

GEOLOGIC MAP OF THE CALLVILLE BAY QUADRANGLE

NEVADA AND ARIZONA

by

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DESCRIPTION OF MAP UNITS

The ages of surficial deposits shown on the map are based on visual estimates of the degree of soil development on those deposits and on their elevation above the modern stream channel. The latter factor approximates the degree of dissection. Error ranges for radiometric ages of igneous rocks can be found in the source references.

Qm Manmade feature (latest Holocene) Areas where excavations or fill by man has modified the land surface to the extent that its natural character is obscured. Modifications are mostly for campsites, road access, boat ramps, and parking areas in vicinity of the Callville Bay Marina. Modifications along North Shore Road are not shown.

Qe Eolian sand and associated deposits (Holocene and late Pleistocene?) Fine- to medium-grained, pale orange-gray and pale yellowish-brown, unconsolidated moderately well-sorted sand. Forms irregular masses draped over preexisting topography, and ramps to bedrock highlands. Sand was probably derived from sources along the Colorado River. Mostly forms a thin veneer, but where sand fills preexisting channels, thickness exceeds 10 m. During periods of strong wave action along Lake Mead shores, ephemeral escarpments are cut into these unconsolidated deposits. Such exposures reveal common pods, lenses, and irregular stringers of angular cobbles and boulders of dark andesite suspended in the pale yellowish-brown sand. These strongly bimodal deposits could have formed by fluvial remobilization of eolian sand and mixing with coarse colluvium. Alternatively, they could be primary fluvial deposits recording flood events along reaches of an ancestral Colorado River. If so, they may correlate with the Chemehuevi Formation. Along shores of Lake Mead, the sand is reworked into beaches popular for bathing and recreation.

Stream Deposits

Qsy Young-sidewash alluvium (Holocene and late Pleistocene?) Mostly light gray to grayish-orange, medium to coarse, angular to moderately rounded, unlithified, moderately to poorly sorted gravel, sand, silty sand and some bouldery gravel at level of modern washes or slightly (<2 m) above that level. Mapped as quasi-continuous bands along many of the larger intermittently active washes. Equivalent in age and origin to the young (and generally lowest) parts of deposits mapped as alluvium (Qa). In narrow reaches of washes, modern storm-generated runoff activates these surficial deposits over their entire width, producing a serious flood hazard. In broad reaches, activation occurs over limited widths, and sparse vegetation is established in the inactive parts. Anastomosing bar and swale topography and braided channels are common, pavements generally absent. Most exposures show no obvious soil development. Maximum exposed thickness in washes about 3 m, but unexposed thickness is probably several times greater than that.

Qso Old sidewash alluvium (late Pleistocene) Mostly pale yellowish-brown to grayish-orange, unlithified to weakly lithified, medium to coarse, angular to poorly rounded, unsorted to weakly sorted polymictic gravel and bouldery gravel with matrix of coarse to very coarse moderate-red sand. Includes 1- to 5-cm-thick beds of medium to coarse moderate-red sand. Beds are of mixed fluvial and debris-flow origin, and individual debris-flow beds are 5 to 30 cm thick. Equivalent in age and origin to the old (and generally highest) parts of deposits mapped as alluvium (Qa). The deposits form discontinuous strath terraces or streamlined terrace remnants directly adjacent to modern washes (not shown in all areas). Erosionally dissected, and the surfaces developed on these deposits stand 3 to 15 m higher than the modern washes. Bar and swale

topography is uncommon. Erosional remnants of a weakly developed (stage I–II) carbonate soil cap the deposits locally. Exposed thickness mostly 2 to 3 m, but unit is as much as 20 m thick.

QTrg Mainstream alluvium (Pleistocene and Pliocene?) Very pale orange to grayish-orange-pink, weakly lithified, fluvial sandstone, pebbly sandstone, and roundstone gravel; includes some moderately lithified thin-bedded silty claystone. Sand is mostly quartzose, moderately well sorted, fine to medium grained, very indistinctly to very distinctly bedded, flat-bedded to complexly cross-bedded. Cut-and-fill channel deposits are common. Some massive beds contain very sparse to common suspended pebbles and, locally, suspended cobbles, suggesting they are, in part at least, high-energy flood deposits. Gravel beds are mostly sandy and are clast supported, consisting of strongly bimodal assemblages of rounded and angular clasts in highly variable proportions, suggesting complex intercalation of locally derived and far-traveled detritus, especially near the contact with locally derived sidewash alluvium (TS). Rounded pebbles and cobbles of yellowish-gray quartzite and dark brown chert are common. Silty claystone is thin-bedded, rhythmically flat-bedded, and more varied in color than the sandy beds. Age based on intensity of pervasive folds and an angular unconformity with overlying gravel (QTa) on which a well-developed (stage IV?) calcrete is formed. Unit may represent deposition by the Colorado River or a precursor to it.

Piedmont-Slope and Colluvial Deposits (Holocene and Pleistocene) The Callville Bay Quadrangle lacks Pliocene-Quaternary mountain-front fault-related deposition characterized by accumulation of well-defined alluvial fans or fan complexes. Instead, talus and colluvium near bedrock highlands grade downslope to relatively thin (generally <20 m) piedmont-slope deposits or erosional remnants of such deposits. Many small deposits of colluvium in highland areas occur within other map units.

Qp Piedmont-slope deposits (early Holocene and late Pleistocene) Mostly pale red, light brown to grayish-orange-pink weakly lithified, weakly bedded, poorly to moderately sorted sand and gravel. Gravel clasts are polymictic and angular to moderately rounded. Sand is fine to very coarse and locally silty. Forms sheet-form deposits atop pedimented bedrock, but preserved mostly as irregular-shaped erosional remnants of such deposits. Surfaces relatively smooth. Soil development varies from very weak (possibly erosionally stripped) to a 1- to 15-cm-thick eolian silt/sand Av layer overlying a weakly developed reddish argillic layer to 50 cm. Thickness generally <3 m.

Qcp Undivided colluvium and piedmont-slope deposits (Holocene and late Pleistocene) Talus and mixed clast- and matrix-supported gravel with similar range of lithology and similar origin and thickness to units mapped as colluvium (Qc) and piedmont-slope deposits (Qp).

Qc Colluvium (Holocene and late Pleistocene)

Mostly moderately consolidated to unconsolidated massive to indistinctly bedded talus and slope wash with some windblown sand. Talus consists of angular to subangular pebble- to block-sized clasts with minor amounts of sand. Disoriented and loosely compacted clast arrangement in upper parts grades downslope to compacted pediment gravels with weak bedding. Color varies widely reflecting predominant colors of adjacent source rocks. Surface clasts mostly unvarnished to weakly varnished and unweathered to moderately etched. Undersides of surface clasts lack carbonate coatings in some deposits but contain coatings to 3 mm in others, especially in areas of dark volcanic rocks. Some deposits moderately cemented by calcium carbonate or salts, especially gypsum. Forms cones and aprons on many moderate slopes beneath steep escarpments, but is especially common beneath cliffs of carbonate rock such as the Lower Permian Fossil Mountain Member of the Kaibab Formation and Toroweap Formation (Pkf, Pt), Virgin Limestone Member of the Moenkopi Formation (Rmv), and the Bitter Ridge Limestone Member of the Horse Spring Formation (Thb). Many of the irregular patches are erosional remnants of once-continuous colluvial aprons or pediment gravels. Surfaces, though steep, generally lack subsidiary relief except for game trails and slumps. Thickness generally <3 m where well exposed as erosional remnants, but probably reaches several meters locally.

Qa Alluvium (Holocene to middle Pleistocene)

Mostly pale red, light brown to grayish-orange-pink, weakly lithified to unlithified, polymictic sand, gravelly sand, and gravel consisting of moderately rounded to angular clasts. Clast composition (and color) varies laterally and reflects contrasts in exposed bedrock in highland source areas. Forms piedmont-slope deposits. Most exposures of gravel reveal matrix- and clast-supported structure, indicating mixed fluvial and debris-flow origin in laterally discontinuous beds typically 3 to 20 cm thick. Proportion of gravel to sand increases and definition of bedding decreases toward bedrock source areas where deposits of equivalent age are commonly mapped as colluvium (Qc) or mixed colluvium and piedmont slope deposits (Qcp). Contacts between these mapped units are generally gradational, and placement is somewhat arbitrary. Deposits in northwest part are inset into older deposits of similar origin and composition (QTp) but contain generally larger clasts. In east-central part, extent of erosional dissection varies slightly in each deposit. Distal and medial parts of deposits tend to preserve bar and swale topography which is subdued or erosionally destroyed in proximal parts. Surfaces contain extensive rocky pavements and coarse lag accumulations that rest on a thin (<10 cm) layer of silt and sand. Underside of pavement clasts generally lack carbonate coatings or are partially mantled by incipient coatings. Soil carbonate is also inconspicuous to absent in parent materials beneath pavement, especially in distal parts of deposits. Erosional dissection and age of exposed parts

of deposits tends to increase toward source areas. Most deposits are probably latest Pleistocene and Holocene—judging from weak soil development, but proximal or buried parts may be as old as middle Pleistocene. Exposed thickness limited to a few meters, but total thickness beneath large coalesced deposits probably exceeds 10 m.

QTa Older alluvium (Pleistocene and Pliocene)

Medium to light gray to pale reddish-gray sandstone and gravel. Includes thin to thick (to 5 m) beds of medium to very coarse sand and pebbly sand and some beds of very coarse bouldery alluvium containing sandy partings. Cut-and-fill structures with fluvial cross-bedding common. Polymictic clasts are mostly moderately rounded to subangular; some well-rounded clasts may be derived from underlying sedimentary rocks (Ts). Mainly forms south-sloping, undeformed, fluvial piedmont-slope deposits that rest unconformably on erosionally truncated bedrock or faulted and folded sedimentary rocks (Ts) in south part of quadrangle. Deposits range from firmly lithified cliff-forming layers to weakly lithified slope-forming layers. Deposits are commonly more resistant to erosion than underlying sedimentary rocks (Ts). Surfaces have well developed pavements that commonly include rock-strewn calcrete and lack primary depositional morphology. The deposit probably extended as a continuous sheet throughout the Callville Bay area and is now preserved as isolated erosional remnants as much as 40 m above adjacent modern drainages. Preservation results from a resistant calcrete cap that represents the remains of well-developed (Stage IV?) caliche soil. Probably correlative with piedmont-slope deposits in the north part of the quadrangle (QTp). Thickness to 15 m.

QTp Older piedmont-slope deposits (Pleistocene and Pliocene)

Mostly pale reddish-gray to grayish-orange-pink, weakly to moderately lithified boulder-bearing, mixed clast-supported and matrix-supported polymictic gravel with minor amounts of sand. These deposits cap interfluvial ridges and areas in the north part of quadrangle where they represent erosional remnants of a once-continuous, thin (<10 m) sheet of alluvium deposited as debris flows and sheetwash atop erosionally planated faulted and folded bedrock along the south margin of the Muddy Mountains. Upper surfaces that stand as much as 25 m above modern drainages are dominated by pavements and eroded channels, but inconspicuous remnants of debris-flow levees are present. Remnants of an advanced (stage IV?) calcrete soil as much as 1.5 m thick cap many of the ridges and impart a relatively high albedo to the deposits. Probably correlative with older alluvium (QTa) in south part of quadrangle. Thickness 0 to 10 m.

Basin-Fill Deposits (Pliocene and Miocene) The central and southern parts of the Callville Bay Quadrangle contain three main map units that represent syntectonic clastic deposition in coeval small basins that post-date the broader basins in which the Horse Spring Formation was

deposited. Two are partly coeval young units (Ts and Tmc) that postdate major volcanism in the area. Unit Tmc is the Muddy Creek Formation of Longwell and others (1965). The third unit, the red sandstone unit (Trs) of Bohannon (1984), represents synvolcanic and possibly some post-volcanic deposition (Duebendorfer and Wallin, 1991). Some basin-fill clastic strata (Tcc) partly equivalent in stratigraphic position to the red sandstone unit (Trs) are interstratified with locally derived volcanic units and are mapped as part of the volcanic assemblages.

Discrimination of red sandstone strata from clastic strata of the Thumb Member of the Horse Spring Formation is especially problematic in the south part of the quadrangle where the intervening Bitter Ridge Limestone and Lovell Wash Members of the Horse Spring Formation are not found. Criteria used for assigning strata to the red sandstone unit include basal unconformities and presence of clasts of Bitter Ridge Limestone Member and/or volcanic rocks. A criterion used for identifying Thumb Member is the presence of clasts of crystalline basement rock. These criteria are applied arbitrarily in the south part of the quadrangle where discriminations between red sandstone unit and Thumb Member (Tht) are uncertain.

