DIGITAL GEOLOGIC MAP DGM-65

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GEOLOGIC MAP AND REPORT FOR THE PROPOSED STATE ROUTE 95 CORRIDOR, MOHAVE VALLEY, MOHAVE COUNTY, ARIZONA, VERSION 1.0

A REPORT TO THE ARIZONA DEPARTMENT OF TRANSPORTATION

DECEMBER, 2008

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Geologic Map and Report for the Proposed State Route 95 Corridor in Eastern Mohave Valley, Mohave County, Arizona

Parts of the Franconia, Topock, Warm Springs SE, Warm Springs SW, Needles, Needles NE, Boundary Cone, Davis Dam SE, Oatman, Davis Dam, and Union Pass 7 1/2' Quadrangles

A Report to the Arizona Department of Transportation

by

Philip A. Pearthree, Charles A. Ferguson, Bradford J. Johnson, and Jerome Guynn

Reviewed and approved by Jon E. Spencer, Ph.D., P.G.

Report accompanies

Arizona Geological Survey Digital Geologic Map DGM-65

Map Scale 1:24,000 (5 sheets), 44 p. text

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Introduction

These geologic map sheets and report encompass the proposed State Route 95 Relocation Corridor in Mohave Valley, western Arizona, between the Black Mountains on the east and the Colorado River on the west (Figure 1). The maps were developed through compilation of existing geologic mapping and extensive new geologic mapping. The map area includes a portion of the historical floodplain of the Colorado River, a broad swath of the piedmont east of the river, parts of western flank of the Black Mountains, the channels and terraces of Sacramento Wash, and the northernmost piedmont of the Mohave Mountains (the Powell Mountain area). The corridor is predominantly covered with late Miocene and younger alluvium deposited by local tributary washes and the Colorado River. Deposits range in age from modern to at least 8 Ma (millions of years ago), and deposit characteristics and composition vary substantially depending on whether they were emplaced by the modern Colorado River, older versions of the river, or tributary washes derived from the Black Mountains or the northern end of the Mohave Mountains. The northern, northeastern, and southernmost parts of the map include a variety of bedrock types ranging in age from early Proterozoic to middle Miocene. This map and report describe the physical characteristics of geologic units of different ages and sources, the mapped extent of various geologic units, and potential geologic resource and geologic hazard implications of this mapping. These maps include modified versions of portions of several published maps that have been completed in this area since 1997 (Howard et al., 1997; Howard et al., 1999; Faulds et al., 2001; Murphy et al., 2004; Pearthree and House, 2005; Pearthree, 2007; Spencer et al., 2007; Malmon, in review). Extensive new surficial geologic mapping and bedrock mapping was done where needed.

Acknowledgments

Numerous individuals have assisted us in the development of this map and report. Nick Priznar of the Arizona Department of Transportation was instrumental in the development of this project and has provided review and feedback throughout the process. Ron Blackstone of ADOT also provided valuable information and feedback. Berwyn Willbrink of Jacobs Engineering provided logistical support and information regarding highway alignments. We greatly appreciate the input we have received from our colleague Kyle House of the Nevada Bureau of Mines and Geology, who has devoted a tremendous amount of work and thought to understanding the late Cenozoic geology of Mohave Valley. We have also benefitted from discussions with Jim Faulds of the Nevada Bureau of Mines and Keith Howard, Daniel Malmon and Lee Amoroso of the U.S. Geological Survey. Tephra deposits discussed in this report were analyzed by Mike Perkins of the University of Utah and Elmira Wan of the USGS. Jon Spencer of the AZGS reviewed the report and provided many helpful editorial suggestions. Map cartography was done by Stephen Gyetvai, Ryan Clark, and Genevieve Pearthree of the AZGS.

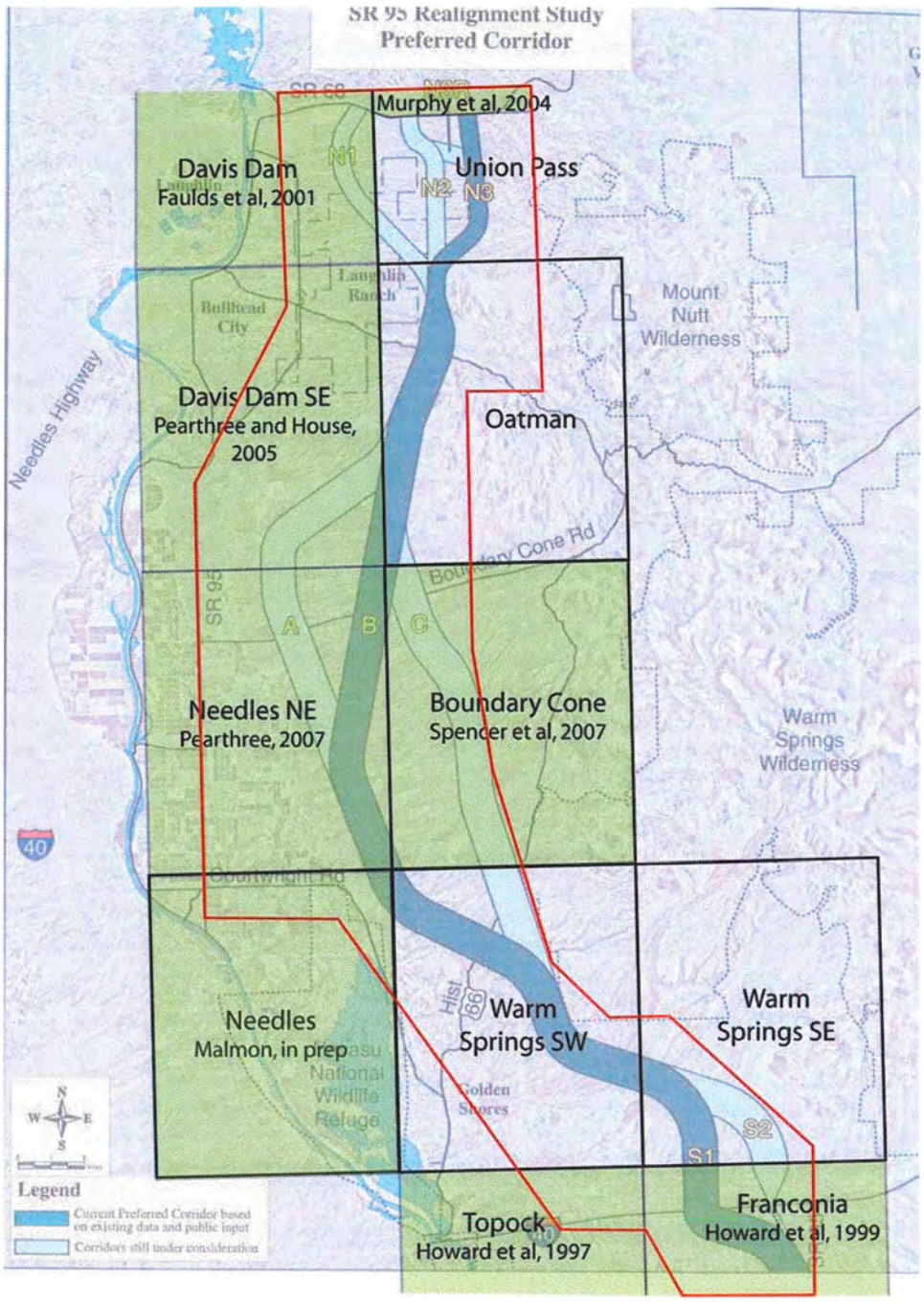


Figure 1. Location of the proposed SR 95 realignment corridors in Mohave Valley, Mohave County, northwestern Arizona. The red polygon outlines the area covered by the maps of this report. Light green shaded areas have been mapped previously. This mapping was modified and integrated into the maps of this report. Unshaded areas involved new mapping.

Mapping Methods

Surficial deposits of the proposed State Route 95 corridor were mapped during several periods beginning in 2000. All of the mapping efforts employed aerial photographs and other remote sensing information with extensive field checking and verification. Several imagery data sets were utilized, including 1:24,000-scale color and false-color infrared aerial photography taken in 1979 for the Bureau of Land Management and color digital orthophotographs taken in 2005 and 2007. Quartz-rich Colorado River sand and gravel deposits were detected and mapped using thermal infrared remote sensing data provided by Simon Hooke of the Jet Propulsion Laboratory. The historical Colorado River floodplain was mapped primarily using black-and-white 1938 and 1953 aerial photos that pre-date significant floodplain modification by agriculture or urban development. Much of the piedmont area in the northern part of the corridor has been covered by new housing developments since aerial photographs were taken in 1979. Opportunities for geologic field observations are limited where the land surface has been altered by development or agricultural activity, but areas are only mapped as "disturbed" if the surface has been profoundly altered. In the remainder of the map, numerous field observations were made between 2000 and the spring of 2008. Mapping was compiled in a GIS format over the digital orthophoto and topographic quadrangle bases, and the final geologic map was generated from the digital data.

Multiple criteria were used to differentiate and map various piedmont and river alluvial deposits. The presence of mature, quartz-rich, typically cross-bedded sand or well-rounded river gravel is the primary evidence used to differentiate Colorado River deposits from piedmont deposits. Deposits associated with Sacramento Wash are somewhat more lithologically diverse than piedmont deposits, but the differences are far less obvious. The oldest deposits in the map area (Tcb and Tfb) are eroded and partially mantled by younger deposits, and do not have preserved alluvial surfaces associated with them. Relative ages of all younger deposits may be determined from topographic relationships between adjacent alluvial surfaces – older surfaces are higher above active washes.

Significant soil development begins beneath an alluvial surface after it becomes isolated from active flooding and depositional processes (Gile et al., 1981, Birkeland, 1999). Over thousands of years, distinct soil horizons develop. In the arid lower Colorado River Valley, calcic horizons (zones of calcium carbonate accumulation) are the most obvious indicator of soil age. Comparison of calcic horizon development on the Black Mountains piedmont with other soil sequences in the western United States is the primary method used to estimate the ages of the different alluvial surfaces (Gile et al., 1981; Machette, 1985; Bull, 1991; Amoroso, 2006). Calcic horizon development varies from very thin, discontinuous coatings of calcium carbonate on gravel clasts in young soils to thick soil horizons cemented with calcium carbonate or silica (caliche) in old soils.

Luminescence dating suggests that fine-grained late Pleistocene Colorado River deposits found up to 100 m above the modern river (map unit Qch) date to 40 to 80 ka (Lundstrom et al., 2008). Based on cross-cutting relationships, Qi2 deposits on the lower part of the piedmont and all Qi3 and Qy piedmont deposits are younger than unit Qch.

Figure 2. Ground photos of Holocene (Qy_1), late Pleistocene (Qi_2), and early to middle Pleistocene (Qo) piedmont surfaces. Holocene surfaces are fairly rough and cobbles and boulders are lightly varnished. Late Pleistocene surfaces are smooth and surface gravel is darkly varnished. Older Pleistocene surfaces have some very darkly varnished gravel clasts but are lighter in color overall because of exposure of carbonate soil fragments and long-term surface erosion related to channel incision.

Figure 3. Aerial photo with geologic map units showing variations in surface color, dissection, drainage patterns with surface age. Active channels, low terraces and active alluvial fans (Qy_2, Qy_1) are light gray in color and have tributary (downstream-merging) and distributary (downstream-branching) channel patterns. Late Pleistocene fans and terraces (Qi_3, Qi_2) have the darkest surfaces and are only moderately dissected by local tributary channel networks. Older Pleistocene alluvial surfaces (Qi_1) are more deeply dissected and are lighter in color because of surface erosion. The oldest alluvial surface in this area (Qo) is an isolated remnant about 40 ft higher than adjacent active washes in the southeastern part of the photo. This area is just south of Boundary Cone Rd, in the north-central part of Map Sheet 3. The black grid lines are 1-km squares; the red lines are one-mile Township and Range grid.

