement exposed at Gold Butte and throughout the eastern Lake Mead region (e.g., Beard et al., 2007).

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