Ts Post-volcanic basin-fill deposits (Pliocene and upper Miocene)

Varicolored heterolithic assemblage of sand and gravel with minor siltstone and claystone. Weakly to very weakly indurated, fluvial sand and gravel consisting of angular to subangular clasts of mostly volcanic rocks. Sand is more abundant than gravel and is generally well sorted and quartz rich, forming bedsets to 2 m, some separated by reddish-gray silty or clayey layers to 5 cm. Near the contact with mainstream gravel (QTrg), the unit includes beds of roundstone gravel and well-sorted sand probably representing intercalation with mainstream deposition. In road cuts along the Callville Bay access road the unit includes tilted and faulted beds of very pale brown, conspicuously cross-bedded, unlithified, well-sorted sand and pebbly sand and moderate red indistinctly bedded sand containing suspended angular pebbles and cobbles of locally derived volcanic rocks. The cross-bedded well-sorted sand and the strongly bimodal deposits of sand and angular cobbles probably formed by fluvial remobilization of eolian sand and local mixing with coarse volcanic-clast colluvium. As noted above, early beds in the various depocenters may correlate with the Muddy Creek Formation. Thickness varies from zero to an estimated 100 m.

Tmc Muddy Creek Formation (Miocene) Mainly gravel and sand accumulated in five depocenters to thicknesses that probably approach a few hundred meters in the deep central parts: 1. North-trending synclinal depocenter northeast of Callville Bay contains a fining-upward sequence of gravel (~20 m), sand (~20 m), and evaporite (~5 m). Gravel is approximately conformable with underlying volcanic rocks and is clast- and matrix-supported, bouldery, and consists mostly of angular to sub-rounded

clasts of volcanic rock interbedded with very coarse sand in lower part. Sand is parallel-bedded, mostly very coarse, and contains beds of siltstone a few centimeters thick in middle part. Evaporite is pale pinkish-gray parallel-bedded gypsum and gypsiferous mudstone. 2. East-trending synclinal depocenter along the west quadrangle margin contains mostly very pale orange to grayish-orange-pink polymictic weakly lithified fluvial gravel and sand composed mostly of angular to moderately rounded Paleozoic limestone clasts but including clasts of Tertiary limestone (Thb) and mafic volcanic rock (Tcv). Basal part includes thin (<3 m) pale reddish-gray sandy lacustrine mudstone and limestone. Beds along south margin of depocenter appear concordant with underlying gently north-dipping volcanic rocks (Tcv₄), but along the north margin they appear buttressed against layers of those volcanics that dip steeply south. 3. Depocenter between West End and Callville washes contains gravel similar to that to the west, but volcanic clasts are abundant in the lower part and carbonate clasts (mainly Paleozoic rocks) in the upper part. Also, beds along the north margin are concordant with underlying moderate (40–55°) south-tilted older rocks, whereas in the south, more gently north dipping beds are discordant with south-dipping older rocks, the opposite relation to that seen in the depocenter to the west. 4. Depocenter north of Hamblin Mountain contains mainly gray to pale reddish-gray, coarse moderately well bedded debris-flow gravel consisting of clasts of variegated volcanic rocks. The beds are horizontal in the south, but are flexed sharply at the north margin, probably resulting from syndepositional faulting. 5. Depocenter northwest of Callville Bay contains lithologically variable but mostly light-gray to grayish-pink, moderately to weakly cemented, primarily fluvial gravel and coarse sand, mostly as partings but locally forming meter-thick beds. Clasts consist of angular to moderately rounded variegated Paleozoic, Mesozoic and Tertiary rocks probably derived from source areas to the north in the Gale Hills and Muddy Mountains. Where these deposits are buttressed against or bury topography formed on underlying volcanic rocks, they generally consist of predominantly angular locally derived volcanic detritus and are conspicuously darker in color, commonly grayish-red purple to grayish-purple. Deposits contain fanning-upward dip patterns, internal folds, and unconformities recording syndepositional deformation.

Trs Red sandstone unit (Miocene) Basin-fill clastic and evaporitic rocks, chiefly sandstone, siltstone, gravel, gypsiferous sandstone and mudstone, and gypsum. Bohannon (1984) defined an informal rock unit in the Lake Mead area consisting predominantly of sandstone rhythmically interbedded with siltstone and claystone as the red sandstone unit and interpreted the depositional setting as primarily basinal (mainly playa) with local fault-front alluvial fan lithofacies. Duebendorfer and Wallin (1991) expanded the distribution and lithofacies and established the synvolcanic and basin-tectonic significance of the unit throughout the western Lake Mead area, including the west-central part of

the Callville Bay Quadrangle. As mapped here, the red sandstone unit includes basin-fill strata of highly variable lithology much of which is conglomeratic and dissimilar to the rhythmically bedded strata described by Bohannon (1984). Correlation is highly problematic because deposition occurred syntectonically in separate depocenters similar to those that received the younger basin fill (Ts, Tmc). Also, tuffs capable of yielding radiometric ages are generally absent.

The main band of discontinuous exposures along the North Shore Road consists of faulted and folded pale red to moderate orange-pink variegated conglomerate, sandstone, siltstone, and gypsum that rest mostly unconformably on older tilted strata. Locally these deposits are rich in clasts of the directly underlying rock. To the west, the northern band of exposures along West End Wash (Sec. 20, T20S, R65E) consists mostly of conglomerate that represents accumulation in a small east-west depocenter. At the north margin of the depocenter, steeply south dipping conglomerate containing abundant clasts of Bitter Ridge Limestone Member (Thb) is overridden along a reverse fault by moderately south-dipping beds of the Bitter Ridge Limestone Member. Along the south margin, steeply north dipping conglomerate rich in clasts of Triassic mudstone are cut by strike slip and reverse faults that place them in contact with mudstone of the Triassic Moenkopi Formation. At the east margin of the depocenter, sandstone and conglomerate, locally with clasts of Bitter Ridge Limestone as large as 3 m, is deposited unconformably on and faulted against beds of Lovell Wash Member (not shown on map) and Bitter Ridge Limestone Member. These structural and lithologic associations suggest clast derivation from directly adjacent fault-bounded highlands. If the basin and its bounding faults have not been rotated around steep axes, deposition in a structurally controlled east-west depocenter is indicated.

South of the narrow band of Moenkopi Formation along West End Wash, red sandstone strata consist of coarse conglomerate in the upper and lower parts and moderate orange-pink sandstone, silty sandstone, and siltstone in the middle part. Clasts of Paleozoic rocks and Cenozoic limestone (Thb) were derived from sources to the north as indicated by paleocurrent directions (Çakir and others, 1998). These beds are probably younger than the red sandstone beds directly to the north and were probably deposited in a separate east-west depocenter. At their northernmost part, they rest on an erosionally truncated anticline (not apparent on map) formed in red mudstones of the Moenkopi Formation. That anticline probably reflects uplift at the south margin of the slightly older depocenter directly north (described in previous paragraph). Thickness ranges from 0 to ~500 m.

Unit is correlative, in part, with volcanic and interstratified clastic sedimentary rocks informally referred to as Callville volcanics (Duebendorfer and Wallin, 1991). The Callville volcanics have yielded ages ranging from 11.41 ± 0.14 Ma (Harlan and others, 1998) to about 8.5 Ma (Feuerbach and others, 1991), and an air-fall ash from within 50 m of the base of the red sandstone unit yielded an age of

11.10 ± 0.08 Ma (Harlan and others, 1998). Tentatively mapped as red sandstone unit are sandstone, mudstone, gypsiferous mudstone, tuffaceous sandstone, and bedded gypsum interstratified with upper units of the volcanic rocks of Hamblin Mountain (Tvv, Tvv₃) east of Callville Bay and west of Hamblin Mountain. The uppermost flow in the thick volcanic pile at Hamblin Mountain yielded an ⁴⁰Ar/³⁹Ar age of 10.06 Ma (sample 11-714-71, Anderson and others, 1994), consistent with this choice to map the mudstones and gypsum interstratified with upper flows of that volcanic pile as red sandstone unit.

Trsl Landslide and debris-flow deposits (Miocene)

Massive medium gray landslide breccia interstratified with indistinctly bedded medium gray debris-flow deposits north of southwest corner of quadrangle (SW¹/₄ Sec. 8, T21S,R65E). Most breccia is monolithic consisting of porphyritic granodiorite of probable Miocene age. Enclosing sediments (Trs) are fine-grained and commonly gypsiferous, indicating sliding from steep bedrock into an adjacent evaporitic depocenter. Nearby landslide masses (Thl) are enclosed in similar sediments, but consist of Proterozoic crystalline rocks. These laterally abrupt contrasts in lithology probably record active oblique slip on the Hamblin Bay fault separating the depocenters from highlands on the south. Stratigraphic assignment of the enclosing sediments to the red sandstone unit and Thumb Member in this area is highly uncertain and based mainly on the composition of the enclosed landslide masses. Forms pods to 200 m thick.

Horse Spring Formation (Miocene) Lithologically variable continental sedimentary rocks overlying Paleozoic and Mesozoic rocks conformably or with slight angular discordance. Strata record multiphase history of basin development that progressed from a single broad sag basin to more restricted fault-bounded partially connected to unconnected basins (Anderson, 1973; Bohannon, 1984; Beard, 1996; Duebendorfer and others, 1998). Unit named by Longwell (1921, 1922) for exposures in the southern Virgin Mountains, Nevada and redefined and subdivided by Bohannon (1984) on the basis of studies that included the Callville Bay Quadrangle. Subdivided into four members (descending): Lovell Wash (Thl, type area in north-central Callville Bay Quadrangle), Bitter Ridge Limestone (Thb), Thumb (Tht), and Rainbow Gardens (Thr), and several mapped lithofacies. All four members exhibit large thickness variations, but the Thumb Member also has major lateral variations in lithofacies and mode of deposition. Detailed stratigraphic studies have not been made in this quadrangle, so the structural/tectonic significance of the variations is not fully appreciated.

Th Horse Spring Formation, undivided Unit mapped directly north of Callville Bay consists mostly of red clastic rocks somewhat resembling the Thumb

Member but includes small amounts of silty and sandy limestone and some tuffaceous rocks possibly equivalent to the Bitter Ridge Limestone and Lovell Wash Members. On the basis of clasts of andesite, some beds probably belong to the red sandstone unit (Trs). Thus, stratigraphic equivalency of these rocks is uncertain.

Thl Lovell Wash Member Mostly light gray to pale yellowish-gray limestone and dolomite, light gray and pinkish-gray claystone, and gray to pale greenish-gray bedded tuff, tuffaceous sandstone, and sandstone. Forms whitish areas conspicuous in the landscape and on aerial photos. Named for very well exposed section along Lovell Wash directly north of the center of quadrangle (Bohannon, 1984), where strata are well exposed in the Lovell Wash syncline (cross section D–D'). That area includes an abrupt local lateral gradation to a conglomeratic lithofacies (patterned on map and cross section D–D') that records basin-margin faulting (Bohannon, 1984; Çakir and others, 1998). Most limestone is medium to thin bedded and interbedded with claystone and calcareous mudstone, but the unit includes thick-bedded limestone similar to that which typifies the Bitter Ridge Limestone Member (Thb). Includes laminated “eggshell” stromatolitic beds and mounds of limestone or chert as well as parallel-bedded algal limestone and lithographic limestone. Also includes beds and bedsets of parallel-bedded tuffaceous and nontuffaceous sandstone ranging to tens of meters thick with common internal cross-bedding and locally containing interbeds of pebbly sandstone and gravel. Strata mapped as Lovell Wash Member across Callville Wash south of quadrangle center (Sec. 26, T21S,R65E) are atypical, consisting mostly of well-bedded reddish-gray calcareous sandstone with minor biotite-bearing light-gray tuffaceous sandstone at base. Assignment of these strata to the Lovell Wash Member is speculative.

Strata mapped as Lovell Wash Member along east quadrangle boundary east of Hamblin Mountain consist of a few tens of meters of gray to yellowish-gray sandstone, tuffaceous sandstone, and siltstone overlain by a similar thickness of dark grayish-red-purple volcanoclastic coarse-grained, poorly sorted sandstone and fluvial gravel rich in clasts of basaltic andesite to 10 cm. These beds underlie the volcanic rocks of Hamblin Mountain (Tvv), documenting earlier mafic volcanic activity in the area. To the southeast, beyond the quadrangle boundary, these and variegated overlying(?) limy gypsiferous lithofacies are interstratified with and intruded by igneous rocks related to the Hamblin-Cleopatra volcano, showing that early construction of the volcano is, probably, of Lovell Wash age. Some of these rocks, serving as screens for abundant dikes along the Hamblin Bay fault, are mapped and described with the intrusive rocks (Tihl).

Radiometric ages are reported from a variety of materials: fission-track age of 13.0 ± 0.8 Ma (Bohannon,

1984); $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 13.12 ± 0.24 Ma on plagioclase; 13.40 ± 0.05 Ma on biotite; 13.12 ± 0.12 Ma on hornblende (C. Henry, pers. commun. 1997); and $^{40}\text{Ar}/^{39}\text{Ar}$ age of 13.17 ± 10 Ma on whole-rock basalt (Harlan and others, 1998). Thickness probably ranges to 500 m, with the maximum in the center of the Lovell Wash syncline.