Several surface characteristics are critical to the mapping process because they are recognizable on the ground and are evident on aerial photographs. Surface color varies with age because of rock varnish and desert pavement development. Piedmont deposits of Holocene age typically are light gray to light brown in color, reflecting the color of the volcanic pebbles and cobbles that make up most of the deposits. Local topography is quite rough because of deposition of relatively coarse sediment in bars alternating with finer-grained swales (Figure 2A). Intermediate-age surfaces have a dark brown color because they have been smoothed by erosion of bars and infilling of swales and are mantled by darkly varnished pebbles and cobbles in desert pavements (Figure 2B). Older intermediate-age surfaces typically have some very darkly varnished patches, but overall are somewhat lighter in color because erosion has exposed more underlying calcareous soil. Old surfaces commonly have some very darkly varnished boulders but limited desert pavement preservation. They generally are lighter in color because of the presence of calcium carbonate litter derived from underlying soil horizons (Figure 2C). Differences in the drainage patterns between surfaces provide clues to surface age as well. Young alluvial surfaces that are subject to flooding commonly display anastomosing (splitting and rejoining) or distributary (branching downstream) channel patterns, although young surfaces may have few channels if unconfined shallow flooding predominates. Active channels commonly are incised less than 1 m below adjacent Holocene deposits. Dendritic tributary (joining downstream) drainage patterns are characteristic of older surfaces that are not subject to extensive flooding, and typically older deposits are increasingly more deeply incised and eroded by tributary drainages. The net result of all of these varying surface characteristics is that surfaces of different ages have quite different aspects on the ground and on aerial photographs (Figure 3).

Bedrock mapping, done in the spring and fall of 2007, was concentrated in a fairly narrow strip along the western margin of the Black Mountains south of State Route 68. Contacts were mapped on the ground, with numerous GPS points on contacts and for structural observations. Mapping was compiled on USGS 7.5' quadrangle base maps (Union Pass and Oatman), which were georeferenced and digitized. Bedrock units were correlated with previously mapped units to the north (Murphy et al., 2004), and south (Spencer et al., 2007). The maps and descriptions of Thorson (1971), Lausen (1931), and Ransome (1923) were used to direct new mapping in the Oatman quadrangle.

Geologic Overview

The map area is located within the Colorado River extensional corridor, an area that was highly extended in the early to middle Miocene (Spencer, 1985; Howard and John, 1987) and subsequently recorded the arrival and evolution of the Colorado River in the latest Miocene to early Pliocene (House et al., 2008). Bedrock in the corridor consists of Proterozoic plutonic rocks overlain by lower to middle Miocene volcanic rocks. The absence of any Paleozoic through early Cenozoic rocks in this area implies a major period of regional erosion associated with the late Cretaceous to early Cenozoic Laramide orogeny. Beginning about 20 Ma this was an area of intense volcanic activity, including the formation of a major caldera. The Miocene volcanic and volcaniclastic sequence is compositionally diverse, and includes rocks of basaltic to rhyolitic composition as well as trachybasaltic to trachytic composition. The regionally significant, 18.5 ± 0.02 Ma Peach Spring Tuff (Nielson et al., 1990) is mapped in the sequence. The volcanic rocks are cut by several northwest-striking, northeast-side-down normal faults related to early to middle Miocene regional extension. The youngest basalts, only mildly tilted, are substantially displaced down to the west by more northerly striking faults. Regionally, faulting, tilting and volcanism were broadly synchronous in the early to middle Miocene.

Middle to late Miocene alluvial-fan and finer-grained sediments were deposited in Mohave Valley as it was down-faulted relative to the Black Mountains. Based on the depth to bedrock, these deposits are thousands of feet thick in the center of southern Mohave Valley (Richard et al., 2007). Deposits of the uppermost part of this section are exposed in the upper Black Mountains piedmont, where they lap onto and partially bury bedrock paleotopography along the mountain front and generally are not faulted.

The history of the Colorado River in this area began with the influx of water and sediment from the north after 5.5 Ma (House et al., 2005, 2008). The first deposits associated with the arrival of the Colorado River in this area contain only locally-derived sediment from the northern margin of Mohave Valley. The deposits that record the initial entry of the river into this area are not exposed in the map area, but are found near the Colorado River in northern Mohave Valley (House et al., 2008). These deposits are succeeded by the fine-grained Bouse Formation, which was probably deposited in a series of lakes as the developing Colorado River spilled over successive divides (Spencer and Patchett, 1997; Spencer and Pearthree, 2001; House et al., 2005, 2008; Spencer et al., 2008). Bouse deposits are exposed on the western and southern sides of Mohave Valley (Metzger and Loeltz, 1973), and on the Black Mountains piedmont (Spencer et al., 2007; this map). Bouse deposits may be several hundred feet thick in the subsurface in parts of southern Mohave Valley (Metzger and Loeltz, 1973), but are 10 feet thick or less in most outcrops in the map area (see Figure 4). Outcrops of Bouse Formation range in altitude from less than 500 to 1800 feet above sea level (asl) and have been inferred in the subsurface to lower altitudes (Metzger and Loeltz, 1973). Thus, these deposits record the presence of a deep lake in Mohave Valley and Cottonwood Valley to the north.

After the Bouse lake overtopped and drained to the south, the early Colorado River began a major phase of aggradation that resulted in the accumulation of about 800 feet of river sand and gravel (the alluvium of Bullhead City, unit Tcb; Figures 5 and 6) interfingered with tributary gravel and sand (Black Mountain fanglomerate, unit Tfb; Figure 7) (Pearthree and House, 2005; House et al., 2005, 2008; Pearthree, 2007; Spencer et al., 2007). The maximum level of river aggradation in northern Mohave Valley was about 1320 feet asl and was attained by about 4 Ma. The estimated age of maximum river aggradation is based on several exposures of the ~ 4 Ma Lower Nomlaki tephra interbedded with tributary alluvial fan deposits at altitudes ranging from 1180 to 1480 ft asl (House et al., 2005; Spencer et al., 2007; this map). At locations below about 1300 ft asl, the tephra and tributary deposits are overlain by the highest levels of Bullhead alluvium (Figure 8). As a result of this major phase of river aggradation, much of the Black Mountains piedmont below 1300 ft asl is probably underlain by Pliocene river sand and gravel. The timing of maximum piedmont aggradation is less well-constrained, but probably also occurred in the middle Pliocene. The highest preserved levels of aggradation on the piedmont are ridges capped by Pliocene to early Quaternary QTa deposits or eroded ridges of late Miocene to Pliocene Tfb deposits.

Figure 4. Photos of Bouse Formation deposits. The top photo shows light-colored tufa deposits draped on a dark bedrock outcrop. The middle photo show thin-bedded marl intercalated between alluvial fan deposits. Both photos were taken along Silver Creek Wash in the northern part of Map Sheet 4. The bottom photo shows much thicker clay, silt and sand deposit near I-40 along the southern part of Map Sheet 2.

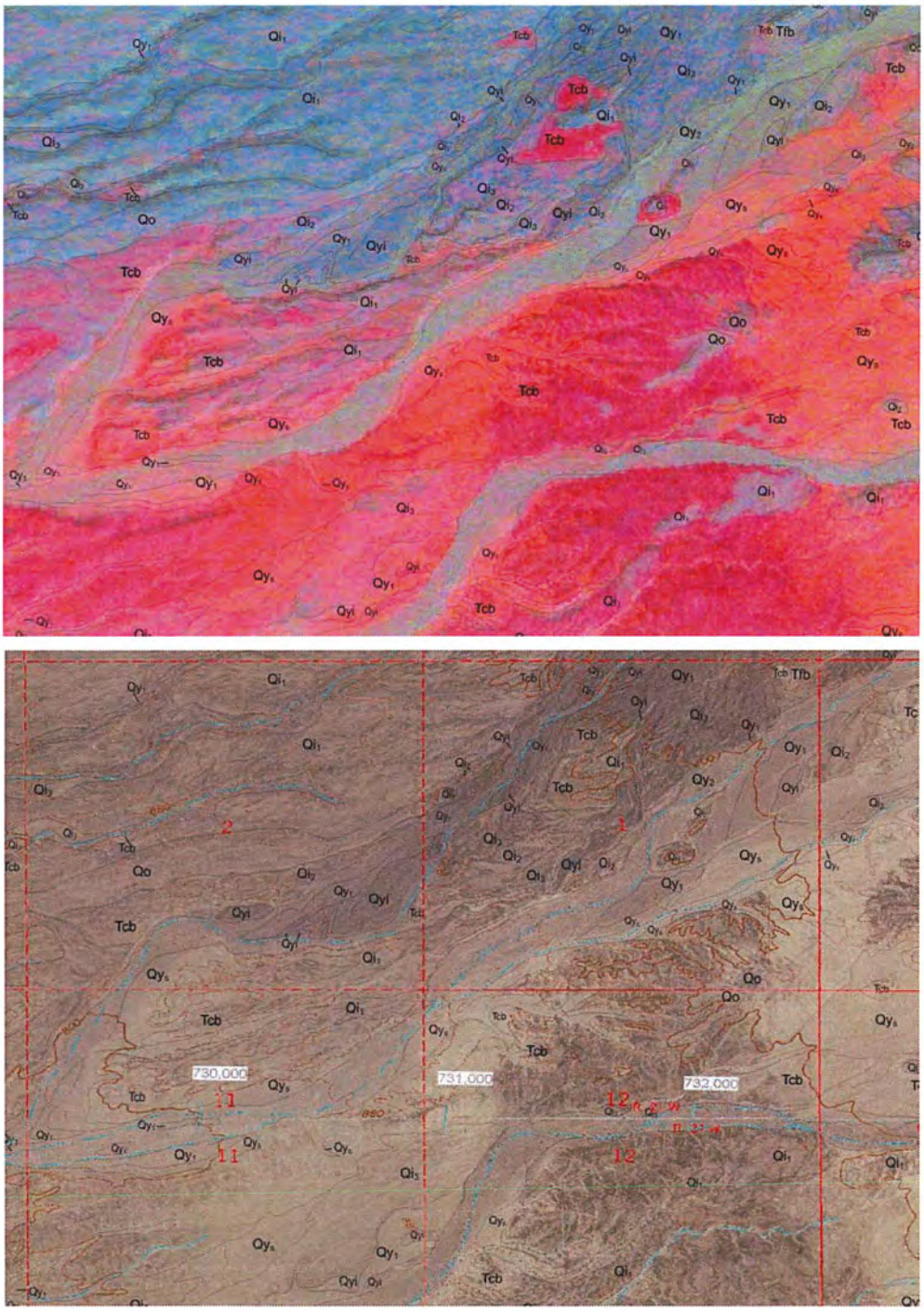


Figure 5. Example of MODIS/ASTER Airborne Simulator (MASTER) remote-sensing imagery (Hook et al., 2001; 2004) highlighting quartz-rich Colorado River deposits. Quartz-rich sand and gravel deposits are bright red in the top image. Locally-derived volcanic-rich gravel shows up as purple, light blue or green. Locally, quartz-rich Colorado River deposits have been reworked and incorporated into tributary deposits, leading to a mix of these colors. The lower image is an aerial photograph of the same area. The dark brown areas in the lower right are covered by varnished river gravel.

Figure 6. Photos of sand and silt beds (top) and gravelly beds of Pliocene Colorado River deposits (unit Tcb). Sand and gravel beds typically are moderately to weakly indurated and exhibit planar to trough cross-bedding. Fine sandy and silty beds that dominate the right part of the exposure in the top photo are less well-indurated. Both sequences are overlain by tributary gravel that was deposited above erosion surfaces cut onto the older river deposits.

Figure 7. Photos of Black Mountain fanglomerate (Tfb). Upper photo is a ~60-foot-high section exposed in Secret Pass Canyon in the southernmost part of Map Sheet 5. Lower photo shows depositional onlap of Tfb deposits onto a gently basinward-sloping bedrock erosion surface, looking north across Secret Pass Canyon. High alluvial ridges in the middle distance are capped by QTa deposits.

