

Report to accompany the Geologic Map of the Mule Wash 7 1/2' Quadrangle, La Paz County, Arizona, and Riverside County, California

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A remnant of light-colored Bouse carbonate (travertine/tufa) draped over Jurassic diorite (729,300E, 3,696,400N).

DIGITAL GEOLOGIC MAP DGM-117

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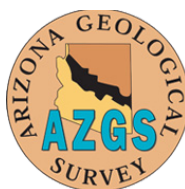
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Introduction

The Mule Wash 7 ½' Quadrangle is located in western Arizona along the Colorado River and southeast of the town of Blythe, California. The map area encompasses the west flank of the northern Trigo Mountains and the piedmont that extends westward from the foot of the range toward the Colorado River. About 60% of the quadrangle is within the Yuma Proving Ground, and the U.S. Army granted access for field mapping. The extreme northwest corner of the map covers a small portion of the Colorado River floodplain in California. Geologic mapping was done in 2014-2015 under the joint State-Federal STATEMAP program, as specified in the National Geologic Mapping Act of 1992, and was jointly funded by the Arizona Geological Survey and the U.S. Geological Survey under STATEMAP assistance award #G14AC00424. Limited field follow-up was done and map revisions to address outstanding issues were completed in 2016. Mapping was compiled digitally using ESRI ArcGIS software.

Most of the quadrangle is covered by Neogene and Quaternary surficial deposits, with exposed bedrock of the northern Trigo Mountains restricted to the southeastern part of map area. Bedrock consists of Jurassic crystalline rocks of the Kitt Peak – Trigo Peaks superunit (Tosdal and Wooden, 2015) – primarily diorite, granite, granodiorite, and gneiss – and Oligocene to Miocene extrusive volcanic rocks and related sedimentary rocks. The mountain peaks are not high but slopes typically are steep and the landscape is quite rugged. The mountains are fringed with calcium carbonate-dominated basal deposits of the Bouse Formation (Metzger, 1968). The upper part of the piedmont around the mountains is underlain by locally derived late Miocene to early Pliocene conglomerate, which is separated into pre- and post-Bouse units where relationships are clear. The post-Bouse conglomerate deposits are interbedded with and transition laterally into the sand and gravel deposits of the Bullhead Alluvium, which records a period of massive Colorado River aggradation in the early Pliocene (Howard et al., 2015). Bullhead Alluvium is widely exposed throughout most of the map area, from bluffs along the river floodplain to very near the mountains. Much of the lower part of the piedmont is mantled by sand, silt, clay and minor gravel Colorado River deposits of the Chemehuevi Formation, which records a substantial period of river aggradation in the late Pleistocene (Malmon et al., 2011). The northwestern corner of the map area consists of Holocene deposits of the Colorado River channel and floodplain; the floodplain on the California side of the river has been substantially altered by agricultural activity. The piedmont is primarily covered by late Pleistocene alluvial fan deposits, with limited remnants of older Pleistocene fan deposits. Holocene tributary deposits are fairly extensive, but generally are confined to fairly broad valleys incised well below adjacent Pleistocene fan and terrace deposits.

Neogene and Quaternary (Surficial) Deposits

Geologic deposits that fill the Colorado River valley and mantle the modern piedmonts were mapped using field observations, georeferenced digital orthophotographs and satellite imagery, and digital elevation models (DEMs). Several distinctive characteristics allowed us to distinguish Colorado River deposits of various ages from locally derived alluvial fan, terrace and channel deposits. Because the Colorado River drains a vast, geologically diverse watershed, river gravel deposits include well-rounded clasts of distinctive lithologies that are not found in the bedrock of adjacent mountain ranges. River sand is rich in quartz, and many of the grains are well rounded. Deposits of tributary drainages are dominated by subangular to angular clasts of locally-derived volcanic or crystalline rock, and sand fractions include various mineral grains, few of which are

rounded. Many outcrops reveal some amount of mixing between river and tributary deposits, including locally-derived and exotic gravel clasts and greater or lesser amounts of rounded quartz sand.

Piedmont Deposits. Relative ages of alluvial deposits were estimated using characteristics of clast weathering, soil development, carbonate accumulation, and position in the landscape (Machette, 1985; Bull, 1991; Birkland, 1999). Soil development begins once a deposit is isolated from active alluvial processes. As a result, the degree of soil reddening and carbonate and clay accumulation are criteria used to estimate the approximate ages of surficial units. Younger alluvial deposits have little to no soil development, retaining the original tan or gray color of the alluvial sediments, and minimal carbonate accumulation. Clasts in these deposits have no weathering rinds and minimal or no surface patinas and typically appear brighter and fresher than older clasts. Young alluvial surfaces retain original depositional characteristics such as bars and swales. Conversely, older alluvial deposits have better developed soils that appear orange in color, with soil horizons reflecting carbonate and some clay accumulation. Clasts on older alluvial surfaces commonly exhibit dark rock varnish and some degree of oxidation (orange surface patina), and thus appear darker on the ground and in aerial photographs. Preserved alluvial surfaces may be smooth and flat (Qi3), becoming more rounded and coarser with age (Qi2). The oldest alluvial surfaces (Qi1) are typically eroded, rounded ridges with planar surface remnants of limited extent, and variable soil preservation. Locally, calcic soil horizon development is quite strong, but we did not find any strongly developed petrocalcic horizons in the map area.