Thb Bitter Ridge Limestone Member Mostly pale yellowish-brown to pale yellowish-gray stromatolitic lacustrine limestone. Limestone is crystalline and porous with bedsets typically 15 to 80 cm thick containing wavy internal continuous to discontinuous laminations. Other sedimentary structures are described and illustrated by Bohannon (1984). Along Lovell Wash north of the quadrangle center, it includes a sandstone and mudstone facies as much as 110 m thick in its upper part. That interval includes varicolored reddish- yellowish- and orange-gray sandstone, pale lavender limestone, and pale greenish-yellow silty limestone. Also in that area, the limestone lithofacies grades laterally through an assemblage of thinly laminated mudstone, limy mudstone and conglomerate to a conglomeratic lithofacies that records basin-margin faulting (patterned on map and cross section D–D') (Bohannon, 1984). Thickness as much as 350 m.

Tht Thumb Member Mostly pale red to moderate reddish-brown sandstone and gray to pale reddish-gray conglomerate (locally mapped separately as Thtc), but includes widespread minor limestone and arenaceous limestone, reddish siltstone and mudstone, and light gray to pale red gypsum and gypsiferous mudstone (locally mapped separately as Thtg and Thtm). Unit is probably mostly lacustrine, but mixed fluvial and debris-flow lithofacies are common and may represent medial to distal alluvial fan settings. Most deposition was in a complex system of partially connected basins as lacustrine and marginal lacustrine facies (Beard, 1996). Ratio of sandstone to conglomerate estimated by Bohannon (1984) to be 4:1, but the ratio varies abruptly across major faults, especially in the Callville Bay Quadrangle where the variations are juxtaposed by faults and thus predate faulting. Sandstone is mostly moderately to poorly sorted, fine- to coarse-grained, and typically forms parallel beds 5 to 50 cm thick. Lenticular, uneven, to discontinuous bedding is common, especially where sandstone is coarse or interbedded with conglomerate. Conglomerate is similar to that described under conglomerate lithofacies (Thtc). Much of the siltstone and mudstone is found transitional to or interbedded with gypsiferous lithofacies, but some is interbedded with sandstone. Evaporites are similar to those described under gypsiferous lithofacies (Thtg, Thtm). Sparse discontinuous beds of dove-gray or pale reddish-gray limestone and arenaceous limestone are widely distributed, but in the upper part transitional to the overlying Bitter Ridge Limestone Member, limestone

is common. Sparse pale greenish-gray tuff beds to about 2 m are widely distributed.

In the central north part (Lovell Wash block, fig. 1), the Thumb Member is chiefly reddish sandstone and siltstone overlain at the south by conspicuously thick sections of Bitter Ridge (Thb) and Lovell Wash (Thl) Members. Upper 30–40 m is a calcareous/siliciclastic lithofacies transitional to the overlying Bitter Ridge Limestone Member. It consists of resistant color-banded pale yellowish-gray and pale reddish-gray limestone and arenaceous limestone. Beneath the limy zone, is about 150 m of pale red to moderate-reddish-brown sandstone siltstone and mudstone interbedded with minor light gray to grayish-orange-pink limestone and calcareous sandstone, siltstone, and mudstone and very minor pebbly gravel containing clasts of moderately rounded Paleozoic and Mesozoic rocks. Beneath that is a layer of gypsiferous mudstone 50 to 150 m thick (mapped separately, Thtm). These varied lithologies form the upper part of a thick (>300 m) folded and faulted but generally south- to southeast-dipping section of predominantly reddish, fine to very coarse, mostly flat-bedded sandstone and silty sandstone. This rather monotonous sandstone sequence contains sparse massive beds to 20 m of sandy mudstone containing sparse suspended clasts. The section includes conspicuously little conglomerate. Minor lag concentrations of moderately rounded pebbles and cobbles of Proterozoic crystalline rocks and lower Paleozoic carbonate rocks, which presumably represent thin conglomeratic beds or clast trains, are found about 30 m below the gypsiferous mudstone (Thtg). The source of these clasts is not known, but because they include crystalline basement rocks, they probably were not derived from the north where exposures of such rocks are unknown. These distinctly fine-grained Thumb Member strata continue beyond the north quadrangle boundary, possibly reaching a total thickness in excess of 1 km.

In northwest part (West End block, fig. 1), unit is overlain at the south by relatively thin Bitter Ridge Limestone Member (Thb) and little, if any, Lovell Wash Member (Thl). This section is very different from that in the adjacent Lovell Wash block. It lacks a gypsiferous interval high in the section, contains abundant fluvial conglomerate with a north-derived clast assemblage (mostly mapped separately as Thtc), contains a thick layer of gypsum low in the section (Thtg), and the base is widely exposed as a resistant, cliff-forming conglomerate resting on light-colored Cretaceous sandstone (Kb) (see cross section A–A'). The gypsum (Thtg) and basal conglomerate (Thtc) were mapped previously with the Rainbow Gardens Member (Bohannon, 1984) but are mapped here with the Thumb Member because locally the conglomerate grades laterally through arenaceous limestone into finer-grained clastic rocks that include beds of greenish tuff similar to those in the Thumb. Also, they rest on landslide masses

that appear to be underlain by Thumb strata (not shown on map). The basal conglomerate may be a time-transgressive lithofacies. With the exception of the basal conglomerate, the stratigraphic position of conglomerate differs within the West End block. In general, conglomerate increases in abundance and coarseness northward.

Thumb Member strata in the northeast part of map represent the southwestern extreme of the large Bitter Spring Valley block (fig. 1). These strata are much more similar to those in the West End block than in the Lovell Wash block separating them. In particular, fluvial conglomerate with a north-derived clast assemblage is abundant, and, beyond the quadrangle boundary, the basal conglomerate and overlying gypsum beds are very similar to those in the West End block. Also, the basal conglomerate rests on Cretaceous rocks in both blocks.

Strata in the southwest part of map are mostly moderately indurated, moderate-orange-pink, silty and gypsiferous sandstone and gypsum with sparse

conglomerate with common clasts of crystalline basement rocks. They enclose map-scale masses of crystalline-rock landslide megabreccias (Thtl, Er) as do the undifferentiated Horse Spring strata (Th) in the southwest area. As with the red sandstone unit in that area (Trs), correlation with strata elsewhere in the quadrangle is very tenuous, in part because overlying members of the Horse Spring Formation are absent.

Bohannon (1984) reported a fission-track apatite age of 13.2 Ma and a whole-rock K/Ar age of 17.2 Ma for the Thumb Member. Faults and folds preclude accurate estimates of thickness in the West End and Bitter Spring Valley blocks, but thickness probably exceeds 500 m.

Thtm Gypsiferous mudstone lithofacies

Mainly reddish-gray mudstone interbedded with light-gray gypsum and gypsiferous mudstone.

Thtg Gypsum lithofacies

Mainly light gray to pale reddish-gray gypsum and gypsiferous mudstone,

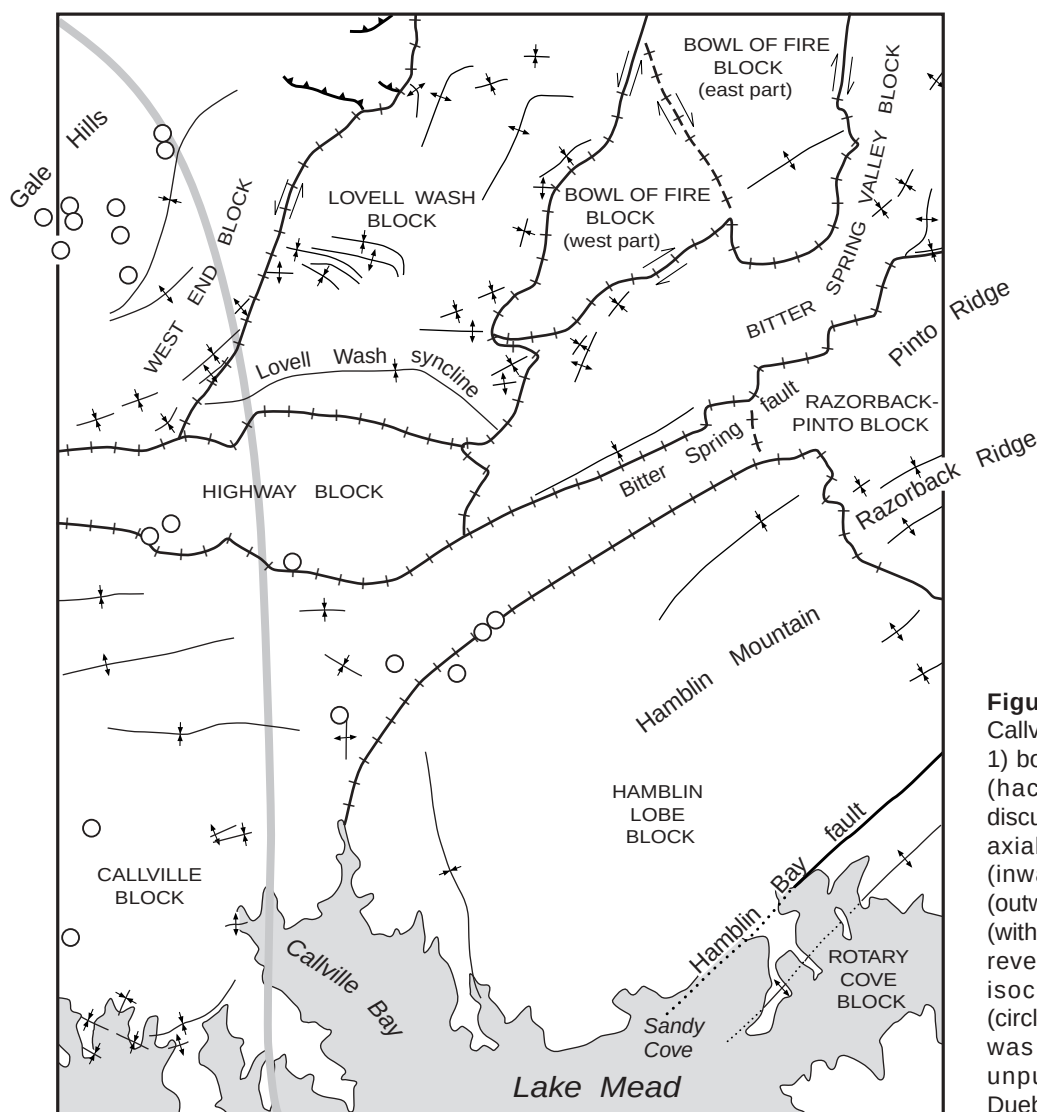


Figure 1. Tectonic map of the Callville Bay Quadrangle showing: 1) boundaries of structural blocks (hachured lines, all faults) discussed in text, 2) distribution of axial-plane traces of synclines (inward arrows) and anticlines (outward arrows), 3) thrust faults (with teeth), and 4) localities where reverse faults or outcrop-scale isoclinal folds are exposed (circles). Area west of shaded line was adapted, in part, from unpublished mapping by E. Duebendorfer.

mostly with indistinct, irregular, or contorted bedding but locally finely laminated. Unit low in section in northwest part contains conspicuously less mudstone than unit high in section in central-north part.

Thtc Conglomerate lithofacies Mostly pinkish-gray to grayish-pink; where content of Mesozoic rock is high, pale red to pale reddish-brown. Polymictic with angular to rounded clasts ranging to boulders and blocks in some beds and consisting primarily of clasts of gray Paleozoic carbonate rocks and lesser reddish Mesozoic clastic rocks in a sand and silt matrix. Most is mixture of matrix-supported and clast-supported lithologies but varies widely. Forms layers and lenses that are slightly to strongly resistant to erosion compared with enclosing sandstone (Tht). Bedding ranges from weak to distinct and is defined by grain-size contrasts or sandstone partings. Exposures of debris flows tend to have a flatter and more distinct layering than fluvial conglomerate, which tend to have discontinuous and non-uniform layering resulting from channel deposition. The broad concave-north band of south-to southeast-dipping conglomerate in central part (Secs. 24, 26, 27, T20S,R65E) is uniformly coarse with common boulders and blocks possibly indicating a fault front depositional environment. If so, the fault-bounded highlands were located directly to the north, assuming no post-depositional steep-axis rotation. As illustrated in cross section (C–C'), the conglomerate (Thtc) probably grades within a few hundred meters down dip into finer grained facies (Tht). Conglomerate that forms base of section is generally distinctive in its very strong induration (cliff-forming habit), its darkish-brown weathering habit, and its strong resemblance to conglomerate at base of Rainbow Gardens Member (Thrc).

In northwestern part of quadrangle, two thick (>200 m) layers of gray coarse to very coarse conglomerate of mainly debris-flow origin are separated by about 150 m of variegated, interstratified, moderate-reddish-orange sandstone, calcareous sandstone and mudstone, conglomerate, and minor beds of yellowish-gray silty and sandy limestone. The finer-grained rocks (Tht) probably thin northward into the massive uniform fault-front conglomerate lithofacies described by Bohannon (1984) as deposited syntectonically against the Gale Hills fault. Thickness of conglomerate layers ranges to >300 m.