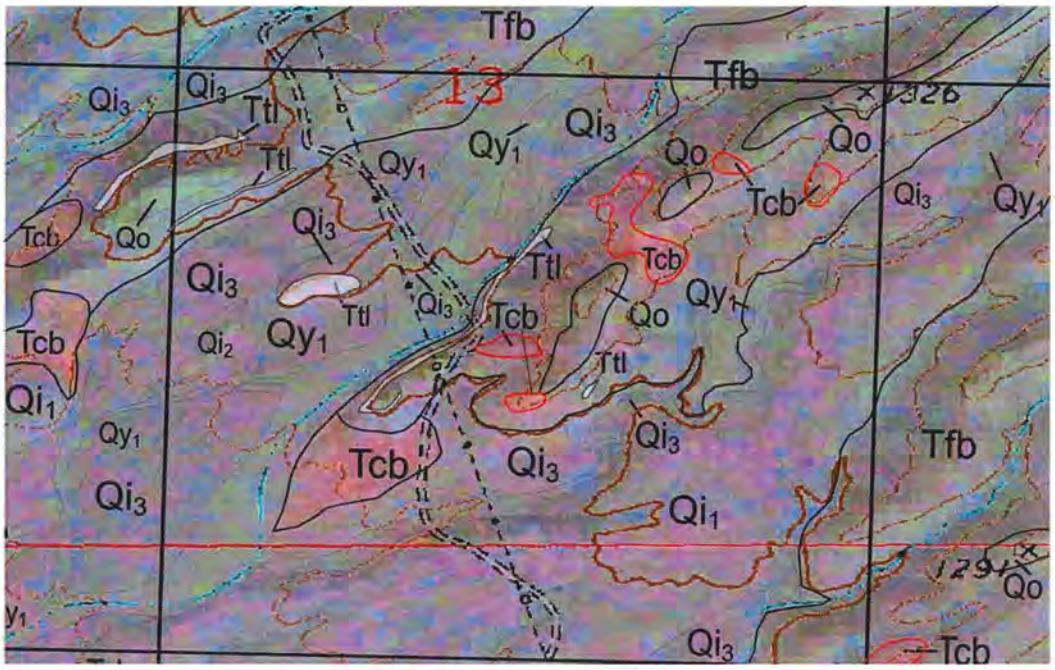


Figure 8. Detail of geologic relations between early Pliocene Colorado River deposits (Tcb), Black Mountain alluvial fan deposits (Tfb), and the Lower Nomlaki tephra (Ttl) in the Boundary Cone quadrangle (Map Sheet 3). The Lower Nomlaki tephra was deposited on a gently west-sloping, fine-grained alluvial fan surface, but Colorado River sand and gravel deposits (Tcb) in the immediate vicinity are found both stratigraphically below (black outlines) and above (red outlines) the tephra bed. Background is a MASTER image, so quartz-rich Tcb deposits are reddish. Ttl outcrops are shown in white for emphasis. The black grid is 1 km (0.62 miles).

The Colorado River had begun to incise into the valley fill by the middle Pliocene when tributary alluvium containing the 3.3 Ma Nomlaki tephra was deposited above an erosion surface that cut across the uppermost part of the old river deposits (Figure 9; Pearthree and House, 2005; House et al., 2005). A tremendous amount of sediment was removed from the valley as the river downcut to a level close to the modern river by the early Quaternary, when Qo alluvial fans were deposited. Subsequently, one or more periods of major river aggradation occurred during the Quaternary. The youngest and best-preserved fine-grained river deposits date to the late Quaternary (unit Qch; Figure 10; Lundstrom et al., 2008; Malmon et al., in review) and reached about 800 to 840 feet asl in this area, 300 to 350 feet above the modern river. There were periods of aggradation earlier in the Quaternary as well, but maximum levels of aggradation in these periods is not well-constrained (House et al., 2005. After the time of maximum late Quaternary river aggradation, at least 2 late Pleistocene to early Holocene terraces at levels of ~520-540 (Qc_1) and 490-500 (Qc_2) feet asl (approximately 40-60 ft and 10-30 ft above the modern river, respectively) record periods of more minor river aggradation, lateral river erosion, or both. The width of the historical Colorado River floodplain varies dramatically in Mohave Valley, widening fairly dramatically from about 0.25 miles in northern Mohave Valley to about 5 miles in the central and southern parts of the valley.

Figure 9. The prominent, lenticular white bed in the upper part of this exposure is the 3.3 Ma Nomlaki tephra interbedded with QTa deposits. This tephra is exposed at several locations on the south side of Silver Creek Wash at altitudes ranging from 1160 to 1280 ft asl (northern part of Map Sheet 4). Thus, by 3.3 Ma the Colorado River had incised below 1160 ft asl.

The Colorado River has been greatly modified by the erection of large dams upstream. Prior to completion of Hoover Dam in 1935 the Colorado River was subject to substantial seasonal and annual variations in flow, with large flood discharges in years with substantial spring snowmelt. Most and possibly all of the historical floodplain was subject to inundation during large pre-dam floods on the river, and clear evidence of recent channel migration and abandonment was preserved in the 1938 aerial photos of the floodplain (Figure 11A). Reduction of flow variations combined with anthropogenic confinement of the river channel permitted the development of modern agriculture on the floodplain, which in large measure masked the underlying river deposits (Figure 11B). The modern channel is quite narrow (it is west of the map area), and most of the historical channel (also west of the map area), recently abandoned channels and floodplain area (unit Qc_{r2}), and slightly older floodplain area (unit Qc_{r1}) has been altered by urban development or agricultural activity.

Tributary washes have responded to the variations in base level imposed by the Colorado River and climate changes during the past 5 million years. As the river aggraded in the early Pliocene, tributary drainages deposited alluvial fans that interfingered with the Colorado River deposits (unit Tfb; see Figure 8). Near the Black Mountains, deposits of this period are exclusively tributary (Figure 7), the lower piedmont is underlain primarily by Pliocene Colorado River deposits, and the middle piedmont contains both river and tributary deposits. As the river began to incise after 4 Ma, tributary alluvium (QTa) was deposited over erosion surfaces cut onto the Colorado River / tributary alluvium. At least 2 separate early and middle Quaternary piedmont aggradation periods are recorded by units Qo and Qi_1. The next widespread piedmont alluvial deposit (unit Qi_2) was deposited locally above an erosion surface cut across the highest level of late Pleistocene river deposits (unit Qch), and thus is also late Pleistocene in age. Several younger late Pleistocene and Holocene piedmont units are graded to the younger river terraces or

the modern floodplain (units Qi_3, Qyi, and Qy_1). On much of the Black Mountains piedmont, Pleistocene to Pliocene deposits are moderately to deeply dissected and modern washes are entrenched far below surrounding remnants of older deposits. In some parts of the piedmont, however, there are no exposures of older Pleistocene and Pliocene deposits, topographic relief between active washes and late Pleistocene deposits is minimal, and complex anastomosing and distributary drainage networks are pervasive (see Figure 3).

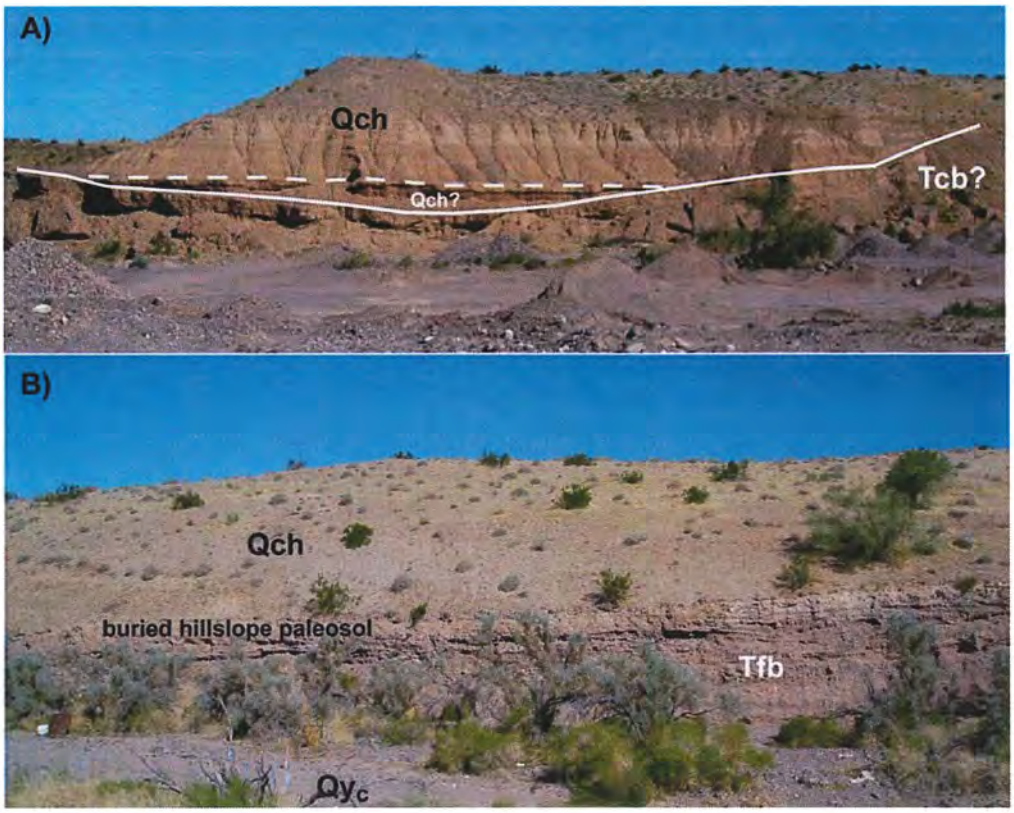


Figure 10. Exposures of late Pleistocene Chemehuevi Formation (unit Qch). (A) Clay/silt beds fill a broad paleovalley, with a fairly well-developed calcic paleosol marking the unconformity (dashed white line). Fine-grained deposits below the paleosol record an earlier episode of partial valley filling. All of these deposits are inset into older Colorado River deposits (solid white line). There is a small aggregate quarrying operation in the valley bottom. (B) Sandy deposits of the Chemehuevi Formation onlap eroded gray Tertiary tributary fan deposits (unit Tfb) over an unconformity marked by a strongly developed calcic soil (thin light tan layer dipping gently to the left). The river deposits buried an old hillslope formed on the Tfb fan deposits.

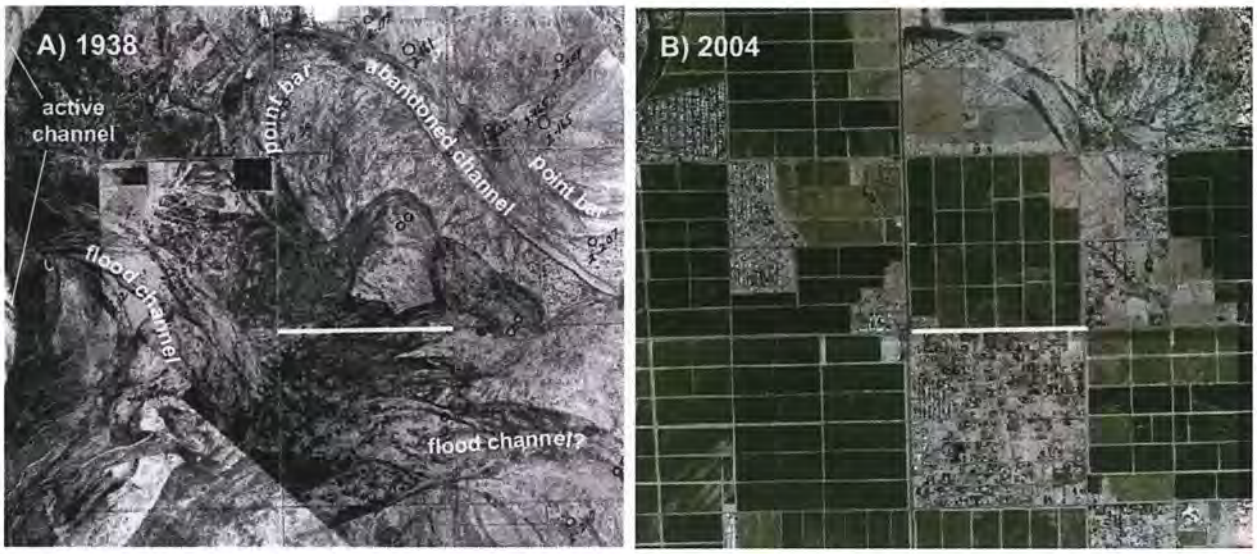


Figure 11. Comparison of the modern and historical Colorado River floodplain. The aerial photograph from 1938 reveals a dynamic floodplain, with abundant evidence of shifts in channel position in the latest Holocene. Large dams on the river limit modern flood inundation and anthropogenic activity has masked most of the floodplain. The bold white lines are 1 mile in length and in the same geographic position in each photograph.

Quaternary Deformation and Seismic Hazard

A series of low fault scarps and larger amplitude possible folds formed on Pliocene and Pleistocene alluvial fan and river deposits extend from the far southeastern corner of the Needles NE quadrangle through most of the Warm Springs SW quadrangle (map sheets 2 and 3; Figure 12). This zone of deformation includes the 4 km-long Needles graben, which was first recognized in the 1970's (Metzger and Loeltz, 1973; Purcell and Miller, 1980; Schell and Wilson, 1982). *[Note – metric units are use in this section because this is the standard for expressing fault slip rates, and metric units are used in formulas to estimate paleoearthquake magnitudes.]* Fault scarps associated with the Needles graben have fairly gentle slopes, and total vertical surface displacement is a few meters or less, consistent with a low long-term fault slip rate. Several larger-scale tectonic features along this trend that have been recognized more recently (K. Howard, in House et al., 2005; this mapping) vertically displace older Quaternary alluvial fan deposits by tens of meters.