Chemehuevi Formation. Deposits of the Chemehuevi Formation (Qch) are found in a strip near the Colorado River. These deposits filled and draped over erosional topography formed on older tributary alluvial fan deposits and Bullhead Alluvium, but also are interbedded with tributary fan deposits. The highest Qch deposits were observed in the northwestern part of the quadrangle at 134 m (440 ft) above sea level (asl), where they unconformably overlap Qi2 lag surfaces and appear to lack a fluvial scarp. These may represent the highest level of Chemehuevi aggradation. In other areas, lateral river erosion cut prominent scarps into Bullhead Alluvium and Qi2 deposits, and exposures in these areas reveal that Qch deposits are incised into older Bullhead deposits and/or tributary alluvium (Figure 1). Much lower and more subtle scarps were cut into deposits of unit Qi3a, as the river approached its maximum level of aggradation. Three to four fluvial terrace scarps have been identified recording the subsequent progressive incision of the river (inset lower scarps), and younger Qi3 deposits are graded to these levels. From these relationships, we infer that the oldest Qi3 deposits are temporally equivalent to the maximum Chemehuevi aggradation. In this map, we have grouped all river deposits associated with these scarps into the Chemehuevi Formation, although some are clearly younger than the maximum aggradation (Malmon et al., 2011). Younger deposits are successively lower and inset into older deposits and generally have a subtle to well-defined fluvial scarp with a few meters of relief, and roughly parallel the main trend of the Colorado River.

Qch deposits consist of primarily fine to medium sand, silt and clay. In the southern portion of the quadrangle, the oldest Qch deposits have abundant sand, but also appear to have well-rounded pebble and cobbles found as a gravel lag on sand-rich deposits. At lowest elevations beneath the youngest Qch surfaces, Qch is capped by latest-Pleistocene Qi3b deposits. Thickness of these youngest Qch deposits range from 1 to 2 m, up to 7 m, where the thicker portions are interbedded with locally-derived tributary gravels, and thinner portions unconformably overly Bullhead deposits and Qi2 fan remnant lag gravel surfaces. We infer that these thicker portions consist of younger Qch deposits inset into older, early aggradation Qch deposits, where the river

interacted with tributary channel deposition. Prior to earliest Qch deposition tributaries incised into Qi2 deposits. During early Chemehuevi aggradation tributary gravels aggraded several-meter thick deposits, and are locally mappable, unit Qi2u, separating underlying Bullhead and overlying Qch sand-rich river deposits.



Figure 1. Base of Chemehuevi sand incised into older tributary alluvium and cross-bedded Bullhead sand. Older tributary alluvium is interpreted to represent post-Qi2, pre-Qi3 deposition of pediment at lower elevations, locally mapped as unit Qi2u. Qi2u deposits may have been contemporaneous with earliest deposition of the Chemehuevi aggradation.

Bullhead Alluvium (Tcb)

Deposits of unit Tcb consist of quartz-rich sand, minor silt and clay, and subangular to well-rounded pebbles and small cobbles, some portion of which are derived from distant parts of the Colorado River watershed. Fine-grained sand, silt and mud (unit Tcbf) is also present several meters thick and extend to large areas of the quadrangle at mappable and unmappable scales. We correlate Tcb deposits with the early Pliocene Bullhead Alluvium, which has been found all along the lower Colorado River and represents a period of major early Pliocene river aggradation (Howard et al., 2015). Sand is typically medium to coarse, with common to abundant rounded quartz grains and some rounded, hematite-stained quartz grains. The sand fraction also includes variable amounts of more angular grains of locally-derived quartz and lithic fragments. Gravel clast content is diverse, varying from a few percent to almost entirely exotic (derived from outside the map area). We consider the presence of even a small fraction of well-rounded, exotic gravel clasts to be diagnostic of Bullhead Alluvium based on mapping north and south of the map area. Quartz-rich sand and rounded exotic gravel layers are interbedded with locally-derived fanglomerate (unit Tfg2), primarily on the margins of the valley proximal to bedrock outcrops but locally near the valley axis. In many cases tributary sand and gravel are

reworked into moderate- to well-sorted cross-beds, presumably by fluvial processes, and almost always with paleo-current indicators transverse to or opposite to the flow of modern drainages (Figure 2). Medium to large amplitude cross beds are common in sand and gravel deposits, and typically they are weakly to moderately indurated. Locally, sand is oxidized to an orange color, and we have found petrified wood in a few localities. Lags of well-rounded exotic gravel over older deposits are also found in a few areas.



Figure 2. Cross-bedded sand, local and exotic gravel in upper Mule Wash. View to north-northeast. Paleo-current direction to right or east-southeast. Middle cross-bedded gravel set approximately 1.2 m thick.