Thtl Landslide blocks and megabreccia Mostly gray irregularly shaped pods or lenses of either crackled blocks exhibiting remnants of internal structure or disaggregated megabreccia. Composition of chief parent rock given in parentheses. Masses in central and south part composed of crystalline

basement rock (Thtl (Pr)) presumably derived from southern sources, those in northwest part composed of Paleozoic rock (Thtl (Pz)) presumably derived from northern sources. Masses enclosed in undifferentiated Horse Spring Formation (Th) in area north of Callville Bay are shown with the same symbol as those in the Thumb Member (Tht). Those masses contain gneiss with garnet retrograded to chlorite whereas minor interstratified gravel contains garnetiferous gneiss and megacrystic granite. This contrast may record landslide blocks derived from proximal exposures (such as those low in the Gold Butte structural block) and deposition of clastic interbeds derived from more distal sources (such as those high in the Gold Butte block) (Fitzgerald and others, 1991; Duebendorfer and others, 1998). Age mostly uncertain because masses generally found in disrupted zones and not in well-organized stratigraphic assemblages. Some of the undivided Horse Spring sediments (Th) enclosing the landslides contain volcanic clasts, possibly indicating a stratigraphic position as high as the red sandstone unit (Trs).

Thr Rainbow Gardens Member Conglomerate, sandstone, siltstone, gypsum, mudstone, and limestone. In central-west part where North Shore Road crosses West End Wash, Lower Jurassic Aztec Sandstone is overlain by an incomplete section of about 30 m of variegated strata consisting of interstratified pale yellowish-orange limestone and sandy limestone and grayish-red limy siltstone, sandstone, and conglomerate overlying a highly lithified reddish-gray basal conglomerate (mapped separately as Thrc). Some limestone beds contain common calcified root tubes or nodular textures typical of Rainbow Gardens elsewhere. Similar strata are found overlying rocks of the Chinle Formation in the central-east part, although there they are strongly folded and faulted with local abrupt structural thinning of sections. In northeast part, the basal conglomerate (Thrc) is overlain by laterally variable sections that range from limestone-dominated to gypsum-dominated. Limestone-dominated sections include limestone, arenaceous limestone, and limy conglomerate, sandstone, and siltstone. Gypsum-dominated sections are mostly light gray to pale red gypsum and gypsiferous mudstone and resemble those mapped at the base of the Thumb Member in northwest part, raising questions about correlation. Thickness is highly variable, 0 to 130 m.

Thrc Conglomerate lithofacies Strongly carbonate-cemented, highly resistant, reddish(gray, indistinctly bedded, clast-supported conglomerate that weathers to a conspicuous dark brown. Discontinuous grayish-red sandstone partings produce indistinct bedding. Clasts are mainly

Paleozoic carbonate rock and Mesozoic clastic rock. Generally forms well-defined marker horizon at base of Tertiary section, but similar resistant conglomerate is found at higher stratigraphic levels in the Thumb Member. Thickness 20 to 50 m.

Strata along Hamblin Bay fault in southeast part of map are mostly medium- to dark-gray, coarse to extremely coarse debris-flow breccia containing sparse beds of coarse calcareous sandstone and gritstone containing sparse pebbles and granules of Paleozoic rocks. Breccia clasts are angular and set in a dark-gray ferruginous matrix. These sedimentary rocks are altered, hornfelsed, and highly indurated by intrusion of the Wilson Ridge pluton (Tw). The lower part of the breccia is conspicuously heterolithic consisting of megacrystic granite, garnetiferous granite and gneiss, biotite-rich retrograded amphibolite(?), and biotite schist. The upper part is conspicuously monolithic composed typically of 95% megacrystic granite and locally exclusively of such granite. According to E. Duebendorfer (oral commun., 1991), the assemblage of gneiss clasts does not match that of bedrock in the Gold Butte area of widely exposed crystalline basement, and the source was probably in the northern Black Mountains. Thickness uncertain because of inflation by intrusive rocks, but may be 150 m, possibly increasing to 500 m eastward into the Boulder Canyon Quadrangle.

Volcanic and Intrusive Rocks and Associated Sedimentary Rocks (Miocene)

The southern part of the quadrangle contains the north extreme of a broad region commonly referred to as the Colorado River extensional corridor (Howard and John, 1987) in which Tertiary rocks are primarily igneous in contrast to areas to the north where they are primarily sedimentary (Anderson, 1973). Three main igneous assemblages are recognized; volcanic rocks of Callville Mesa (Duebendorfer and Wallin, 1991), volcanic rocks of Hamblin Mountain, and intrusive rocks. Along the shores of Lake Mead in the southeast part of map, steep terrain provides excellent exposure of a small part of the large (~200 km²) Wilson Ridge pluton intruded into basement rocks, Paleozoic cover rocks, and Tertiary sedimentary rocks (Anderson and others, 1994). On the northwest side of the Hamblin Bay fault lies the lobate northwest part of a volcano (the Hamblin-Cleopatra volcano). The Hamblin lobe was structurally translated into the area by about 20 km of left-slip displacement (Anderson, 1973). To the west of the Hamblin lobe are widely exposed volcanic rocks interpreted as eruptives from vents satellite to the Hamblin-Cleopatra volcano (Feuerbach and others, 1991). They are referred to as the volcanic rocks of Callville Mesa after Duebendorfer and Wallin (1991) who noted that they are interstratified with the red sandstone unit (Trs). The locations of published radiometric ages are noted on the map.

Intrusive rocks

Intrusive rocks of the Wilson Ridge pluton (Tw) are distinguished from less extensive dikes and plugs (Ti). An area of intensely intruded sedimentary rock along the Hamblin Bay fault is mapped separately (Tihl). Dikes in the Hamblin lobe are not labeled, but numerous attitude symbols give their general trend.

Tw Wilson Ridge pluton Mostly dikes with deuteric alteration ranging widely in color from light gray to dark gray, in composition from mafic to siliceous, and in texture from aphanitic to phaneritic and porphyritic to non porphyritic, representing a conspicuously composite pluton. Typically the volumetric ratio of siliceous to mafic dikes is 20:1. Siliceous dikes (rhyolite, quartz latite, and rhyodacite) are generally older and wider than mafic varieties, ranging up to 250 m in width, but averaging about 20 m. Width of intermediate to mafic dikes (dacite, andesite and basalt) ranges up to about 20 m, but averages about 2 m. They can form complex anastomosing or crosscutting patterns and in rare cases are cut by siliceous dikes. In most areas dikes are arranged in parallel form creating a conspicuous color-layered and erosion-etched landscape that tends to be enhanced by the effects of alteration where a variety of pastel colors mark the siliceous dikes and drab olive-gray colors mark the mafic dikes. Phaneritic intrusions range from medium- to coarse-grained leucocratic granite through monzonite and granodiorite to diorite, and commonly have steep walls and dike-like forms. They are most common in the vicinity of Bighorn Cove and on the islands to the southwest. Secondary hematite and barite are common, and some concentrations have been prospected. Disseminated pyrite is common and is found in a variety of gray rocks that otherwise appear unaltered, but in thin section show extensive deuteric alteration. Large areas have been attacked by oxidizing fluids, which caused widespread bleaching and production of secondary gypsum. The area in Arizona contains a small percent of unmapped, unfoliated coarse-grained leucocratic granite that could be either Tertiary or Proterozoic as well as hornfelsed sedimentary rocks (possibly Thumb Member) with secondary hematite and barite. These are intruded by abundant dikes typical of the full range of lithologic variation seen elsewhere in the pluton, but including a siliceous variety with sparse but conspicuous large feldspar euhedra to 2 cm. Triangle pattern marks breccia in hanging wall of large fault and along Hamblin Bay fault. K/Ar ages from the deep south part of the pluton (beyond map) cluster at 13.4 Ma whereas ⁴⁰Ar/³⁹Ar ages from the shallow north part (represented by area in map) cluster at 12.5 Ma (Anderson and others, 1994). The young ages probably represent alteration history more than emplacement history.

Trih Pendants and xenoliths Small pendants and xenoliths in the Wilson Ridge pluton of varied hornfelsed rocks including breccia of megacrystic granite, sandstone

and calcareous sandstone probably representing the Thumb Member, and limestone, marble, and spotted schist representing metamorphosed lower Paleozoic strata. Only larger of numerous masses are mapped.

Ti Dikes, sills, and plugs Mostly medium to dark gray or dark reddish-brown weakly porphyritic andesite and dacite and equivalent phaneritic equigranular rocks. Some dikes have sparse megacrysts of hornblende, especially in the Hamblin lobe block (fig. 1) where they mark feeders for similar flows. Plagioclase is the most common phenocryst; potassium feldspar is uncommon, even in quartz-bearing rocks. Mafic phenocryst assemblages vary widely; augite and hornblende generally dominate in various proportions, but biotite is common and, in some siliceous rocks, it is the only mafic silicate mineral. Most rocks are deuterically altered with corroded feldspar and replaced mafic silicates. Masses northeast of Callville Marina are mostly sills. The large plug directly east of the quadrangle center was formerly mapped as volcanic rock (Anderson, 1973). It consists of a deuterically altered plagioclase-rich porphyritic dacite with biotite as the only unaltered mafic silicate.

Tihl Intruded sedimentary rocks Mostly blocks and layers of variegated sedimentary rocks probably correlative with the Lovell Wash Member (Thl), but includes brecciated masses of megacrystic granite that may correlate with those in the Thumb Member (Tht). Extensively intruded by dikes and plugs of mainly andesitic composition.

Volcanic rocks of Callville Mesa

Mostly basaltic andesite and basalt with some andesite; forms compound volcanic centers west of, and possibly satellitic to, the Hamblin-Cleopatra volcano (Feuerbach and others, 1991). Divided into four map units (Tcv₄, Tcv₃, Tcv₂, and Tcv₁), but locally undivided (Tcv). Interstratified coarse-grained sedimentary breccia is mapped separately (Tcc). No petrographic study was made of these rocks, but, on average, they appear more mafic than the predominantly andesitic and dacitic volcanic rocks of Hamblin Mountain to which they are partly equivalent in age and partly younger.

Tcv Volcanic rocks of Callville Mesa, undivided Mostly mafic lava and flow breccia in small exposures near Callville Bay and along the North Shore Road. Stratigraphic position relative to the main Callville Mesa volcanic pile is uncertain. Northeast of Callville Marina, steeply southeast dipping grayish-black basalt flows, each about 10 m thick, are interstratified with gray volcanoclastic sediments. Directly south of Callville Marina, rocks are mostly uniformly phenocryst-poor medium gray basaltic andesite breccia with minor volcanoclastic breccia and conspicuously phenocrystic andesite, all cut by mafic dikes. That area may represent a small volcanic center. Directly west and northwest of

Callville Marina, lithologically varied gray and reddish-gray phenocrystic andesite, medium to blackish-gray basalt and basaltic andesite flows and flow breccia form a structurally complex area in which the volcanic rocks are in confusing relationship to enclosing and interstratified sediments. Rocks along North Shore Road are mostly dark gray massive to autobrecciated and vesicular basaltic andesite and basalt flows that partially form the synclinal floors of two small east-trending sedimentary basins (Tmc).

Tcv₄ Basalt Mostly grayish-black to medium-gray, massive to vesicular basalt and basaltic andesite flows and flow breccias forming the mostly weakly deformed upper carapace of the Callville volcanics. Ranges from a single flow to eight or more flows. Slump and slide structures common along south margin. Age of about 11.1 Ma determined from K/Ar whole-rock analysis of basalt from Callville Mesa directly west of quadrangle boundary by Anderson and others (1972) and about 8.5 Ma on plagioclase separates by Feuerbach and others (1991). Anderson and others (1994) reported an ⁴⁰Ar/³⁹Ar age of about 10.05 Ma for an olivine-pyroxene basalt flow directly below a thin sequence of red sandstone beds about 1 km north of Callville Marina (sample 12-799-11 on map). Maximum thickness is about 60 m.

Tcv₃ Basaltic andesite Medium gray, brownish-gray, and dusky-red, flow brecciated to massive basaltic andesite and basalt. Mostly unconformable on early Callville Mesa strata (Tcc, Tcv₂). Subcircular area of exposures in central-west part of quadrangle west of West End Wash (Secs. 28, 29, 32, 33, T20S, R65E) marks a volcanic center where about 8 thin flows of mineralogically uniform basaltic andesite dip outward from a central arch. Flows are reddish-gray, sparsely porphyritic, weakly vesicular and faintly flow layered in interiors and brick-red and scoriaceous at margins. Some are separated by zones of breccia containing volcanic bombs. Thickness along West End Wash ranges to about 80 m.

Tcv₂ Basaltic andesite Flow brecciated gray to brownish-gray flows in part sandwiched between moderately to steeply dipping bouldery volcanoclastic conglomerate (Tcc) along a small wash tributary to Callville Wash. Thickness 0 to 220 m.