Previous reconnaissance investigations and analyses of fault scarps associated with the Needles graben indicated that it has had recurrent Quaternary movement, and that the youngest displacement event occurred in the late Pleistocene (Purcell and Miller, 1980; Shell and Wilson, 1982; Menges and Pearthree, 1983; Pearthree et al., 1983; Anderson and O'Connell, 1993; Pearthree, 1998). Faulting generated a series of low fault scarps on the northeast side of the graben and generally smaller scarps on the southwest side of the graben, with a shallow trough between the scarps. The northeastern fault scarps are as much as 6 m high on early to middle Pleistocene alluvial fans (unit Qo), whereas scarps are less than 2 m high on an adjacent late Pleistocene alluvial fans (Figure 13; Table 1). Holocene and younger late Pleistocene deposits

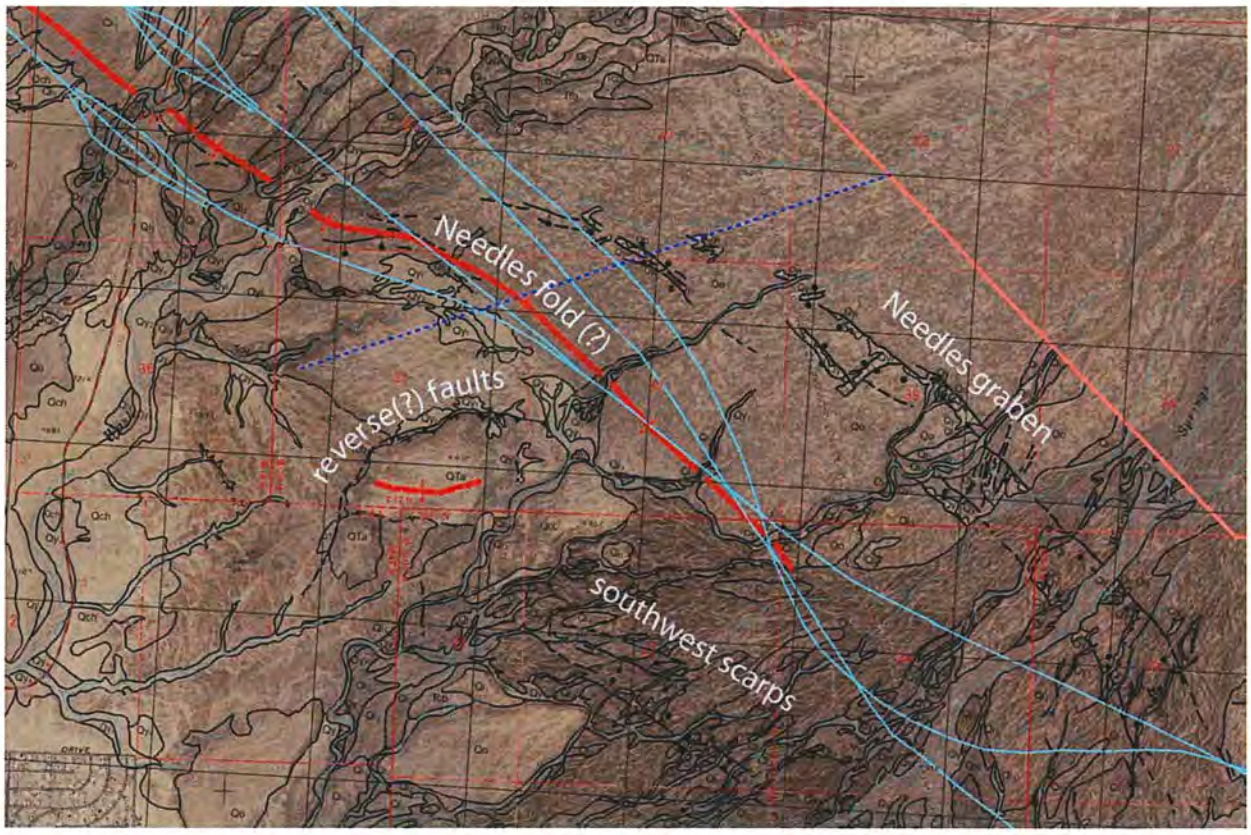
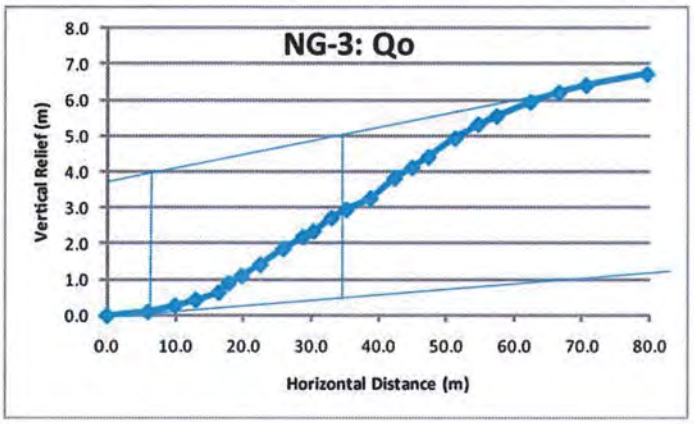
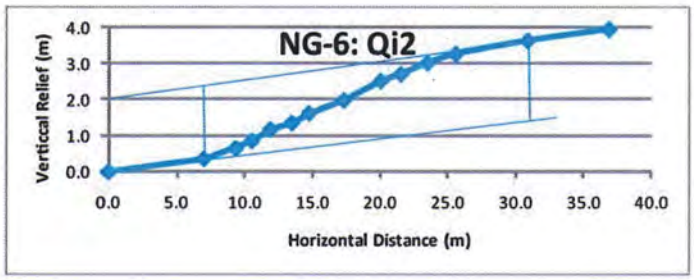


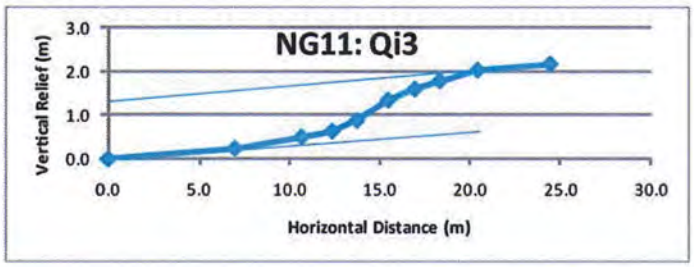
Figure 12. This photogeologic map depicts part of the Needles fold(?) (red) and graben (black faults north and east of the fold), and other faults associated with the structural zone. Northeast- to east-trending faults trending west of the fold(?) may be reverse or thrust faults (K. Howard, in House et al., 2005). The blue dashed line is the location of the topographic profile across the fold(?) shown in Fig. 14. Light blue lines are possible highway alignments.

are not displaced. This indicates that recurrent movement has occurred on these faults during the Quaternary, with the youngest displacement during the late Pleistocene (roughly 15,000 to 130,000 years ago; Pearthree, 1998). The long-term slip rate inferred for the Needles graben was generally low because of the small amount of surface displacement, and the short length of the graben (4 to 7 km) implied that the largest earthquake that would be expected from this fault zone was less than M 6 (Table 1).

Recent geologic mapping in the Needles NE (Pearthree, 2007) and Warm Springs SW (K. Howard, in House et al., 2005) quadrangles and mapping done for this report revealed much more extensive and larger amplitude surface deformation in the area than previously recognized. These investigations identified a large, gently sloping (9 percent or 5° maximum slope) scarp associated with a deformation zone (fold?) located about 1 km west of the Needles graben and extending about 5 km to the northwest (House et al., 2005; this map). The same early to middle Pleistocene alluvial fan surface (Qo) that is cut by faults of the Needles graben is down-dropped to the southwest by at least 30 m across this deformation zone (Figure 14), and there may be a reverse or thrust fault west of the zone (House et al., 2005). In addition, early Pliocene Colorado River deposits exposed along the zone near Old Highway 66 dip ~15°-20° to the west,







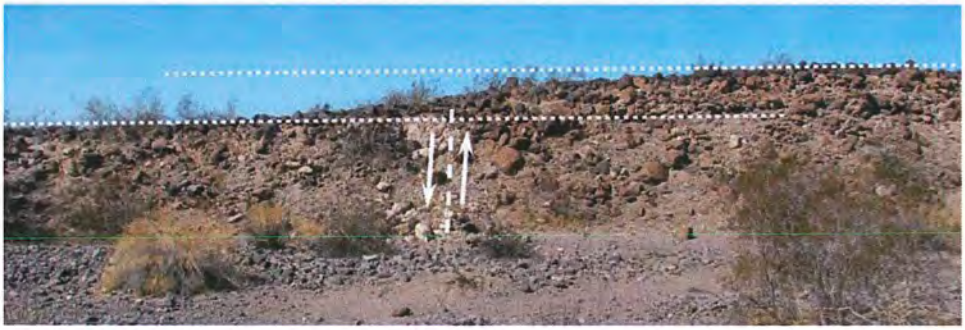


Figure 13. Topographic profiles surveyed across fault scarps associated with the Needles graben (Menges and Pearthree, 1982, unpublished data). The largest scarps formed on early to middle Pleistocene Qo surfaces are about 6 m high, with 4 to 5.5 m of vertical displacement. Displacement of late Pleistocene Qi2 and Qi3 surfaces is substantially less (1-2 m), indicating that recurrent displacement has occurred across this zone and the most recent event or events occurred in the late Pleistocene. The photo shows a profile view of a fault scarp formed on Qi2 deposits on the north side of Warm Springs Wash. Fine-dashed lines are projections of alluvial fan surfaces above and below the fault zone. Larger dashed line and arrows show the likely location of and sense of movement across the fault zone.

Section	Length (km)	vertical displacement (m)	surface age (ka)	slip rate (mm/yr)	Estimated moment magnitude (Mw)	Primary trend
Needles graben[1]	8	3	30-100	0.03-0.1	6.5	
Needles graben[2]	3-7	na	na	na	6 ¼	
Needles graben[3]	7	5	500-1,000	0.004-0.01	6.1	NW
southwest scarps[3]	2	2	50-100	0.01-0.04	5.4	NW
reverse(?) faults[3]	2.2	15-20	500-1,000	0.015-0.04	5.5	E, NE
Needles fold(?)[3]	7	30-40	500-1,000	0.03-0.08	6.1	NW
northern scarps[3]	2, 4.5	0.5-1	50-100	0.005-0.02	5.8	NNE, N, NNW
southwest fold[3,4]	~2.5[4]	unknown	unknown	na	5.5	NW
total deformation zone	20				6.6	NW, N

[1]from Euge et al. (1992) and Schell and Wilson (1982); note that their relatively high slip-rate estimates are based on the relatively young age estimate of faulted deposits. We interpret these deposits as Qo, dating to the early to middle Pleistocene – i.e., 500 to 1000 ka

[2]from Anderson and O'Connell (1993)

[3]this study

[4]length of southwest fold is very poorly constrained

Table 1. Some general parameters of the Needles fold and graben zone. Maximum and minimum slip-rate estimates are derived from maximum displacement/minimum age and minimum displacement/maximum age estimates, respectively. New potential earthquake moment-magnitude estimates are based on mapped fault length using the equation Mw = 5.09 + 1.15*log (length) developed by Wells and Coppersmith (1994) from historical surface-rupturing earthquakes.