Bullhead deposits are found from just above the Holocene river floodplain at ~75 m asl to as high as ~230 m in near the mountains in the southeastern part of the map area. Based on the limited exposures in the area, Bullhead Alluvium apparently underlies nearly all of the piedmont, with a thin veneer of Quaternary alluvial fan and terrace deposits. In some places Bullhead deposits are very close to the bedrock mountain front, whereas in other areas most of the upper piedmont consists of tributary alluvial fan deposits. We infer that this is a result of complex spatial interactions between river and tributary aggradation. In many areas well-sorted cross-bedded sand interfingers with tributary-dominated gravel. Some tributary gravel deposits also appear to be strongly reworked and organized into cross-bedded sand and fine gravel, imbricated east and southeasterly either transverse or opposite to the modern piedmont gradient.

Bouse Formation

We found abundant outcrops of basal carbonate deposits of the Bouse Formation in the quadrangle. Primarily these outcrops are fractured, massive gray travertine and gray calcarenite limestone (typically call “tufa” by previous workers). The tufa deposits were deposited over complex local topography, as they mantle gentle to

moderately steep hillsides over locally-derived colluvium or bedrock and can be traced into and out of valleys. We also found bedded shell-rich bioclastic limestone (coquina and marl) in some localities, generally in modern valleys that presumably existed as paleovalleys when the Bouse Formation was deposited. Where relationships are evident, the bioclastic limestone beds are stratigraphically above and down-dip from adjacent tufa deposits, which dip in various directions mimicking the underlying paleotopography. In addition, we found concentrations of locally-derived well-rounded pebbles just outboard of intact tufa layers in a few areas. The rounded gravel deposits in these settings are banked against or draped over bedrock hillslopes and are interpreted to represent bedrock-derived colluvium and alluvium reworked in a shallow-water nearshore or beach environment. At one locality (728,600E, 3,698,250N) a wave-reworked debris flow or landslide deposit is underlain by and overlain by bedded calcarenite (Figure 3).



Figure 3. A wave-reworked debris flow or landslide deposit overlain and underlain by bedded calcarenite.

Although the depositional environment of the southern Bouse Formation is disputed, we favor a lacustrine interpretation based on strontium isotopes (Spencer and Patchett, 1997; Roskowski et al., 2010) and on the relationship between Bouse strata and first arriving Colorado River deposits in the Bullhead City area in northwestern Arizona (House et al., 2008; Pearthree and House, 2014).

The relationships between Bullhead Alluvium and siliciclastic deposits of the Bouse Formation are not obvious because we found no clay or silt deposits that we interpreted as siliciclastic Bouse deposits in the map area. Based on one well 2.2 km west of the map area (well B(01-23)28BAA), a sequence of sand and gravel (presumably Bullhead Alluvium and younger Colorado River deposits) overlies a sequence of blue and yellow clay (presumably Bouse siliciclastic deposits; see cross-section AA'). Well records were provided by the USGS Water Research Center public records archives (USGS, 2016). Deposits in this well suggest that Bullhead Alluvium abruptly overlies Bouse fine-grained siliciclastic deposits at 9 m asl. We infer that this contact is erosional due to its sharp nature and regional relationships between these units (Pearthree and House, 2014;

Howard et al., 2015), but do not know for certain the nature of the contact. We infer an erosional and onlapping relationship between the Tcb and Tbs deposits in the valley axis, although the contact between Tcb and Tbs as shown in cross-section AA' is not known. A gradual contact is projected towards the basin margin, inferring Bouse siliciclastic deposits may be present at depth up to elevations around 130 m based on a fair to poor-quality well log north of the map area (55-596773). The relationship and range of elevations between Tcb and Tbs are consistent with outcrops mapped southwest of the map area near Cibola (Gootee et al., 2016).

Bedrock geology

Bedrock in the map area consists primarily of Jurassic granitoid rocks with less abundant Oligocene to early Miocene felsic volcanic rocks and shallow intrusions. Granitoids are dominated by dark hornblende diorite to hornblende-biotite quartz diorite, with less abundant granodiorite and leucodiorite. The granitoids are associated with diorite schist and gneiss and biotite augen gneiss. Most if not all of these Jurassic granitoid units are thought to be part of the Kitt Peak–Trigo Peaks superunit and that was emplaced regionally at ~173–158 Ma (Tosdal and Wooden, 2015). Foliation generally strikes northwest and dips northeast and is associated with a northeast plunging lineation (see stereonet; stereonet plots and calculations from Stereonet 8 software as described in Allmendinger et al., 2012, and Cardozo and Allmendinger, 2013).

The Oligocene to early Miocene volcanic units include both shallow intrusions and bedded volcanic-lithic clastic to volcanoclastic units. At one location an intrusive contact between a felsic intrusion and bedded volcanic-lithic conglomerate is clearly exposed (Figure 4). The bedded rocks are tilted steeply to the northeast and, although faulted against the Jurassic granitoid rocks, suggest that all of the exposed bedrock was tilted steeply to the northeast by Miocene extensional faulting (e.g., Sherrod and Tosdal, 1991).



Figure 4. Steeply-tilted bedded volcanic-lithic clastic to volcanoclastic beds.

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