Tcc Conglomerate Mostly somber-gray to pale-reddish-gray, moderately lithified, mostly bouldery to blocky (to 2.5 m), poorly sorted, well-bedded, clast-supported conglomerate with coarse sandstone partings. Includes some matrix-supported debris flows. Clasts are variegated angular to moderately rounded andesite and basaltic andesite, but includes limestone, crystalline basement, and sparse tuff. Lowest beds are intercalated conformably with lower volcanic rocks (Tcv₁, Tcv₂) and are overlain unconformably by a middle sequence which

is, in turn, overlain unconformably by young volcanics (Tcv₃, Tcv₄), showing synvolcanic deformation, erosion, and sedimentation. Probably in part equivalent to red sandstone unit (Trs), but mapped with the volcanic pile to emphasize syngenetic and syntectonic significance. Mainly exposed west of conspicuous concave-west horseshoe bend in Callville Wash (Secs. 34, 35, T20S,R65E). Thickness 0 to 200 m.

Tcv₁ Andesite Steel-gray, weakly flow-layered, conspicuously porphyritic andesite flow overlain by grayish-brown andesite flow breccia. Exposed only along a small deeply incised wash directly west of conspicuous concave-west horseshoe bend in Callville Wash (Secs. 34, 35, T20S,R65E) where unit dips steep to north and is about 60 m thick. Contact with Thumb Member (Tht) mapped as a reverse fault, but in one wash cut the lava appears to rest depositionally on the Thumb Member.

Volcanic rocks of Hamblin Mountain

Mostly uniform andesite, but includes sparse dacite and basalt. Autoclastic breccias and lava flows predominate with a ratio of about 2:1, with a total thickness of about 1,800 m. Pyroclastic and tuffaceous rocks are conspicuously sparse. The rocks at Hamblin Mountain form an undivided sequence of flows and breccias (Tvv). The east part of these exposures is folded and the basal flows are interstratified with sedimentary rocks mapped as Lovell Wash Member (Thl). To the west of the main part of Hamblin Mountain, equivalent volcanic rocks are divided into four volcanic units (in descending order, Tvv₄, Tvv₃, Tvv₂, and Tvv₁). Flows of the upper subunits are interstratified with sedimentary rocks mapped as red sandstone unit (Trs). Subdivision of the volcanic rocks is done for the purpose of showing structure, and does not represent important contrasts in volcanic-rock composition. The boundaries are not readily recognized in the undivided part (Tvv). Eruptive activity spanned about 2 Ma from 13.5 to 11.5 Ma (Thompson, 1985).

Tvv Volcanic rocks of Hamlin Mountain, undivided Mainly andesite in various shades of gray, but variants include shades of brownish-, purplish-, and olive-gray. Includes massive to flow-layered dark-colored flows, and lighter-colored autobrecciated flows, and minor weakly stratified cold mudflow breccia and conglomerate. Individual accumulations of massive unlayered autoclastic breccia range to 300 m thick. Clasts in mudflow breccia range from sand size to 5 m. Autoclastic breccia structure ranges from indistinct in which fragments resemble matrix, to conspicuous in which varicolored clasts of contrasting texture are set in yellowish-gray to greenish-gray matrix. In some breccias, dark, angular, resistant blocks ranging to several meters weather in positive relief compared with lighter-colored less-resistant matrix. Volcanic and sedimentary breccias are most common in upper part, lavas predominate in

lower part. Rocks are generally not vesicular. On east flank of Hamblin Mountain, unit includes volcanoclastic and tuffaceous sedimentary rocks possibly equivalent to rocks mapped elsewhere as Trs and Thl.

Most andesite is inconspicuously porphyritic, but tiny light gray to milky white plagioclase and dark augite, hornblende, or biotite phenocrysts are common in some rocks. Hornblende phenocrysts range up to 2 cm and augite to 5 mm in some andesites, and in others plagioclase phenocrysts are lacking to sparse. Matrix textures range from uncommon glassy to common finely crystalline and less-common medium-grained holocrystalline in the interiors of thick eruptive layers. Trachytic texture is common. Rock type varies from uncommon biotite-hornblende dacite, through very common two-pyroxene andesite (rarely with sparse hornblende or biotite or both) to less common olivine-bearing two-pyroxene basaltic andesite. The varied rock types are distributed throughout the volcanic pile such that the full range of compositional variation appears to have been available throughout the eruptive history. Plagioclase phenocrysts are commonly rimmed by inclusion-rich overgrowths, but more commonly have reaction or resorption rims or ragged borders resulting from late-stage crystallization of matrix. Plagioclase textures suggest magma mixing (Thompson, 1985). Clinopyroxene generally greatly exceeds orthopyroxene, but in some rocks they are subequal. In most of these two-pyroxene andesites, orthopyroxene has been replaced by pseudomorphous oxyhornblende, and in many others by complexly variable secondary assemblages of chlorite, calcite, hornblende, iron oxide, and epidote. Pseudomorphing of orthopyroxene by oxyhornblende may have occurred prior to eruption. Primary hornblende is generally rimmed or replaced by secondary iron oxide. Intensity of hydrothermal alteration increases downward in volcanic pile such that early eruptives are mostly drab-olive-gray propylites in which it is generally not possible to reconstruct original phenocryst assemblages. However, these altered rocks appear similar structurally, texturally, and, in general, mineralogically, to those high in the sequence. Upper lava in stack yielded an ⁴⁰Ar/³⁹Ar age of about 10.07 Ma (sample 11-714-71, Anderson and others, 1994). Thickness is uncertain due to fanning nature of dips (shown by form lines in cross section C-C'), but conservatively estimated at 1,800 m.

The mass of undivided volcanic rock in central-east part of quadrangle (NE of intrusive mass, Ti) was previously mapped (Anderson, 1973) separate from the Hamblin Mountain volcanics, but petrographic study shows lithologic similarity, and mapping shows that the mass forms the north limb of a syncline in the Hamblin Mountain volcanics. Thickness in the north limb of the syncline is less than one fourth that in the south limb beneath Hamblin Mountain (cross section C-C'), possibly suggesting that the volcano developed in an

asymmetric sag similar to that inferred for the red sandstone unit (Trs), Muddy Creek Formation (Tmc), and other basin-fill sediments (Ts).

Tvv₄ Andesite breccias and flows and associated sedimentary rocks Mainly gray porphyritic two-pyroxene andesite breccia with clasts to 3 m. Individual layers are typically 10 to 20 m thick, have grayish-red oxidized and vesicular upper parts and are separated either by bouldery volcanoclastic debris flows or by pinkish-gray tuffaceous sandstone. Lithology similar to that described for undivided volcanic rocks (Tvv). Thickness probably as much as 150 m.

Tvv₃ Andesite and dacite flows Mainly medium-gray, purplish-gray, brownish-gray and greenish-gray, weakly to strongly porphyritic, massive to vesicular, locally autobrecciated, two-pyroxene andesite lava flows and minor dacite flows that are texturally and structurally similar and contain biotite and hornblende phenocrysts in varying proportions. Flows, typically 30 to 100 m thick, have reddish vesiculated upper parts and dark-gray glassy to finely crystalline basal parts. Phenocryst content generally less than 10%. Similar to undivided volcanic rocks (Tvv) except for sparse large (to 2 cm) hornblende phenocrysts in some flows. In central and north part, dacite is abundant low in section and is sparse to absent in upper part. Unit generally lacks interbedded sedimentary rocks, but in main part some flows are separated by sparse interbedded fluvial gravel, and in western exposures, lavas are interbedded with mudstone, gypsiferous mudstone and gypsum (locally mapped separately as Trs). Unit thins to south and west. Average thickness about 100 m, but may range to 300 m in north part.

Tvv₂ Andesite and dacite autoclastic breccia and debris-flow breccia Mostly pale greenish-gray, gray, light brownish-gray, light olive-gray, and pale red-purple sheets consisting of sand- to block-size (to 5 m) clasts of variegated andesite and dacite. Forms thick, (to 300 m) massive, sheets. Although generally similar in lithology to rocks mapped as undivided volcanics (Tvv), thick sections contain sparse (<5%) small phenocrysts and are thus indistinctly porphyritic. Generally produce lighter tones in landscape than units consisting mainly of flows (Tvv₃). Thins southward from about 600 m to about 20 m.

Tvv₁ Andesite and dacite flows and autoclastic breccias Upper part mostly massive to indistinctly layered, gravely to bouldery breccia forming thick accumulations interspersed with minor flows. Lower part mainly massive to indistinctly layered flows. Lithology is similar to undivided volcanic rocks (Tvv). Large areas are affected by weak to moderate propylitic alteration giving rocks a characteristic drab olive-gray color. Strata are cut by abundant mafic to siliceous dikes,

only a few of which are shown on map. Dikes tend to form a radial pattern, the convergence area of which marks the central vent complex of the volcano where dikes can form a greater volume than volcanic rock. Thickness approximately 800 m.

Pre-Cenozoic Sedimentary Rocks Correlated with regional stratigraphic units wholly on lithologic criteria.

Kb Baseline Sandstone (Cretaceous) Mostly white, pale yellowish-gray, quartz arenite exposed only in northwest part of map. Includes minor pebbly sandstone and conglomerate containing rounded sandstone clasts in a sand matrix. Large-scale trough cross-bedding common. Mostly equivalent to white sandstone member mapped by Bohannon (1984), but includes minor associated conglomerate. Thickness about 200 m.

Ja Aztec Sandstone (Lower Jurassic) Distinctly red-weathering, moderate reddish-orange, fine- to medium-grained, texturally uniform, quartz-rich, eolian sandstone characterized by conspicuous large-scale cross-bedding and composed of well-sorted, well-rounded sand grains. Moderately indurated with hematitic cement. Thickness is about 1,200 m, including beds mapped separately as unit Jaw.

Jaw Lower sandstone unit Pale reddish-gray and pale yellowish-gray sandstone distinctly lighter in color than main part (Ja), mapped separately to show structure in northeast part.

Jkm Kayenta and Moenave Formations undifferentiated (Lower Jurassic) In northeast part of map, upper part of unit consists of reddish-brown sandstone lenses intercalated in siltstone; this overlies thick lithologically variable main part of unit consisting of siltstone, sandstone, and silty limestone and limestone. At base are a few meters of cross-stratified sandy conglomerate. In central-west part of map, unit consists mostly of brick-red, lenticular- to flat-bedded, fine-grained sandstone enclosed in minor flat-bedded red siltstone and shale. Unit there contains conspicuously less siltstone and shale than strata described for southern Nevada by Marzolf (1990) and could all be Kayenta Formation. Early Jurassic age based on review of age in Hintze and others (1994). Upper contact with Ja highly uncertain, some parallel-bedded sandstone with meter-scale cross-bedding in upper part may be part of the Aztec Sandstone. Thickness 0 to 350 m.

Ꞥc Chinle Formation (Upper Triassic) Sandstone, siltstone, claystone, conglomerate, arenaceous limestone and limestone of mixed fluvial, paludal, and fluvial-lacustrine deposition. Undifferentiated unit mapped in central-west part mainly includes lithologically variable rocks mapped elsewhere as unit Ꞥcs with conspicuously thin strata equivalent to Ꞥcu. Uppermost part in that area may include

the basal conglomerate of the undifferentiated Kayenta and Moenave Formations. Thickness about 250 m.

Ṛcu Upper part Mostly light reddish-brown to dusky-red, locally lavender-gray mudstone, gypsiferous mudstone, and siltstone in discontinuous, wavy, nonparallel beds 10 to 15 cm thick interbedded with pale purple to light greenish-gray sandstone. Mostly equivalent to the Petrified Forest Member. Thickness 150 to 200 m.

Ṛcs Shinarump Member Mostly pale yellowish-gray to tan sandstone, pebbly sandstone and conglomerate. Conglomerate is mostly clast-supported fluvial with rounded clasts mainly of yellowish-brown quartzite, varicolored chert, and white vein quartz. Sandstone lenses in conglomerate are fine- to very coarse-grained, poorly to moderately sorted and commonly trough cross-stratified. Sparse petrified wood is common; some logs are 50 cm in diameter. Locally unit includes at base dark-weathering reddish-brown, generally cross-stratified, sandy-matrix limestone-pebble conglomerate containing interbedded lenticular bodies of calcareous ripple-laminated fine-grained sandstone and siltstone. Thickness 50 to 200 m.

Ṛm Moenkopi Formation (Middle? and Lower Triassic) Continental clastic and evaporite strata and marine limestone divided into four members following Stewart and others (1972), from top down: upper red member, Shnabkaib Member, Virgin Limestone Member, and lower red member. Where unit is mapped as undifferentiated (Ṛm), it is mostly reddish-brown and grayish-red mudstone, siltstone and sandstone probably equivalent to the upper red member (Ṛmu). Depositional environment includes near shore marine, tidal flat, and sabkha.

Ṛmu Upper red member (Middle? and Lower Triassic) Mostly pale reddish-brown and pale brown, poorly exposed, weakly resistant, ripple-laminated mudstone and siltstone interbedded with lesser yellowish-gray sandstone and gypsum and sparse pebbly sandstone. Bedding varies from flat and continuous to discontinuous and lenticular. Vein gypsum is common and locally abundant. Thickness varies from about 40 to 400 m, possibly due to structural attenuation.