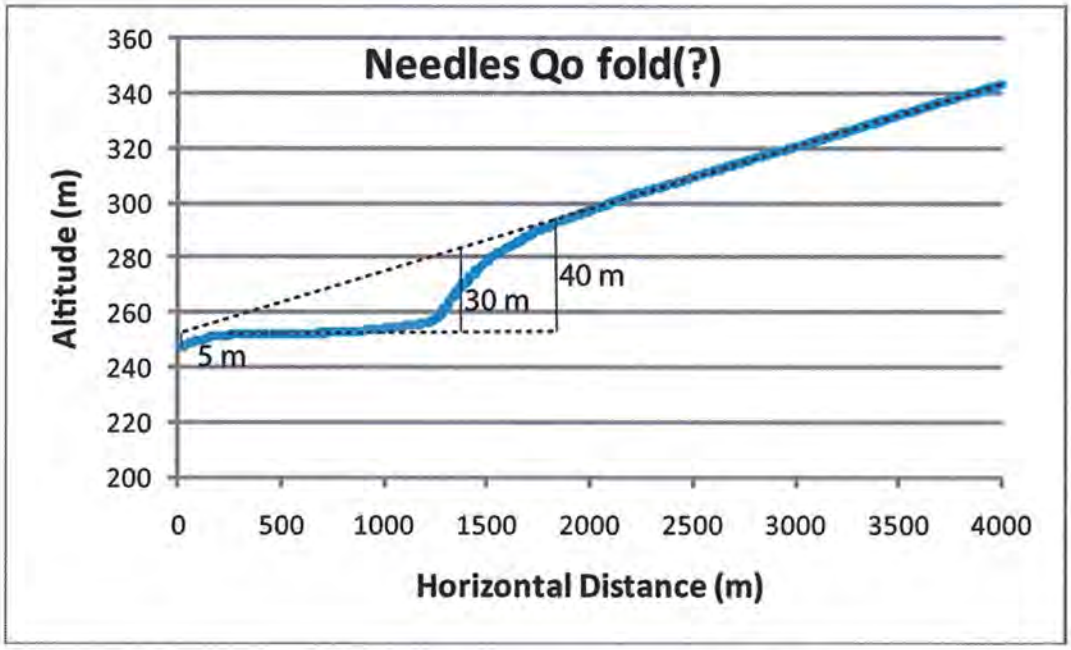


Figure 14. Topographic profile across the large scarp associated with the main, NW-trending deformation zone. The height of the scarp formed on the early to middle Pleistocene Qo surface is more than 40 m. Net vertical displacement across the structure may be much less, however. Although the alluvial fan surface above the scarp and small surface remnant at the western end of the profile both dip about 2.5 percent (1°) to the west, the Qo surface immediately west of the structure is essentially flat (0.2 percent dip to the west). This suggests that the Qo fan surface has been tilted to the east below the deformation zone, and net displacement across the zone may be 5 m or less. The western end of the profile is on the westernmost continuous part of the Qo surface – it is eroded farther west (see Figure 12).

substantially greater than the dip of the deformed Qo surface. Greater deformation of older deposits implies that they were tilted and then an erosion surface was cut across them prior to deposition of the Qo deposits, which were subsequently deformed as well. This indicates that the deformation zone has been active through at least the late Pliocene and Quaternary, although the total amount of displacement during that time is unknown. The relatively large amount of Pliocene and Quaternary displacement across the deformation zone implies that it is the primary structure in this area and that the Needles graben is a related feature. Middle Pleistocene Qi1 deposits are clearly displaced across the deformation zone, but it is not clear whether late Pleistocene Qi2 and Qi3 deposits are displaced. The gentle slope and broad width of the large scarp associated with this zone suggests that the Qo surface has been folded, or that deformation across the zone is distributed fairly broadly. The apparent back-tilting of the Qo to the northeast below the scarp, however, is consistent with roll-over or local graben formation due to decreasing fault dip at depth, a phenomenon that is common along normal fault zones (e.g., Amoroso et al, 2004). At this time, nothing is known about amounts of displacement in individual faulting events that generated the large fault scarp. Quaternary and Pliocene deposits

are also folded in the southernmost part of Mohave Valley near Topock (extreme southwestern part of Map Sheet 2; Reynolds et al., 2007).

The total length of the zone of deformation is much greater than the Needles graben. The current mapped length of the Needles graben and closely associated fault scarps is about 7 km (Table 1). The larger amplitude possible fold is clearly expressed for about 7 km; part of its length overlaps with the Needles graben (Figure 12). Discontinuous low fault scarps continue another 2 to 5 km north of the monocline. Substantial gaps exist between fault scarps, however. Two other sets of fault scarps are located southwest of the possible fold (Figure 12). The "southwest scarps" cut late Pleistocene fan deposits (units Qi2 and Qi3) and are less than 2 m high. The reverse(?) faults cut much older Qo and QTa deposits, and there is a ~15 m high scarp associated with the northern reverse fault. Thus, local deformation across the reverse faults is only slightly less than that across the fold immediately to the northeast.

The potential seismic hazard posed by the Needles fold and graben system is poorly understood at this time. Previous seismotectonic analyses of this region have assumed a maximum credible earthquake magnitude of M 6 ¼ to 6 ½ (Euge et al, 1992; Anderson and O'Connell, 1993), but these estimates assumed a fault rupture length of 7-8 km. Long-term average slip rates inferred for the fault zone were generally quite low because of the small amount of displacement associated with the graben, but varied substantially because of differing age estimates for the deposits mapped as Qo in this report (Table 1). Average slip-rate estimates presented in this report are derived from vertical displacement estimates divided by surface age estimates. These slip-rate estimates are higher than most previously reported estimates (the exception is Euge et al, 1992) because of the larger displacement across the possible fold. This study does not provide any new information regarding vertical displacements in individual faulting events. Displacement of late Pleistocene alluvial surfaces along the Needles graben suggests that 1-2 m of displacement occurred in the youngest faulting event along the graben, but we know nothing about individual surface displacements associated with the larger fold. Of clear significance for seismic hazard assessments is the increase in the estimated length of the deformation zone from 7-8 km to 20 km, as this increases the estimated maximum earthquake magnitude to about 6.6 (Table 1).

Flood Hazards

The surficial geology of the map corridor combined with local topography provide clues to the extent and character of flood hazards. Geologically young fluvial deposits (units Qy_2 and Qy_1 along tributary washes and units Qy_2r and Qy_1r along Sacramento Wash) record recent fluvial activity. Sacramento Wash is incised and flooding is restricted to the broad valley bottom. The fact that the valley bottom is covered by Holocene deposits strongly suggests that most of the valley bottom is the floodplain and has been subjected to relatively recent inundation, deposition, and changes in channel positions.

The character of flood hazards posed by tributary washes along the proposed realignment corridor varies substantially, in some cases over relatively short distances. Along much of the proposed alignment for SR 95, tributary washes are moderately to deeply incised into Pleistocene or Pliocene deposits (Figure 15). The primary drainage pattern in these areas is downstream-merging (tributary), so the map pattern of active washes is relatively simple. In these areas, flooding is restricted to valley floors that are covered with Holocene deposits. Valley sides are

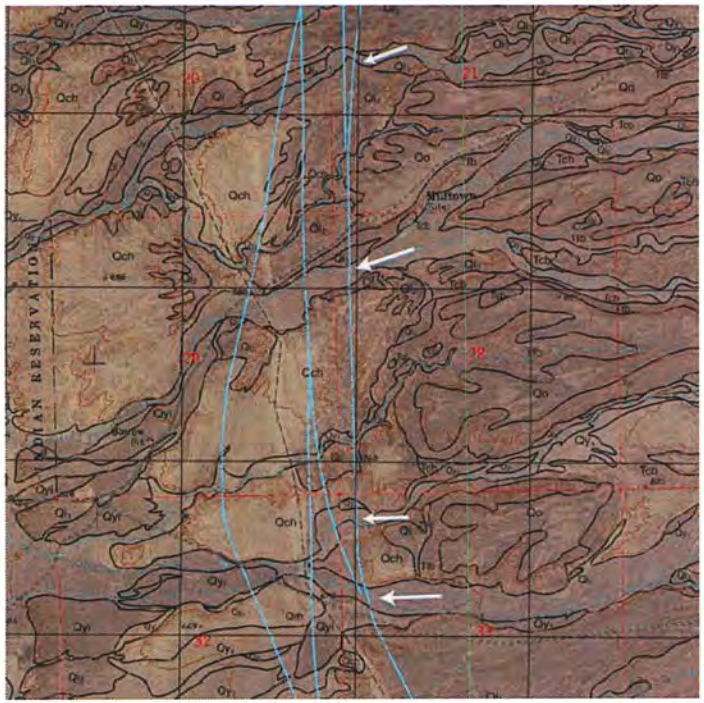


Figure 15. An example of drainages incised into Pleistocene and Pliocene tributary and river deposits (southern part of Map Sheet 4). In this area, young deposits are limited in extent and there is substantial local topographic relief between active washes and adjacent older deposits. Flooding is confined to a few relatively broad valley bottoms (white arrows), so there would be only 4 significant drainages to cross in this roughly 2.5 mile stretch of highway.

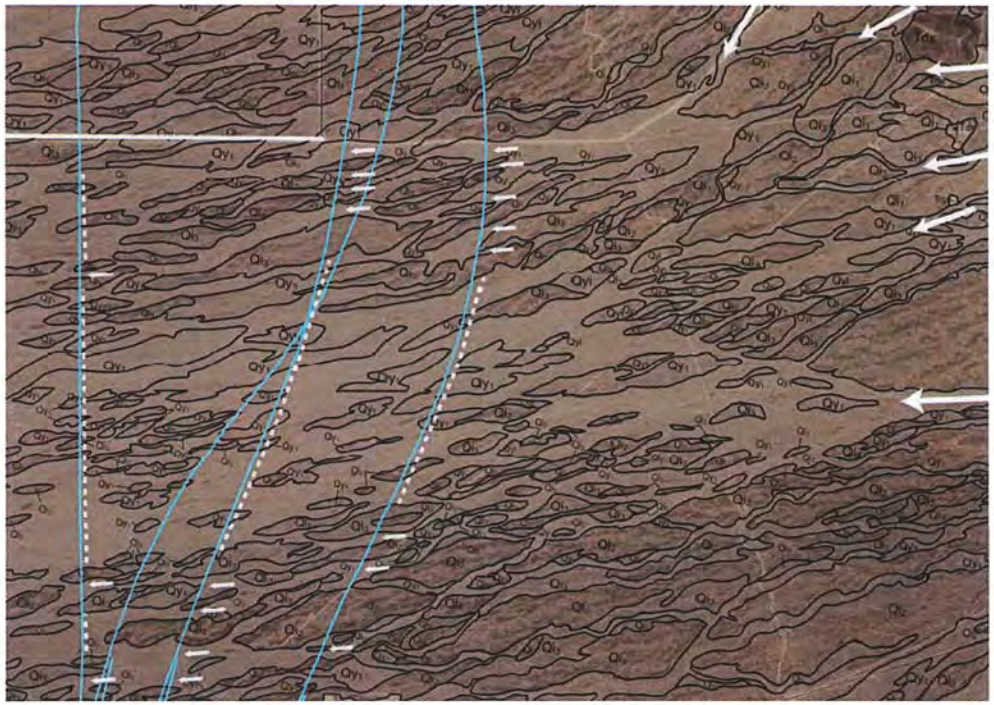


Figure 16. Sheetflood area north of Boundary Cone Road and south of the Mohave County Landfill (Map Sheet 4). Local topographic relief is a few feet or less along the proposed highway alignments and drainage patterns are very complex. Late Pleistocene alluvial surfaces (dark areas) are a few feet or less higher than the extensive, light-colored Holocene alluvial surfaces. Several moderately well-confined washes feed into the area from the east (large white arrows), but through this area drainage patterns are complex and distributary, with broad areas of sheetflooding. The dashed lines along highway alignments show areas of probable sheetflooding and smaller arrows show more topographically confined distributary drainages. The solid white bar is 1 mile.

commonly formed by moderately indurated older deposits; bank erosion clearly occurs locally during floods, but in small increments because of the resistance of the bank materials.

Flooding is much more complex in areas where local topographic relief is minimal, channel patterns are very complex, and younger deposits are extensive (Figure 16). The extensive young deposits indicate broad inundation and probably changes in channel positions have occurred during the Holocene (Pearthree et al., 2000, 2004). Channel patterns in these areas are primarily distributary (downstream-branching) and anastomosing (branching and re-combining downstream). Channels of smaller washes commonly are discontinuous, disappearing downstream in areas of flow expansion only to re-emerge at the downstream ends of the expansion. Given the minimal lateral topographic confinement and evidence of laterally extensive young deposition, it is clear that large floods substantially exceed channel capacity, resulting in widespread sheetflooding.

Flood hazards associated with the upper portions of active alluvial fans present a similar challenge. The apex of an active alluvial fan is the area where flow transitions from laterally confined to unconfined conditions. In confined reaches, the channel system typically consists of one or several fairly large and obvious channels with relatively limited flanking young terraces. In the apex area, channels branch downstream and young deposits become much more extensive (Figure 17). Downstream from the apex, channels typically continue to branch and individual channels are much smaller. The potential for significant channel changes is relatively high near fan apexes, and any change that occurs there will affect flow patterns downstream on the fan (Field, 2001; Pearthree et al., 2004). Choice of alternate highway alignments in these environments may substantially affect the cost of highway engineering and construction. For example, choice of the eastern alternative route crossing Warm Springs Wash would effectively avoid the active alluvial fan and minimize the width of potential flow that would need to be crossed (Figure 17).

Geologic Resources

Late Cenozoic Colorado River and tributary deposits in the Highway 95 relocation corridor are an abundant source of potential aggregate for construction. At this time, small to moderately large aggregate operations are extracting gravel and sand from early Holocene and late Pleistocene, quartz-rich gravelly river terrace deposits (units Qc_1 and Qc_2) along the margins of the historical river floodplain in the Needles NE quadrangle (western part of Map Sheet 3). Thicker late Pleistocene deposits (unit Qch) are generally quite fine-grained (sand and finer) and no sizable aggregate operations are exploiting these deposits. In the Davis Dam quadrangle to the north, much larger aggregate operations are mining extensive and thick Pliocene Colorado River deposits (unit Tcb) and old tributary gravel deposits (units Tfb, Qo and Qi_1) (Figure 17). Tcb deposits are widely exposed in the Davis Dam, Davis Dam SE, Needles NE, Boundary Cone, and Warm Springs SW quadrangles and probably underlie much of the piedmont below about 1300 feet. Thus, much of the mapped area likely has significant potential for high-quality, Colorado River-derived aggregate resources.

Another potential source of aggregate is the extensive, coarse, basalt-rich tributary alluvium on the the Black Mountain piedmont. Tributary alluvial fan deposits in the northern part of the map corridor typically have a mix of volcanic lithologies, including basalt but also more felsic rocks such as dacite and rhyolite. Farther south, granite clasts are common in addition to mixed

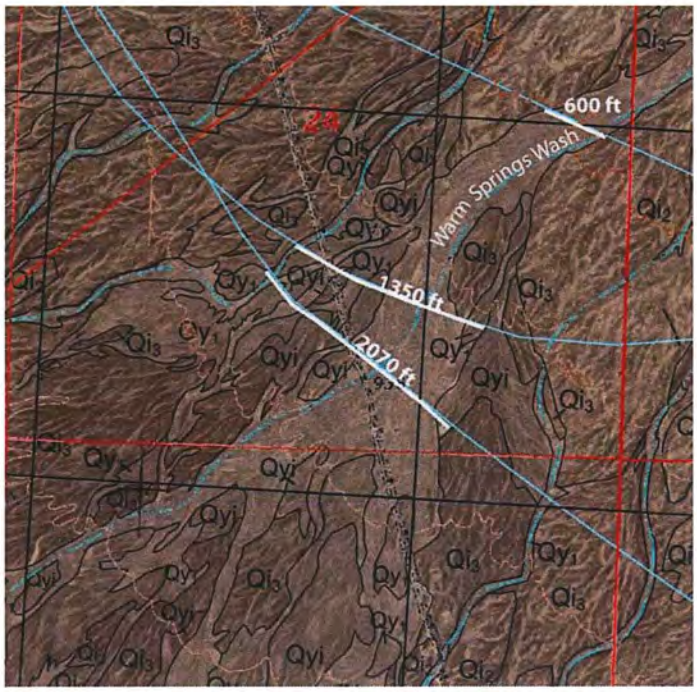


Figure 17. The apex area of Warm Springs alluvial fan, Map Sheet 2. The light blue lines are alternative highway alignments. The northeasternmost alignment would cross Warm Springs Wash where it is relatively narrow and confined between late Pleistocene alluvial fan deposits. Downstream alignments would cross the fan apex, where possible flow paths are much broader and less predictable. The red lines are 1-mile township boundaries.

Figure 18. Large aggregate operation is outlined in white along Secret Pass Wash in northern Bullhead City, just west of the map area and Bullhead Parkway. Background is a MASTER image over an orthophoto. Based on distant field observations and the red color in the MASTER image, the aggregate operation is exploiting a combination of Pliocene Colorado River sand and gravel and tributary gravel.

Figure 19. Examples of basalt-dominated alluvial fan deposits in the Warm Springs SW quadrangle. The upper photo shows the surface of a Qi2 fan; subsurface carbonate accumulation is minimal here. The lower photo shows a Qo fan, which has substantial calcium carbonate accumulation in the near subsurface (the upper ~10 feet of the deposit).

volcanic lithologies (for example, in the area of Figure 16). In the southern 2/3 of Boundary Cone quadrangle and most of Warm Springs SW quadrangle, however, very extensive tributary fan deposits are dominated by resistant basalt cobbles and boulders (Figure 19). Younger Pleistocene and Holocene deposits have minor calcium carbonate accumulations in the uppermost few feet; older Pleistocene deposits typically have several feet or more of substantial carbonate accumulation. Many of the basalt cobbles and boulders are quite resistant to

weathering, as relatively intact clasts mantle alluvial surfaces that are hundreds of thousands to millions of years old (units Qo, QTa).

There are extensive exposures of Miocene basalt in the Black Mountains (see for example, Spencer et al, 2007), but the accessibility of these potential aggregate resources is uncertain. There are, however, small outcrops of basalt on the western (downthrown) side of the Roadside Mine fault near or within the proposed highway alignments about 2 miles south of State Route 68 (Map Sheet 5) and about 2 miles east of the highway alignments in the southeastern corner of Map Sheet 4.

Potentially Unstable Substrate

Most of the tributary and river deposits beneath the proposed highway realignment corridor are likely to be fairly stable. Two map units contain significant clay- and silt-rich deposits that may be locally unstable – the late Pleistocene Colorado River deposits of the Chemehuevi Formation and the latest Miocene to early Pliocene deposits of the Bouse Formation. Chemehuevi outcrops typically are capped by fairly thick sandy deposits, but underlying deposits are generally fine-grained and locally clay-rich (Figure 10). The fine-grained deposits locally contain small veins of gypsum and other whitened areas that are probably gypsum, and in some clay-rich areas the surfaces of outcrops are extensively cracked, suggesting some degree of expansion and contraction with wetting and drying cycles.

Unstable substrate problems associated with the Bouse Formation deposits have caused substantial maintenance issues for the Arizona Department of Transportation along Interstate Highway 40 (Map Sheet 1; N. Priznar, ADOT, oral communication). In this area, the Bouse Formation is predominantly clay and silt, and the basal marl is not exposed (Figure 4, bottom). All Bouse Formation deposits exposed south of Sacramento Wash, in the southern part of Map Sheet 1, are similar in character and may be unstable, and Bouse deposits may well be more extensive in the shallow subsurface in that area. The proposed interchange of SR 95 and I-40 is very close to extensive Bouse Formation outcrops, and it is likely that Bouse deposits are more extensive in the shallow subsurface in that area (Figure 20).

Bouse deposits are exposed at many localities in middle and upper piedmont areas north of Sacramento Wash. Almost all of the Bouse exposures consist of very thin (less than 20 feet) marl or calcareous sandstone. These thin Bouse deposits will almost certainly present no engineering problems. Thicker, fine-grained clastic Bouse deposits are exposed along both sides of Secret Pass Canyon between 1240 and 1400 ft asl. On the north side of Secret Pass Wash, large blocks of indurated alluvial fan deposits (unit Tfb) that overlie the Bouse deposits have foundered and slid downslope, partially mantling the Bouse deposits (Figure 21). In the Secret Pass Wash area, proposed SR 95 alignments are closer to the Black Mountains where Bouse deposits consist of thin marl and sandstone. Although there are no other exposures of thick clastic Bouse deposits north of Sacramento Wash, it is likely that they underlie other parts of the piedmont at unknown depth.

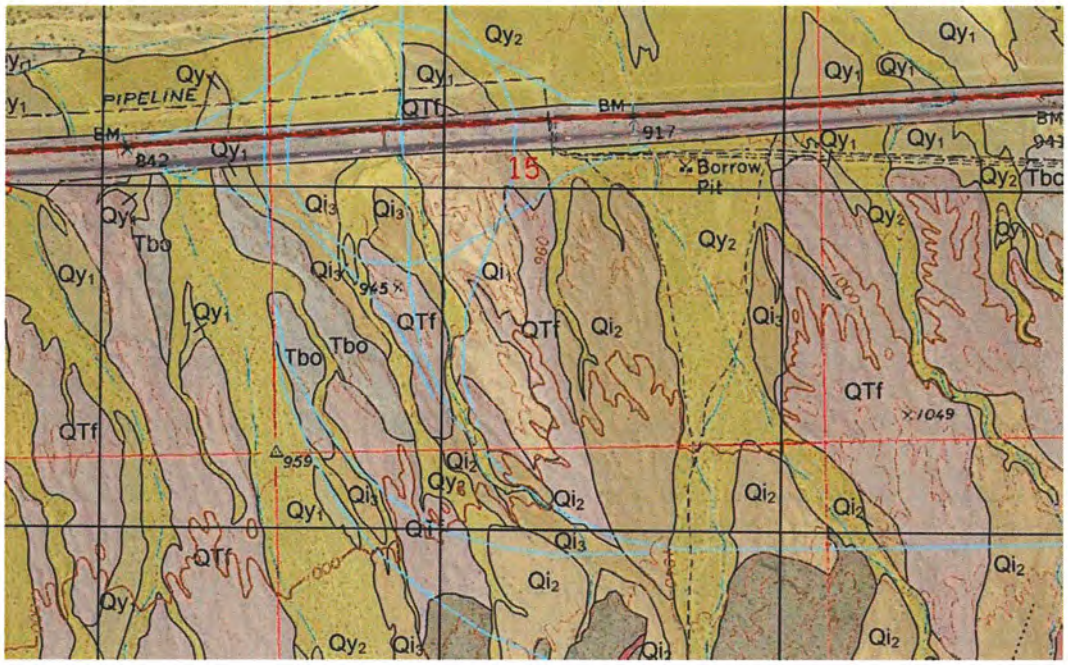


Figure 20. Geologic map of the proposed SR 95 – I 40 interchange, Map Sheet 1. Light blue lines are alternative highway realignments, including the proposed interchange. Interstate Highway 40 is the gray strip running roughly east-west across the top; the edge of Sacramento Wash is in the upper left. Extensive Bouse outcrops (labeled Tbo) exist immediately southwest of the proposed interchange and at the eastern edge of this area, and likely are more extensive in the subsurface.

Figure 21. Slump blocks of moderately indurated Tfb deposits over Bouse Formation deposits in Secret Pass Canyon. Blocks have detached from the outcrops exposed on the upper right and have slid and rotated down the slope, which is underlain by fine-grained Bouse deposits.

Bedrock Geology

Bedrock units of the Black Mountains are dominated by a 2 km thick section of Early Miocene volcanic rocks intruded by intermediate to felsic porphyry. Bedrock constitutes less than 20% of the total outcrop area within sheets 4 and 5 of this report. The volcanic pile and the intrusive rocks range in age between 19 and 13 million years (Thorson, 1971; DeWitt et al., 1986; Murphy et al., 2004), and overlie or intrude strongly weathered Proterozoic crystalline rocks. The nonconformity at the base of the Tertiary units is exposed only in a narrow belt that extends discontinuously from the bedrock mouth of Times Gulch (southeast corner of Sheet 4) 10 km southeast to the base of Boundary Cone just to the east of the edge of the map area. At Times Gulch, the nonconformity is abruptly truncated by the southern margin of the Silver Creek caldera.

Structurally, most of the study area lies within a broad, gently (5-30°) east-dipping homocline. To the south, volcanic strata arch over a gently southeast-plunging anticlinal boundary that transects the northern third of the Boundary Cone 7.5' quadrangle (Spencer et al., 2007). This anticline extends into the extreme southeast corner of Sheet 4 where it appears to merge or be coincident with the range-bounding Roadside Mine fault. Bedrock units in the hanging wall of this fault are sparsely preserved, but are significantly younger and fresher than rocks in the footwall, and these constitute the western part of the Oatman mineral district.

The Oatman district is an epithermal gold system (Durning and Buchanan, 1984) that was probably formed by hydrothermal activity associated with the Silver Creek caldera, a newly defined silicic ash-flow tuff caldera and its associated intrusions. These rocks are spectacularly exposed along the range front throughout Sheet 4. The caldera, originally described and named the Alcyone caldera by Thorson (1971), is the probable source of the well-known Peach Spring Tuff (Young and Brennan, 1974), an early Miocene (18.5 $\pm$ 0.02Ma, $^{40}Ar/^{39}Ar$ sanidine and biotite, Nielson et al., 1990), potassium-rich, trachyte ash-flow tuff whose outflow sheet extends over an approximately 40,000km^2 area of the Mohave desert in Arizona, Nevada, and California (Glazner et al., 1986).