Ṛms Shnabkaib Member (Lower Triassic) Poorly exposed, weakly resistant, gray and yellowish-gray, thin-bedded dolomite interbedded with gypsum, limestone, and minor fine sandstone and siltstone. Mixed lithologies such as calcareous mudstones, gypsiferous mudstones, and sandy siltstones are common. Dolomite and siltstone can be ripple-laminated and carbonate lithofacies can be oolitic. Thickness to 250 m.

Ṛmv Virgin Limestone Member (Lower Triassic) Resistant, well-exposed, well-bedded, thin-

bedded, yellowish-gray and light- to medium-gray marine limestone interbedded with minor calcareous siltstone and sandstone and sparse dolomite and gypsum. Limestone contains common crinoids, pelycypods and gastropods, and some beds are bioclastic. Brown-weathering gray chert and ooids in some beds. Thickness to 300 m.

Ṛml Lower red bed member Friable, poorly exposed, pale reddish-brown and pale brown mudstone and grayish-red siltstone and sandstone with minor grayish-red arenaceous limestone and common vein gypsum. Some bedded gypsum, especially in upper part. Includes common pale grayish-orange, angular-clast, pebble- to cobble-conglomerate at base marking an unconformity at the Pennsylvanian-Triassic boundary. Abrupt lateral thickness variations, possibly due to structural attenuation. Thickness mostly about 50 m, ranges to 100 m.

Pk Kaibab Formation (Lower Permian) Divided into Harrisburg and Fossil Mountain Members following subdivisions adapted by Cheevers and Rawson (1979) and Nielson (1981) Undifferentiated unit (Pk) only mapped in fault block in central east part of map where rocks are broken and attenuated.

Pkh Harrisburg Member Mostly medium- to thick-bedded light gray limestone and cherty limestone interbedded with thin-bedded yellowish-gray dolomite and minor gypsum. Unit is lighter colored and more distinctly bedded than underlying Fossil Mountain Member (Pkf) and contains less gypsum than typical for the Harrisburg (Hintze, 1986). Fossils include brachiopods, crinoids, and bryozoans. Thickness 0–30 m, missing locally, possibly due to combination of faulting and erosion at the Permian-Triassic unconformity.

Pkf Fossil Mountain Member Mostly massive- to well-bedded, light to medium gray, cherty, fossiliferous limestone with bedding defined by trains or layers of nodules, pods, or lenses of dark-brown-weathering chert set in medium-gray, fine- to medium-crystalline limestone. Fossils include corals, brachiopods, and mollusks and abundant crinoid debris. Forms resistant brownish-weathering cliffs that are conspicuously darker than underlying cliff-forming Brady Canyon Member of the Toroweap Formation. Generally shows strong internal deformation. Thickness estimated at 100 m.

Pt Toroweap Formation (Lower Permian) Divided into Woods Ranch, Brady Canyon, and Seligman Members following Nielson (1981). Where shown as undivided (Pt), the unit mostly combines the Brady Canyon and Seligman Members.

Ptw Woods Ranch Member Weakly resistant, poorly exposed, well-bedded, gray to orangish-gray gypsiferous or calcareous siltstone interbedded with white to light gray gypsum and pale-grayish-orange limestone and gray dolomite. Bedding disturbed locally, possibly from dissolution. Forms conspicuous recessive zone between resistant cliffs of Brady Canyon Member and Fossil Mountain Member of the Kaibab Formation. Map mainly depicts covered interval between the cliff exposures. Thickness estimated at 40 m, but unit is apparently thinned or eliminated locally, either structurally or by dissolution.

Ptb Brady Canyon Member Mostly light to medium gray, thick-bedded to massive, medium- to coarse-crystalline, cherty limestone. Chert occurs either as isolated nodules and irregular masses or as concentrations of nodules, lenses, and discontinuous layers that define a weak to prominent bedding. Fossils generally indistinct, but include brachiopods, corals, and crinoid fragments. Forms massive cliffs that are distinctly lighter colored than overlying cliffs of Fossil Mountain Member of Kaibab Formation. Where separated by the recessive Woods Ranch Member (Ptw), the two cliffs form a diagnostic twin-cliff landscape. Strong internal deformation common. Thickness estimated at 60 m.

Pts Seligman Member Interbedded color-laminated gray gypsum and yellowish-gray dolomite, mostly brecciated or with disturbed bedding. Thickness is as much as 20 m but with abrupt lateral variations that are probably due to dissolution.

Pr Red beds (Lower Permian) Mostly pale red to pale yellowish-orange, fine- to medium-grained, moderately to weakly lithified sandstone. Contains sparse partings or beds of red-brown siltstone and gypsiferous mudstone. Castor and others (2000) define grains as typically subrounded consisting of quartz and subsidiary K-spar, plagioclase, and accessory zircon and muscovite. Bedding ranges from thick to thin, discontinuous to parallel, and conspicuous to faint. Gentle cross stratification is discernable in most exposures. Unit is probably equivalent to either the Queantoweap Sandstone of McNair (1951) or the Esplanade Sandstone of the Supai Group (Rowland, 1987). Only about 130 m exposed; base not exposed.

Ip Callville Limestone (Pennsylvanian) Medium gray, micritic limestone and cherty limestone that forms resistant beds 1–3 m thick separated by reddish-gray silty limestone. Forms part of structural blocks in northwest part that may be landslides.

Mm Monte Cristo Limestone (Mississippian) Medium to dark gray resistant limestone, cherty limestone, and dolomitized limestone with common calcite veins. Forms massive cliffs, commonly with indistinct bedding.

Commonly fractured and brecciated; forms part of structural blocks in northwest part that may be landslides.

Pr Crystalline basement rocks (Proterozoic) Gneiss, schist, megacrystic granite, and granite pegmatite. Foliated and unfoliated crystalline rocks thought to be Proterozoic basement are found as screens between dikes in the Wilson Ridge pluton. Only two are mapped. Some contacts with intrusive rocks are faulted but locally dike-like masses cut the crystalline rocks at a high angle to foliation.

STRUCTURE

The east-directed Muddy Mountains thrust of the Cretaceous and early Tertiary(?) Sevier orogeny is widely exposed in the Muddy Mountains directly north of the Callville Bay Quadrangle (Bohannon, 1983a), but no structures directly associated with this thrusting have been identified in the quadrangle. Although the possibility exists that the blocks of Mississippian and Pennsylvanian rock in the northwest part were in the upper plate of the thrust, they have been translated into the Callville Bay Quadrangle either by younger south-directed strike-slip and thrust faulting or by landsliding. Bohannon (1983a) discussed at length the possible tectonic significance of these blocks. The Baseline Sandstone (Kb) exposed south of the blocks was deposited in the foreland basin beyond the east or southeast limit of thrusting.

Southeast of the Hamblin Bay fault, the Callville Bay Quadrangle includes part of the northernmost extreme of the broad northwest-trending Kingman uplift, of possible latest Cretaceous to early Tertiary (Laramide) age. Xenoliths of crystalline basement rock, hornfelsed variegated lower Paleozoic rock, and hornfelsed Tertiary sedimentary breccia within the Wilson Ridge pluton probably represent intruded-out remnants of the north flank of the uplift. However, most of the pre-Miocene rocks in the quadrangle probably were located well beyond the area of Laramide(?) uplift.

The opportunity to assess the extent of pre-Miocene deformation in the Callville Bay Quadrangle is limited by: 1. Most contacts between Tertiary and pre-Tertiary rocks are faulted; 2. The basal Tertiary conglomerate at depositional contacts is time transgressive from the Rainbow Gardens Member into the Thumb Member of the Horse Spring Formation. Despite those limitations, concordant to slightly discordant depositional contacts are widely enough distributed to give a general sense of little or no earlier tilting. An exception is found at the south margin of the west part of the Bowl of Fire block (fig. 1) where steeply southeast dipping basal Tertiary conglomerate rests on gently dipping Jurassic Aztec Sandstone. If dip in the Miocene conglomerate is restored to horizontal, the Aztec beds dip about 35° north, possibly reflecting dip off the north flank of the Kingman uplift. Alternatively, the basal conglomerate could belong to the Thumb Member and the early tilting could be of early Thumb age, similar to relations identified by Beard (1996) in the South Virgin Mountains to the east.

In any case, most of the extreme deformation in the Callville Bay Quadrangle is Miocene or younger.

The Callville Bay Quadrangle is located astride the structural boundary between the northern Colorado River extensional corridor and a zone of large-magnitude lateral tectonic transport (figs. 1, 2). The latter zone of transport is part of a regionally extensive area of complex deformation comprising the south apex of the Great Basin sector of the Basin and Range (Anderson, 1973; Anderson and others, 1994). In the Callville Bay Quadrangle, the complexity results, in part, from the interplay between two major synextensional strike-slip fault systems, the right-lateral Las Vegas Valley shear zone, and the left-lateral Hamblin Bay and Bitter Spring Valley faults (fig. 2) of the Lake Mead fault system. Also, the north part of the quadrangle displays south-directed displacement and strong internal deformation of several separate structural blocks that are described separately in the paragraphs that follow (fig. 1).

The Rotary Cove block in the southeast exposes a small part of the approximately 200-km² Wilson Ridge pluton. The north part of the pluton is hypabyssal and was growing between about 13.5 and 12.5 Ma by a process of dike-on-dike emplacement that represents a maximum of about 15 km of synemplacement upper crustal extension directly south of the Hamblin Bay fault (Anderson and others, 1994). It contains numerous small pendants and xenoliths, some of which are mapped separately (TPzh, Pr). During and following emplacement, the dike system was strongly deformed by a combination of: 1. Arching reflected in strong (to 90°) outward tilting of dikes and country rock (not well illustrated in the Callville Bay Quadrangle), 2. Major vertical collapse by faulting toward the axis of the arch, and 3. Major south-directed horizontal collapse of the part of the pluton directly south of the Hamblin Bay fault, as reflected in disharmonic steep-axis bending of the dikes (Anderson and others, 1994). The latter deformation is well illustrated in

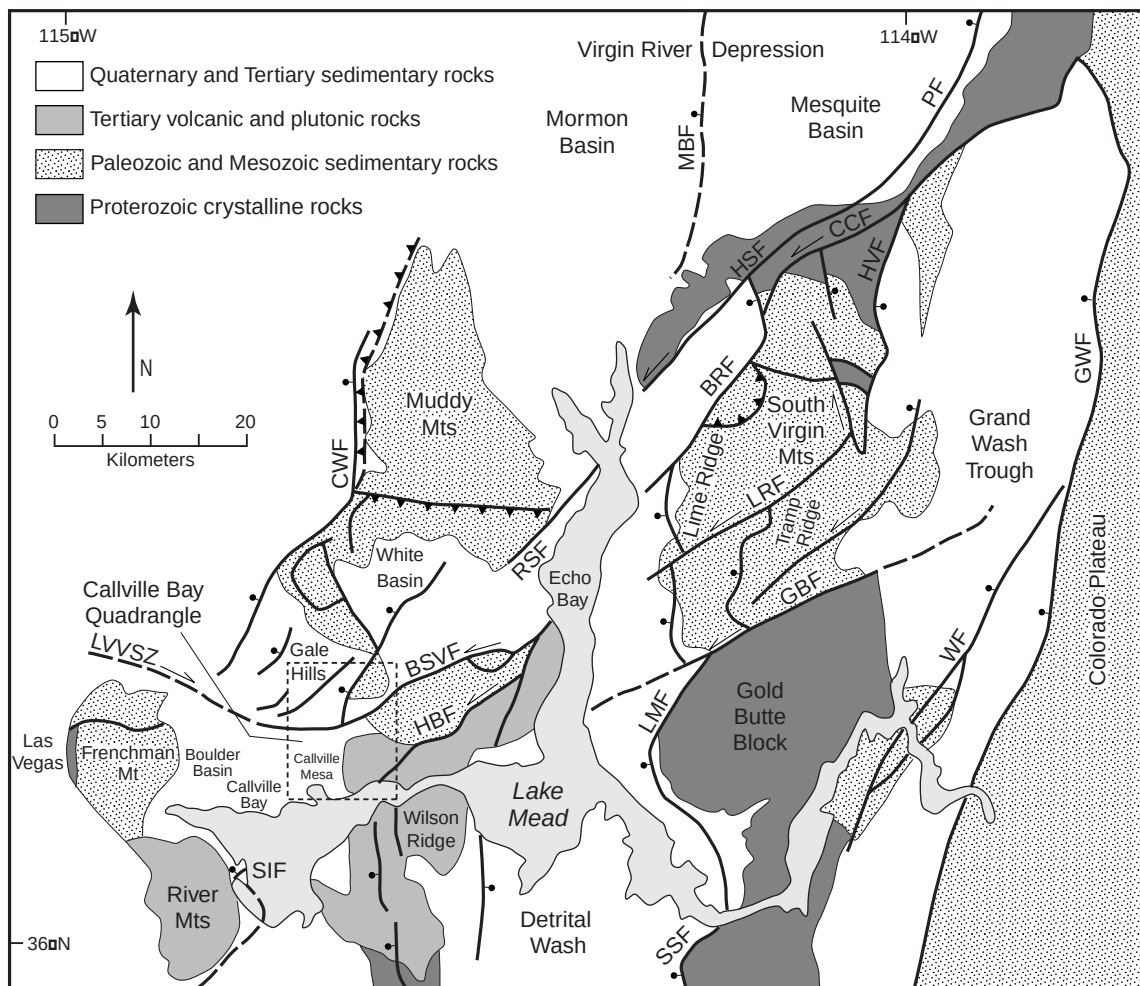


Figure 1. Highly generalized geologic map showing location of the Callville Bay Quadrangle (hachured line) relative to major faults (teeth on thrust faults, bar and ball on normal faults, arrows mark slip sense on strike-slip faults). BRF-Bitter Ridge fault, BSVF-Bitter Spring Valley fault, CCF-Cabin Canyon fault, CWF-California Wash fault, GBF-Gold Butte fault, GWF-Grand Wash fault, HBF-Hamblin Bay fault, HSF-Hen Spring fault, HVF-Hungry Valley fault, LRF-Lime Ridge fault, LMF-Lakeside Mine fault, LVVSZ-Las Vegas Valley shear zone, MBF-Mormon basin fault, PF-Piedmont fault, RSF-Rogers Spring fault, SIF-Saddle Island fault, WF-Wheeler Ridge fault. Modified from Duebendorfer and others, 1998.