Volcanic Rocks

Volcanic rocks of the Black Mountains are traditionally divided into three main sequences (Thorson, 1971; Durning and Buchanan, 1984; DeWitt et al., 1986) that are considered valid and used throughout this report. The three stratigraphic divisions are: 1) a lower strongly altered sequence dominated by dacitic to trachydacitic lava, 2) a middle variably altered sequence of intermediate lavas, including and interleaved with the18.5 $\pm$ 0.02Ma (Nielson et al., 1990) Peach Spring Tuff, and 3) a younger sequence consisting of silicic (trachyte to rhyolite) lavas capped by olivine basalt. Rhyolite lavas and intrusions (Trx of this report) from the younger sequence just to the north of the study area have been dated at 16.15 $\pm$ 0.07, 16.16 $\pm$ 0.08, 17.40 $\pm$ 0.06, and 17.39 $\pm$ 0.6Ma (Murphy et al., 2004). The youngest part of the sequence, consisting of olivine basalt, has been dated at 13.71 $\pm$ 0.13Ma (Murphy et al., 2004).

Lower Volcanics. Most of the study area is underlain by rocks of the lower volcanic division, which comprises a section up to 1km thick of dark-colored, medium- to coarse-grained, plagioclase phenocryst-rich dacitic to trachydacitic lava, mafic lava, coarse-grained breccia, conglomerate, sandstone, mudstone and shale. The mafic lavas are thin, sparse, and found

overlying crystalline basement only in the northern part of the Boundary Cone quadrangle (Thorson, 1971; Spencer et al., 2007) just to the east of the study area. The sedimentary rocks (Tso) typically overlie basement, and underlie or interfinger with the dacitic lavas (Td). Minor transitional units of questionable origin, principally a heterolithic volcanic-clast breccia that may be volcanic and/or plutonic and/or volcaniclastic (Txd) are also present. Abundant granitic detritus derived from the Proterozoic crystalline basement, and thin algal laminated limestones are also important parts of the sedimentary sequence. Rocks of the lower division are pervasively altered to assemblages including the minerals calcite, chlorite, $\pm$ epidote, $\pm$ clay (Ransome, 1923; Lausen, 1931; Thorson, 1971; Clifton et al., 1980 Durning and Buchanan, 1984).

Middle Volcanics. Rocks of the middle division crop out extensively just to the east of the study area, dipping gently eastward at the base of the steep west-facing escarpment that defines the main crest of the Black Mountains. The sequence consists of a complex suite of intermediate lavas including two distinctive units; the Oatman andesite and the Gold Road latite (Ransome, 1923; Lausen, 1931; Thorson, 1971; DeWitt et al., 1986). As depicted on current maps (Ransome, 1923; Lausen, 1931; Thorson, 1971), these two units are shown as the main host rocks for precious metal mineralization in the Oatman district. Work in progress however, shows that large areas of lava previously mapped as Oatman andesite and Gold Road Latite are in fact part of the lower volcanics. The middle volcanic sequence also includes the Peach Spring Tuff (Tsp), a widespread, voluminous trachyte ash-flow tuff of regional significance (Young and Brennan, 1974, Glazner et al., 1986; Hillhouse and Wells, 1991). The tuff is referred to as Peach Spring instead of Peach Springs, as it was originally defined (Young and Brennan, 1974), because the moniker Peach Springs had previously been used to describe a member of the Paleozoic Muav Limestone (Billingsley et al., p. 43-44, 1999). The only exposure of outflow facies Peach Spring Tuff in the study area is in the north where it is interbedded with relatively thin, fine-grained mafic to intermediate lavas (Tmv). To the south, Peach Spring Tuff is interbedded with flows of what we consider to be the true Oatman andesite, a basaltic trachyandesite lava (map unit Txb of Spencer et al., 2007)[1] with a distinctive clinopyroxene-orthopyroxene-plagioclase phenocryst assemblage. Large areas of dark-colored dacitic lavas that contain abundant plagioclase, $\pm$ pyroxene, but also hydrous mafic phases such as biotite and hornblende as well, have been mapped by many workers as "Oatman Andesite" throughout the Oatman area. Mapping in progress indicates that these rocks, which display the characteristic alteration assemblage of calcite, chlorite, $\pm$ epidote, $\pm$ clay, and which host significant epithermal gold deposits, underlie the true Oatman andesite.

Silver Creek caldera. Very thick exposures of intracaldera facies Tuff (Tsp) have been identified in a 75 km^2, west-facing, half moon-shaped area along the western edge of the Black Mountains between Times Gulch and Secret Pass Canyon. The area is interpreted as the eastern half of the source caldera for Peach Spring Tuff, and is herein named the Silver Creek caldera. The western half is either faulted away and/or buried by valley fill (unit Tfb).

The Silver Creek caldera is closely associated with the previously described Alcyone caldera of Thorson (1971). The Alcyone caldera was interpreted to be source of the Alcyone trachyte, a major division of the complex Alcyone Formation and the principal unit of the lower volcanic division (Ransome, 1923; Thorson, 1971; Durning and Buchanan, 1984; DeWitt et al., 1986). The Alcyone caldera was located with the Times Porphyry lying near its center, as if it were a

[1] Incorrectly labeled Txa on cross-section E-E' of Spencer et al. (2007)

resurgent pluton (Thorson, 1971), but in fact it intruded along the eastern caldera margin. The new name, Silver Creek caldera is introduced for three reasons. The Alcyone caldera was improperly located, the unit thought to have erupted from it is too old, and its namesake, the Alcyone Mine, does not lie within or near either structure. Despite these issues, Thorson's (1971) descriptions of the main caldera fill (including several well-documented avalanche deposits), petrographic descriptions of the ash-flow tuff, and his assertion that the structure is a major silicic ash-flow tuff caldera are correct.

Tuff within Silver Creek caldera is characterized by extensive zones of lithic breccia (Tspb, Tspd, Tspc, and Tspg) in the form of swarms of boulder to cobble sized clasts mixed with ash-flow tuff matrix, and very large (several hundred meter) coherent blocks that resemble intact outcrop belts. One of these, a 3 km wide block of mixed dacitic lava and coarse-grained volcaniclastic turbidite just north of the bedrock mouth of Silver Creek, was previously interpreted as part of a coherent stratigraphic section (Thorson, 1971). The outcrop belt is reinterpreted as a lithic block partly because some of its sedimentary sequences are overturned.

Tuff within the Silver Creek caldera is reinterpreted as the Peach Spring Tuff based mainly on its distinctive phenocryst assemblage. Thorson (1971) provided detailed petrographic descriptions of the unit which closely match the phenocryst assemblage of the Peach Spring Tuff outflow sheet; 20-35% feldspar with K-feldspar greater than plagioclase, and the ratio decreasing up-section from 5:1 to 3:1. Accessory phases include 1-2% biotite, 2% opaque oxides, <0.5% quartz, and trace amounts of hornblende, clinopyroxene, sphene, zircon, and apatite (Young and Brennan, 1974; see also Glazner et al., 1986; Murphy et al., 2004; Spencer et al., 2007). Limited petrographic observations (6-8 thin-sections) done during this study confirm Thorson's (1971) observations for exposures of the intracaldera tuff west of the Times and Moss porphyries. Welded phenocryst-rich ash-flow tuff units interbedded with dacitic lavas of the Thorson's (1971) Alcyone Formation to the east of the porphyries, however, are distinctively different, containing a more mafic phenocryst assemblage of plagioclase-biotite, $\pm$ hornblende and pyroxene, with rare to nonexistent K-feldspar. These tuffs are interpreted as local units associated with the extensive dacitic to trachydacitic lavas of the lower volcanic division.

The southern lobe of Silver Creek caldera was investigated in detail by Thorson (1971) who identified the ash-flow tuff and its breccia lenses as caldera-fill deposits. His observations in this area became one of the principle lines of evidence for his definition of a caldera complex in which the Times porphyry was a central, resurgent stock (Thorson, 1971). We agree in general with this interpretation, but also recognize that the stock intrudes the caldera margin and that rocks farther east, interpreted by Thorson (1971) as caldera fill, are actually pre-caldera volcanic strata belonging to the lower volcanic division. Thorson's detailed descriptions of his intracaldera tuff (members 1, 2, and 3 of his Alcyone Formation, with member 2 corresponding to granitic breccia lenses) are reproducible and accurate, and his petrographic observations of the tuff are a key line of evidence we use to rename and redefine his caldera-filling tuff as the Peach Spring Tuff.

Upper Volcanics. Rocks of the upper division, constituting a bimodal rhyolite-basalt succession (Tr, Trp, Tdx, Tt, Tb, and Trx), are present only in the extreme north along and near highway 68, and in two narrow outcrop belts in the immediate hanging wall of the Roadside Mine fault. Lying along the western edge of the range front, the narrow belts are barely exposed, consisting of sparse low hills and narrow stretches of gullied, pedimented outcrop. The northern belt dips gently to the northwest, whereas the southern belt dips moderately to steeply to the west-

southwest. In both areas the rocks are relatively fresh and unaltered (unlike the pervasively altered rocks exposed in the footwall). Correlation of these rocks with strata that represent the upper volcanic division is uncertain, but highly probable since displacement along the Roadside Mine fault is at least 2km down-to-the west where it crosses highway 68 at the northern edge of the study area (Murphy et al., 2004).

Plutonic rocks

Volcanic rocks of the lower and middle divisions are intruded by two composite plutonic bodies along the eastern margin of the Silver Creek caldera. Both plutons intrude intracaldera Peach Spring Tuff to the west. These granitoids are broadly equivalent to previously identified units. The Times Porphyry (Ransome, 1923) to the south is a K-feldspar porphyritic fine- to medium-grained granite and the Moss Porphyry (Ransome, 1923), to the north, is dominated by plagioclase-porphyritic, fine-grained matrix quartz monzonite. The stocks appear to grade into each other where they interact just south of Silver Creek. Previous investigators report conflicting age relationships in this area. Ransome (1923) states that the Times is younger, whereas Thorson (1971) and DeWitt et al. (1986) state that the Moss is younger. U-Pb zircon dates of 18.5 ± 0.5Ma for both stocks are identical. Our map separates two phases, a quartz monzonite to quartz syenite and syenogranite (Tg) corresponding to all of the Times and the main part of the Moss, and a monzodiorite to quartz monzodiorite (Tgm) occupying the core of the Moss and other smaller zones, mostly north of Silver Creek. Both porphyry stocks are intruded by several generations of porphyry dikes.

Structure

The structural configuration of volcanic strata in the map area is controlled by two main structures, the Roadside Mine fault in the north, and an anticlinal tilt-domain boundary in the south. The Roadside Mine fault is the range-bounding down-to-the west normal fault in the northern part of the study area that defines the western edge of the mountain range south of SR 68. Bedrock units in its hanging wall are found in only three areas. The largest, a belt north of SR 68, consists of east-tilted volcanics of the middle and upper volcanics cut by an array of similarly oriented normal faults. The other two areas are narrow belts of upper volcanics, barely emergent from beneath the late Miocene to Pliocene basin fill along the mountain front. Strata in the northern of these two belts dip gently to the northwest, but in the southern belt, dips are fairly steep ($\geq 45°$) to the southwest. In both strips, the westerly dip is opposed to the regional gentle easterly dip of strata in the footwall.

The Roadside Mine fault is shown dying out to the south only because of lack of data (it might die out, or continue buried by valley fill west of the mountain front for some distance). At its southern end the Roadside Mine fault is roughly coincident and/or parallel to the northwestern continuation of a major, northwest-trending anticlinal tilt-domain boundary. The boundary, as defined by several volcanic marker units, is an asymmetric, gently southeast-plunging anticline with a steeper southwestern limb. The structure transects the northern third of Boundary Cone quadrangle just south of Boundary Cone, and defines the northeastern edge of a tilt domain characterized by fanning dips (meaning that dips increase down-section) and a general increase in tilting of the entire sequence towards the southwest (Spencer et al., 2007). Rocks of this tilt domain, although not exposed in the map area, are likely present in the subsurface of the southern part of the map area.