the quadrangle by the strong contrast in strike of dikes defining a fold parallel to the Hamblin Bay fault (strikes shown on map by double-hachure symbol). Although dike emplacement is fracture controlled, post-emplacement fractures tend to penetrate the dikes rather than concentrate at their boundaries. In some areas, early siliceous dikes are tilted and cut by uniformly steeper mafic dikes, illustrating synemplacement deformation.

The Hamblin lobe block moved into the area of the Callville Bay Quadrangle by about 20 km of left-sense displacement on the Hamblin Bay fault (Anderson, 1973). It is not clear how much of the internal deformation of this block is synvolcanic as opposed to being associated with the large displacement. The swarm of radial dikes and associated plugs served as feeders during eruption and record a small amount of permanent synvolcanic dilation. The volcano may have formed in a downwarp or fold though, as suggested by the dramatically thinner stratigraphic sections outboard of the western and northern fold axes as compared with sections inboard of those axes. Although the strain significance of such synvolcanic folding is difficult to assess, it is unlikely to record much, if any, synvolcanic extension. The dip of flow layering and bedding in the central and east parts of the lobe is generally about twice that expected for maximum primary dips, suggesting structural tilting. This tilting defines northeast-trending open folds or warps that appear spatially and genetically linked to right slip on north-northwest to northwest-striking faults, especially the large-displacement fault that separates the Hamblin lobe from the Razorback/Pinto block. Small-scale stratal bending at that fault and sparse gently plunging striations on the fault indicate right slip, and because the Mesozoic rocks in the Razorback/Pinto block lack any evidence of a history of Neogene igneous activity, a large magnitude of right slip is suspected. The pattern of folding and tilting on northeast trends parallel to the Lake Mead fault system continues to the northeast into the Boulder Canyon Quadrangle, where other examples of genetic links to transverse faults are found (Anderson and others, 1994). The structural pattern may indicate post-volcanic transpression along the Lake Mead fault system, and the synvolcanic folding may record similar strain. Normal faults recording significant east-west extension are sparse to nonexistent. Paleomagnetic data from the Hamblin lobe show no significant steep-axis rotation (Wawrzyniec and others, 2001), in sharp contrast to severe counterclockwise bending in the Wilson Ridge pluton bordering the Hamblin lobe block on the southeast (Anderson and others, 1994), and severe clockwise bending in the Gale Hills (West End block of fig. 1) (Sonder and others, 1994). Unfortunately, the paleomagnetic data are from a part of the Hamblin lobe that could be very dissimilar rotationally from the northwest margin of the lobe, where the volcanic rocks are locally conformable with steeply southeast dipping strata in the Callville block. Thus, the data place no constraints on rotation of the Callville block, from which paleomagnetic data are not reported.

The Callville block is a poorly defined feature that extends north from Lake Mead to a mostly buried concave-

north fault bounding it against the Highway block. It includes a northeast finger of homoclinally southeast-dipping Miocene strata separating the Hamblin lobe and Bitter Spring Valley block (fig. 1). Rocks in its west part are much more complexly deformed than in the homocline finger, exhibiting several dip-direction discordances and internal unconformities that record strong syndepositional deformation, mostly during deposition of the Callville volcanics. For example, tilted early volcanic rocks (Tcv₁, Tcv₂) and intercalated coarse clastic rocks cannibalized from the volcanics (Tcc) are separated from one another and from younger volcanics by angular unconformities. Also, contorted clastic and evaporitic sedimentary rocks speculatively assigned to the Thumb Member (Tht) and red sandstone unit (Trs) enclose large lenticular landslide masses and are extensively invaded by intrusive masses of varied orientations. Stratal contortion may be related to a combination of pluton emplacement and mechanical contrasts between landslide masses and the enclosing mechanically weak sedimentary rocks. Structures in the young volcanics (Tcv₃, Tcv₄) and post-volcanic basin-fill strata (QTrg, Ts, Tmc) are somewhat more orderly than in the older strata. They include small east-trending asymmetric basins, reverse-slip easterly striking faults, and east-trending open folds. Strike-slip faults are also present. A northwest-striking right-lateral fault, along which isoclinal folds are developed locally, is exposed along the Callville Marina access road (Sec. 5, T21S, R65E). Part of the boundary between the Callville block and Hamblin lobe is defined by a northeast-striking left-lateral fault along which small isoclinal folds are also developed locally (Anderson, 1973, Fig. 5). Projection of that fault to the southwest into the area between the volcanic rocks of Hamblin Mountain and the volcanic rocks of Callville Mesa is speculative because juxtapositions are between rocks of very similar lithology. In that area, lateral displacement may be absorbed in east-west folds. Most structures in the Callville block suggest north-south shortening. North-south normal faults recording tectonically significant east-west extension are sparse to nonexistent here and in areas to the west in the Government Wash Quadrangle (Duebendorfer, 2003).

The Highway block is an east-oriented lozenge-shaped mass of uplifted and south- and southwest-tilted Paleozoic and Mesozoic rocks. It is part of the area, along with the Callville block, forming the eastern Boulder basin structural block of Duebendorfer and Wallin (1991). Its south boundary is defined, in part, by an easterly striking fault with probable right-normal displacement in its west part and left-normal displacement in its east part (Bohannon, 1984; Anderson and others, 1994). The Highway block is cut internally by many mainly northeast-striking faults that are chiefly left normal, with one right normal. Large left separation of the Permian-Triassic contact on some of these faults tends to be absorbed to the southwest in mechanically weak rocks of the Moenkopi Formation such as the Shnabkaib Member. The large-displacement left-normal fault near the east end of the block terminates at the north-bounding fault, the one

near the middle of the block offsets the north-bounding fault, and others seem to terminate within the block, suggesting a complex history of internal deformation. The internal structural pattern is similar in many respects to that of the Razorback/Pinto block (this map and Anderson, 1973), suggesting a common structural history.

The Razorback/Pinto block is a long (~15 km) northeast-trending mass of uplifted Paleozoic and Mesozoic rock that actually consists of two separate generally southeast-tilted sub-blocks (the Razorback Ridge and Pinto Ridge blocks (Anderson and others, 1994). Only the westernmost part is in the Callville Bay Quadrangle. Similarities between the internal structural pattern and that of the Highway block include: 1. Internal faulting is primarily left-lateral on faults transverse to the boundaries of the block. 2. Some of the displacement on those faults is absorbed in mechanically weak Mesozoic strata. 3. In each block, a sub-block bounded by transverse left-normal and right-normal faults appears to be downdropped and shifted northward toward the north-bounding fault. 4. Sharp comers are formed where the north-boundary faults are offset at transverse faults, and the mechanically weak strata north of the sharp comers tend to wrap around the comers of mechanically resistant Paleozoic rock. On the basis of unpublished mapping in the Razorback/Pinto block by the author, another similarity is seen at the east ends of the blocks, which show mild north-south extension. The similarities suggest a common structural history within an overall zone of large lateral tectonic translation (see Discussion section below). The chief differences between the blocks are: 1. The structural pattern in the Highway block is rotated clockwise about 30° relative to the similar pattern in the Razorback/Pinto block. 2. The Razorback/Pinto block is complicated by a right-slip fault separating it from the Hamblin lobe. This latter fault is highly significant because, along with splays of the northeast-striking, left-lateral Lake Mead fault system (Bohannon, 1983a), it translates the Razorback/Pinto block southward relative to the Hamblin lobe block, effectively inserting a non-igneous block into the north margin of the igneous terrain.

The north part of the quadrangle is part of a broad region of Miocene deformation and associated mostly non-volcanic basinal sedimentation stretching at least 80 km west from the west edge of the Colorado Plateau. The area is highly broken by faults, making division into structural blocks dependent on the scale of concern. Parts of four major structural blocks are recognized across the north part of the quadrangle (fig. 1). From west to east, they are, West End, Lovell Wash, Bowl of Fire, and Bitter Spring Valley blocks. Kinematic indicators on boundary faults, coupled with analyses of adjacent fault-related structures and stratigraphic relations, show that the West End and Bitter Spring Valley blocks are translated south relative to the two central blocks, and the Lovell Wash block is translated south relative to the Bowl of Fire block (fig. 1).

The Bowl of Fire block is bounded by a triangle-shaped pattern of faults and can be subdivided into east and west

parts (fig. 1). It exposes uplifted Mesozoic rocks flanked on the south by a thin veneer of Rainbow Gardens strata, on the west by the west Bowl of Fire fault, and on the east by a set of unnamed northerly striking right-normal faults. The east and west parts are separated by a northwest-striking, sub-vertical, right-normal fault. Southwest of the fault, rocks dip homoclinally southeast, the Rainbow Gardens strata more than twice as steep as the underlying Aztec Sandstone, either reflecting pre-Miocene dip away from the core of the Kingman uplift (Bohannon, 1983b) or early Thumb-age deformation as noted above. Northeast of the fault, the Mesozoic rocks are folded into a broad, open, northeast-plunging anticline and are faulted, possibly reflecting pre-Miocene deformation. Also, Rainbow Gardens strata in the area of the fold rest on the Chinle Formation; a conspicuously lower stratigraphic level than represented by the Aztec strata across the fault. The fault separating the two parts is either a large-displacement Miocene structure or a pre-Miocene structure reactivated in Miocene time. The south boundary fault of the Bowl of Fire block is a northeast-striking right-normal fault, a fault of possible major tectonic significance, as noted in the Discussion section below.

The West End and Bitter Spring Valley blocks are large (Bohannon, 1983a), and because only parts of their respective east and west edges are included in the Callville Bay Quadrangle, discussion is brief and is focused on lithologic similarities and the nature of the structural boundaries with the two middle blocks. The Miocene Horse Spring Formation in the two blocks rests on Cretaceous Baseline Sandstone and includes a resistant basal conglomerate overlain by a gypsiferous lithofacies, both probably belonging to the Thumb Member. Overlying Thumb Member rocks include abundant conglomerate lithofacies rich in clasts of Paleozoic and Mesozoic rocks and almost devoid of crystalline basement rocks, an assemblage strongly suggestive of northerly provenance. These beds are deformed into folds of various orientations; some with conspicuously curved axial-plane traces. In the West End block, numerous very steep normal and reverse faults, most too small to map, parallel the fold hinges. The east boundary fault of the West End block is an irregular, generally northeast striking, fault transverse to the internal structure of the adjacent blocks. The fault has sparse left-slip kinematic indicators. The widespread conglomeratic lithofacies in the adjacent Thumb Member show no evidence of accumulating in a basin spatially and genetically related to throw on this boundary fault. The fault appears to feed some of its displacement into obliquely oriented folds and thrust and reverse faults in the southern most part of the block. Also, south-directed Tertiary thrusting and folding of Paleozoic rocks near the north quadrangle boundary appears related to this boundary fault. Sub-thrust(?) landslide masses of Paleozoic rocks in the Thumb Member may indicate that the boundary fault was active during Thumb time. Alternatively, all exposed Paleozoic rocks in the northwest part of the map could be Miocene landslides derived from highlands in the Muddy Mountains to the north.

Contoured potential-field data (Langenheim and others, 2001) suggest that magnetic basement is structurally deep in the vicinity of the blocks of exposed Paleozoic rock, supporting their origin as landslide blocks.

The south boundary of the West End block is a very enigmatic fault that is located along the eastward projection of the large-displacement right-lateral Las Vegas Valley shear zone and, as such, should be a right-lateral fault (Duebendorfer and Wallin, 1991). Kinematic indicators, including stratal bending and Riedel shears, are well exposed on steep splays near the west margin of the Callville Bay Quadrangle and indicate mostly left-lateral motion; and west of there, the youngest displacement is reported to be reverse (Çakir, 1990). Bohannon (1983a) referred to this fault as the left-lateral west Bowl of Fire fault and Duebendorfer and Wallin (1991) referred to it as the right lateral Las Vegas Valley shear zone. Anderson and others (1994) summarized evidence for left-lateral movement on its eastern extension at the south boundary of the Lovell Wash block (fig. 1).

The west boundary fault of the Bitter Spring valley block is a generally north-striking fault zone transverse to the strike of bedding in the Bowl of Fire block. Right-normal displacement is indicated by associated thrust faults and stratal bending at the fault, as well as by striae orientations. To the extent that the folding and faulting of the east part of the Bowl of Fire block is Miocene, it is probably linked to right slip on this boundary fault. There are some sub-thrust coarse breccias in the Thumb(?) Member that contain clasts derived from the directly overlying upper-plate Rainbow Gardens Member rocks, suggesting that thrusting was active during Thumb time. However, as with the east-bounding fault of the West End block, the widespread conglomeratic lithofacies in the Thumb Member show no evidence of accumulating in a basin spatially and genetically related to throw on the boundary fault. The south boundary of the Bitter Spring Valley block is the left-lateral Bitter Spring Valley fault of Bohannon (1983b). In the Callville Bay Quadrangle, that fault shows extreme segmentation by northerly striking left-slip faults transverse to its strike (fig. 2).

The Lovell Wash block trends northeast and consists of a very thick sequence of Miocene strata of the Horse Spring Formation deformed into faulted folds of diverse orientation with conspicuously curved axial-plane traces. The east and south boundaries are formed by a single fault, called the west Bowl of Fire fault by Bohannon (1983b, Fig. 5). It is steep and mainly left slip where it enters the quadrangle from the north. To the southwest along its dogleg trace, it decreases in dip, becomes more dip slip than strike slip, and bends sharply around the southwest apex of the Bowl of Fire block. Finally, it bends sharply west and reestablishes a predominantly left slip between the east end of the Highway block and the Lovell Wash block. Part of its complexity in orientation and slip sense probably results from interference by other faults such as the northeast-striking right-slip fault at the south margin of the Bowl of Fire block, which appears to feed some of its displacement directly into the West Bowl of fire fault. Its hanging wall in the south part of the Lovell Wash block is

strongly folded. Whether the fault is folded or simply absorbs the fold strain in its hanging wall, or both, is not known, but the positions of a hanging-wall anticline along the west projection of the southwest apex of the Bowl of Fire block and a syncline directly to the south at a conspicuous easterly excursion of the fault suggest the fault is folded. If the fault absorbs strain associated with the large Lovell Wash syncline, it would have to extend as a listric fault beneath the entire southern part of the Lovell Wash block. Over most of its complex trace it cuts beds transversely, and at no point along its trace is there a suggestion of reverse-drag flexing of hanging-wall strata, as might be expected if it were a basin-bounding listric normal fault. Also, at no point along its northerly striking trace is there a suggestion that the adjacent footwall supplied detritus to the hanging wall, as might be the case if it were a basin-bounding listric normal fault.

Numerous easterly trending folds are spatially associated with the east and west boundary faults of the Lovell Wash block. Some exhibit dramatic decrease in wavelength and increases in amplitude as the boundary faults are approached; revealing close genetic ties between the folding and independently determined left slip on the boundary faults. The Lovell Wash syncline is the largest fold in the Lovell Wash block and the only one that extends across the entire block. The strong bending displayed by its axial surface (clockwise north of the east end of the block and anticlockwise north of the major left step in the west part of the block) probably reflects post Horse Spring structural buttressing by the resistant uplifted north margin of the Highway block. Collectively, these fault/fold relations reflect generally south translation of the Lovell Wash block relative to the Bowl of Fire block and the West End block relative to the Lovell Wash block. This latter translation may be large, as suggested by lithologic contrasts. The thick Thumb Member strata in the Lovell Wash block contain none of the north-derived conglomeratic lithofacies that are abundant in the directly adjacent parts of the West End block. The small quantity of gravels found in the southern part of the Lovell Wash block have south-derived clast assemblages that are not found in the adjacent West End block. Because the Thumb Member strata lack lithofacies recording derivation from highlands either to the east or west across the block-bounding faults, the lithologic contrasts record either north or south derivation and suggest several kilometers of post-Thumb left slip on the boundary fault, large enough to juxtapose the blocks. Large displacement on other north-striking block-bounding faults, such as the one separating the Bowl of Fire and Bitter Springs Valley blocks, are suggested by similar lithologic contrasts as well as by the large block-to-block contrasts in stratigraphic level of rocks on which the basal Tertiary strata rest.

DISCUSSION

The area directly north of the Callville Bay Quadrangle exposes large-scale thrusts that formed during the late Cretaceous Sevier orogeny, and the area directly south of

the quadrangle exposes a broad uplift that may have formed during the latest Cretaceous through Eocene Laramide orogeny. Although rocks deposited during those orogenies may be present in the quadrangle, no structures known to have formed during them are recognized.

Two factors make determination of the extent and timing of pre Miocene deformation difficult in the Callville Bay Quadrangle: 1. Most Tertiary/pre-Tertiary contacts are faulted. 2. The possibility exists that lithologically similar well-cemented resistant conglomerate at the Tertiary/pre-Tertiary contact spans a range of age within the Horse Spring Formation and is thus an unreliable time-stratigraphic marker. Although most contacts between Tertiary and pre-Tertiary strata are faulted, sparse depositional contacts are widely enough distributed to provide a general sense of little or no post-Proterozoic/pre-Miocene deformation. In general, basal Tertiary conglomerate, whether belonging to the Rainbow Gardens or Thumb Members of the Horse Spring Formation, are either concordant or slightly discordant to underlying pre-Tertiary strata. Bohannon (1983b) noted similar evidence for little pre-Horse Spring deformation in the Muddy Mountains to the north. Clearly, most of the strong deformation in the quadrangle is Miocene or younger.

Deposition of the Rainbow Gardens Member of the Horse Spring Formation between about 26 and 17.2 Ma (Bohannon, 1984; Beard, 1996) was in a single sag basin and was probably not accompanied by strong local deformation. Facies changes spatially associated with specific structures are not reported. By contrast, stratigraphically higher Horse Spring strata belonging to the Thumb, Bitter Ridge, and Lovell Wash Members include debris-flow deposits and, in the case of the Thumb Member, landslide masses interpreted to record strong local relief resulting from local deformation. The landslide masses composed of basement rock contained in Thumb strata north and west of Callville Bay in the southwest part of the quadrangle and those composed of Paleozoic rocks in the northwest part (possibly including the large mapped blocks of Mississippian and Pennsylvanian rocks) probably record coeval uplift in areas to the south and north of the Callville Bay Quadrangle (Thumb-age coordinates) respectively. The >4.5-km-long concave-north band of Thumb Member conglomerate in the central part of the quadrangle is primarily of debris-flow origin and contains common clasts throughout >0.5 m in diameter. The deposit probably records uplift directly to the north (present-day coordinates). The conglomerate facies in the north part of Sec. 23, T20S, R65E, into which fine grained lacustrine facies of the Bitter Ridge and Lovell Wash Members grade abruptly, probably records local severe topography caused by local uplift directly to the south (present-day coordinates). In most of these examples, provenance ties to adjacent source rock cannot be established. The absence of obvious source rocks is probably due to large-magnitude lateral displacements that have dislocated the sources, and possibly also to large-magnitude steep-axis rock rotations that alter source-rock azimuths as discussed in the paragraphs that follow.

It is well established that sometime after about 16 Ma the Frenchman Mountain/Sunrise Mountain structural block, now directly east of Las Vegas (fig. 2), was translated about 65 km along a vector summation pathway oriented 245° (Duebendorfer and others, 1998). The pathway goes through the geologic terrain now occupied by the Callville Bay Quadrangle. Two main processes have been suggested for this translation: 1. Low-angle normal faulting or detachment faulting (upper-plate active) (Duebendorfer and Wallin, 1991; Duebendorfer and Simpson, 1994), 2. Tectonic rafting on a flowing undermass (upper-plate passive) that changed shape during flow (Anderson and others, 1994).

Duebendorfer and Black (1992) suggested that 20 km of extension occurred between Hamblin Mountain and Frenchman Mountain on kinematically coordinated systems of upper-plate normal faults and a master detachment fault. Within the Callville Bay Quadrangle, the breakaway for the detachment fault would be located between the Callville and Hamblin lobe volcanic centers, and distributed northerly striking listric extension faults should be common to the west where Callville volcanics and the red sandstone unit are widespread. No breakaway fault is apparent, and distributed listric extension faults are sparse to nonexistent, as they are farther west toward Frenchman Mountain. Also, unless there has been about 90° of young steep-axis rotation southeast of the Gale Hills (including the north part of the Hamblin lobe), deposition of the basin-fill units (Ts, Tmc, Trs) was mostly in east-trending fold-controlled depocenters, not in north-trending fault-controlled basins. North-striking extension faults are also sparse in the Hamblin lobe, a structural block that was displaced 20 km by the same translation process. Thus, geologic relations in the Callville Bay Quadrangle provide no direct support for the detachment fault process. Also, an upper-plate-active detachment fault model for lateral translation of Frenchman Mountain is not supported either by potential field data or seismic reflection data (Langenheim and others, 2001).

Regardless of the process, the translation of the Frenchman/Sunrise Mountain block, measuring at least 20 km south to north, must have involved right-lateral displacement on faults at the north block boundary and left-lateral displacement at the south block boundary. Whereas there are left-slip faults, such as the large-displacement Hamblin Bay fault and the Bitter Spring Valley fault (prior to its segmentation by transverse faults), on which part of the south-boundary translation could have occurred, there are no through-going large-displacement right-lateral faults in or east of the Callville Bay Quadrangle. Given the 245° displacement vector, we should expect some of the north-boundary right-lateral faults to strike northeast. The right lateral fault at the south margin of the Bowl of Fire block is an obvious candidate fault, but it is not a through-going structure. Post-Thumb Member deposition patterns and widespread structures suggesting north-south shortening abound in the Callville Bay Quadrangle and are especially apparent in the south translation of the Bitter Spring Valley, Lovell Wash, and West End blocks relative to the Bowl of

Fire block. The south translation provides a means of obscuring the northern right-lateral boundary; either by stepping it southward, structurally overriding it by reverse and thrust faults, by structural occlusion in the wake of the westerly extruded Frenchman/Sunrise structural block, or by a combination of these processes. The south margin of the Bowl of Fire block may be the only surviving segment of the right-lateral fault system.

The north-south structural shortening or tectonic occlusion following passage of the Frenchman/Sunrise Mountain block probably records major shape change in a flowing undermass (Anderson and others, 1994). The lozenge-shaped Highway and Razorback/Pinto blocks, composed of rocks correlative with the north part of the Frenchman/Sunrise Mountain block, may represent pieces of the tectonically rafted block that were torn off and left behind, further obscuring planar attributes of the north boundary. That such tectonic fragments are at the same current structural elevation as the Frenchman/Sunrise Mountain block is more compatible with tectonic rafting than displacement on a west-dipping detachment fault.

Dips ranging from 50° to 75° are common along the north or south margins of open east-trending folds formed in Muddy Creek Formation (Tmc). Also, roundstone gravel and associated sand and rhythmically bedded clay in the southwest and south-central parts of the quadrangle are folded with dips as great as 40°. These strata were probably deposited by latest Tertiary or earliest Quaternary streams precursor to the current Colorado River. Longwell (1936) reported similar deformation in river gravels currently beneath the waters of Lake Mead. The style and youthfulness of this deformation suggests that contractional strain similar in origin to that which dominates the Miocene structural fabric in the Callville Bay Quadrangle is part of the neotectonic regime. Longwell (1936) noted reverse displacement of probable Quaternary age on the Mead Slope fault south of the quadrangle. Whatever seismic hazard may exist in this area may have closer affinities to contractional deformation than extensional deformation.

ACKNOWLEDGMENTS

This work began under a U.S. Geological Survey Gilbert Fellowship to the author and Ted Barnhard and was completed under a U.S. Geological Survey project to map the Lake Mead 1:100,000 sheet managed by Gary Dixon and Pete Rowley. Darwin Russell, U.S. Bureau Reclamation, provided a boat, and the U.S. Park Service provided housing and camp space for the early part of this work with Ted Barnhard. I am grateful to Ernie Duebendorfer for providing pre-publication maps of the adjacent Government Wash Quadrangle and for sharing his preliminary mapping in the west part of the Callville Bay Quadrangle. Discussions and field visits by Ernie Duebendorfer, Sue Beard, Keith Howard, Scott Lundstrom, and Atilla Aydin were very helpful. The map and text were improved by technical reviews by Bob Bohannon, Ernie Duebendorfer, and Jim Faults.

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