Eutaxitic foliation of the Peach Spring Tuff within the northern lobe of the Silver Creek caldera (north of Silver Creek) probably does not reflect regional structural tilt. The foliation dips moderately to gently to the southwest over a large area, as does most of the bedding and foliation within several included megabreccia blocks, a fact that may have contributed to confusion regarding the origin of these outcrops (Thorson, 1971 interpreted these rocks as part of a coherent sequence that overlay the welded tuff). Farther north the eutaxitic foliation is folded and warped around a gently west-northwest plunging antiform that transects the northern third of the northern lobe. The axial region of the fold is defined by very steep dips in both directions. The fold is probably a reomorphic structure (meaning that it was developed while the rocks were still hot and plastic) that developed during or shortly after collapse of the caldera, a hypothesis that could be tested with paleomagnetic analysis.

In the southern lobe of Silver Creek caldera, eutaxitic foliation consistently dips gently (10-25°) to the west-southwest. No areas of folded foliation or changes in orientation are known, suggesting that dips in this area might reflect regional tilt. If so, this might help define the location of the anticlinal tilt domain boundary that projects into this area from the southeast. Again, this might be tested with paleomagnetic analysis.

In the southern lobe of Silver Creek caldera, several tabular megabreccia blocks and zones of avalanche breccia, composed mostly of granitic material, are oriented parallel to the regional eutaxitic foliation in the host tuff. Intervals of faintly medium- to thick-bedded ash-flow tuff along the upper contact of some of these breccia lenses suggest that the lenses were deposited as avalanche deposits during hiatuses separating flow-units of the tuff (Thorson, 1971). The hiatuses were probably of short duration since there is no evidence that the flow units correspond to discrete cooling units. Interestingly, the outflow sheet of the Peach Spring Tuff approximately 15km to the south of the caldera (Spencer et al., 2007) includes two flow-breaks that are occupied by flows of the distinctive Oatman andesite lava. Whether these flow-breaks or hiatuses in the eruption of the Peach Spring Tuff are correlative is a issue that hopefully will be addressed by continued research in the area.

One particularly large breccia lens, whose western edge is barely preserved along the eastern edge of the study area about 2km north of Times Gulch, caps a very steep north-trending ridge. The western edge of this unit is a basal contact that represents a gently west-dipping contact separating rock units of vastly different competence and character. This contact "daylights" at the base of a very steep slope, and as such should be tagged as a possible hazard in terms of civil engineering. Another smaller lens that caps the peak about one km farther northwest also has a basal contact that "daylights" to the west.

Alteration and mineralization

The area of bedrock exposure between Silver Creek and Secret Pass Canyon hosts epithermal gold mineralization of the Oatman district, and much of the bedrock in this area has been affected by associated alteration. Gold-bearing quartz-calcite-adularia veins in this area were among the first in the district to be discovered and exploited (Ransome, 1923; Lausen, 1931). In 1863 or 1864, John Moss, one of J.H. Carleton's Fifth California Volunteers who occupied Arizona to deter Confederate advances during the Civil War, found the mineralized vein that today bears his name. Buildings and ruins in this area and a few kilometers to the south along Silver Creek near the confluences with Mossback Wash and Grapevine Canyon date from this era.

Phenocrysts and matrix of the lower volcanic sequence throughout the southern Black Mountains are pervasively altered to the mineral assemblage chlorite-epidote-calcite. This type of alteration is not present in the intracaldera Peach Spring Tuff or any other units of the middle and upper volcanic divisions. The Moss Porphyry has been extensively altered in some areas, especially in the southern part of the intrusion and near contacts with country rocks. In contrast with the alteration in the volcanic rocks, alteration zones within the porphyry are characterized by bleaching and iron-oxide staining. The alteration appears to range from silicification to quartz-sericite to argillic. In the Mossback Wash area, strong to intense alteration is widespread, affecting nearly all of the porphyry and rendering it indistinguishable from its country rocks. This alteration zone contains relics of less-altered Moss porphyry, as well as rocks that resemble aplite, porphyry dikes, and dacite.

A high concentration of mineral prospects, shafts and adits are shown on the Oatman USGS 7.5' topographic quadrangle map. However, several additional adits and shafts that are not shown on the USGS map, each associated with large waste dumps, were identified and located on our map, and are described in field note databases.

Of additional importance are numerous mill sites in the vicinity of Moss Mine, many of which are identified as man-made structures on the Oatman 7.5' USGS quadrangle. Although each mill was probably associated with tailings dumps, we only encountered one identifiable dump about 500 meters south-southeast of the Moss Mine. The tailings consist of white, very fine-grained leached ore. The most conspicuous part of this dump consists of a cylindrical pile several meters high resting on a concrete pad that probably used to be contained by a metal tank, long since corroded away. The pile is surrounded by an expanse of tailings that extend into the main wash and merge with its active and recently active alluvium. It is highly probable that many, if not all of the mills in the area, were associated with similar tailings dumps, and that much of the material has been washed into and mixed with the recent alluvium.

Map Unit Descriptions

Piedmont Deposits

Qy_2 Late Holocene sand, pebble, cobble, boulder, and silt deposits in active stream channels, low terraces, and alluvial fans – Very young deposits in channels and on active floodplains, alluvial fans and low terraces. Channel deposits typically consist of sand, pebbles, cobbles and some small to medium boulders; deposits remain quite coarse across the map area. Terrace and fan deposits typically consist of gravel, sand and silt. Fan and terrace surfaces typically are gently undulating, with gravel bars and finer-grained swales. Desert pavement development is minimal and rock varnish is very light or nonexistent. Soil development is very weak. Surfaces are minimally eroded with channel incision of less than 1.5 m. Channel patterns are variable, including linked anastamosing or distributary channels, discontinuous channels, and separate small tributary channels feeding into larger channels.

Qy_1 Late to early Holocene deposits on channel bars, terraces and active alluvial fans – Young deposits associated with recently active washes and alluvial fans. Deposits typically are poorly sorted, consisting cobbles, pebbles, sand, boulders and silt. Bar and swale topography is common where deposits are gravelly. Soil development is weak, with minimal soil structure and minor carbonate accumulation, but gravelly surfaces appear darker brown than younger Qy_2 surfaces due to moderate rock varnish accumulation.

Qys Holocene sandy channel and fan deposits – Young sand and fine gravel deposits derived from older Colorado River deposits. These deposits typically consist of thin sheets of reworked, quartz-rich sand in valleys cut into Pliocene Colorado River sand deposits or along the flanks of eroded river deposits. Channel development in these areas typically is minimal and discontinuous. Soil development is weak.

Qyf Holocene fine-grained alluvium – Fine-grained deposits that have accumulated in structural depressions associated with the Needles fold and graben system. Deposits consist primarily of gray silt, with lesser amounts of sand and clay. Surfaces are planar and undissected, and soil development is weak to moderate.

Qy Holocene alluvial deposits, undifferentiated.

Qyi Late Pleistocene to early Holocene alluvial fan and terrace deposits – Youngest intermediate terrace deposits. Moderate pavement development in swales and brown rock varnish on gravel clasts; well-preserved bar and swale topography; terrace surfaces are inset below adjacent Qi_3 terraces.

Qi_3 Late Pleistocene alluvial fan and terrace deposits – Younger intermediate deposits associated with inactive alluvial fans and terraces along washes. Deposits typically are poorly sorted mixtures of silt, sand, pebbles and cobbles with some small boulders. Surfaces are moderately dissected by tributary drainages that head on the surfaces and through-going distributary channels. Local surface topographic relief varies from about 1 to 3 m. Soil development is weak, with no clay accumulation and weak (stage I) calcic horizon development with fine filaments and discontinuous clast coatings. Desert pavement development typically is moderate to strong, and rock varnish is brown to dark brown.

Qi_2 Late Pleistocene alluvial fan deposits – Intermediate-age deposits associated with extensive relict alluvial fans. These deposits are graded to a river level below the maximum level

of late Quaternary Colorado River aggradation, which has been dated at 60-100 ka (Lundstrom et al., 2008). Deposits are poorly sorted, including sand, pebbles, cobbles, and boulders, with minor silt and clay. Qi_2 surfaces are drained by extensive, incised tributary drainage networks. Surfaces are moderately to deeply dissected, with local topographic relief varying from about 2 to 5 m. Original depositional topography typically is modified by erosion along incised valleys, but surfaces commonly are quite smooth between valleys. Well-preserved surfaces are typically dark brown due to darkly varnished, tight pebble-cobble pavements. Soils have weak clay accumulation and slight reddening in the upper 30 cm beneath the surface, and calcic horizons typically are stage II with continuous coatings on gravel clasts and some whitening of the soil matrix.

Qi_1 Middle Pleistocene alluvial fan deposits – Oldest intermediate deposits associated with relict alluvial fans. These surfaces have fluvial scarps cut into them near the ~800 foot level (above sea level) of late Quaternary Colorado River aggradation, so predate that aggradation. Deposits are poorly sorted, including sand, pebbles, cobbles and boulders. Surfaces are moderately to deeply dissected, with local topographic relief varying from about 2 to 10 m. Original depositional topography has been extensively modified by erosion, and surfaces are rounded and seldom planar. Surfaces are slightly higher and are much more eroded than adjacent Qi_2 surfaces, but are inset well below adjacent Qo surfaces.

Qi Middle to late Pleistocene alluvial deposits, undivided.

Qo Middle to early Pleistocene alluvial fan deposits – High, old relict alluvial fan deposits. These surfaces are truncated at high erosional scarps associated with the 800-foot-elevation terrace of the Colorado River. Deposits typically are very poorly sorted, including angular to subangular cobbles, pebbles and boulders, with sand and minor silt and clay. Surfaces are moderately to deeply dissected, with 5 to 30 m of relief between channels and ridgecrests. Original fan surfaces have been removed by erosion in many areas; in these areas the characteristic topographic expression is alternating ridges and valleys. Planar surfaces are preserved locally, however, and these are quite smooth with concentrations of very darkly varnished boulders. Soil development is strong and is dominated by carbonate accumulation. Surfaces typically have some carbonate fragments derived from eroded or perturbed petrocalcic horizons, which combined with dark remnant boulder bars gives Qo surfaces an alternating light and dark appearance on aerial photographs.

QTa Late Pliocene to early(?) Pleistocene alluvial fan deposits – Coarse, very old fan deposits capping the highest ridges and fan remnants in the upper piedmont. Deposits consist of cobbles, pebbles, boulders and sand. Surfaces typically are 20 to 50 m above active washes. Surfaces typically are light in color because they are covered with debris churned up from indurated petrocalcic horizons, but they are also commonly littered with darkly varnished cobbles and boulders of resistant fine-grained volocanic rocks. Exposures along the margins of QTa deposits commonly reveal 2+ m thick, indurated petrocalcic horizons with laminar carbonate caps. QTa deposits rest unconformably on underlying Bullhead alluvium and tributary fan deposits (units Tcb and Tfb). A volcanic tephra found in QTa deposits along Silver Creek has been identified as the 3.3 Ma Nomlaki tephra (House et al., 2005), so some and possibly all of the deposits in this unit date to the late Pliocene.

QTf Late Miocene to early Quaternary fan deposits from the Mohave Mountains – Gravelly fan deposits derived from northernmost Mohave Mountains dominated by clasts of granite and gneiss.

Ttn Middle Pliocene Nomlaki tephra - Thin, discontinuous white tephra beds exposed on the south bank of Silver Creek Wash. Tephra bed is up to about 0.5 m thick, and locally the upper part of the tephra bed is mixed with tributary sand and fine gravel. Tephra is found within tributary gravels of unit QTa, at altitudes ranging from 1280 to 1160 feet asl. Samples from the eastern exposure have been identified as the 3.3 Ma Nomlaki tephra (House et al., 2005; House et al, 2008; Sarna-Wojcicki et al., 1991).

Ttl Early Pliocene Lower Nomlaki tephra – Thin, discontinuous, white to gray tephra beds exposed extensively in a portion of the upper piedmont on the Boundary Cone quadrangle. Tephra bed is up to about 1 m thick, and locally the upper part is mixed with tributary sand and pebbly sand (fine gravel). Tephra is found within fine tributary gravels of unit Tfb, at elevations ranging from 1240 to 1180 feet above sea level. An exposure of a tephra that may be correlative with this unit is present at 1400 feet elevation near the southeast corner of the map area (west edge of section 3). Samples from the primary tephra outcrop area have been identified as the ~3.6-4.2 Ma Lower Nomlaki tephra (House et al., 2005; House et al., 2008; Knott and Sarna-Wojcicki, 2001).

Tfb Late Miocene to middle Pliocene alluvial-fan deposits – Very old tributary-fan deposits exposed in the middle and lower portions of high, eroded ridges. This alluvium was deposited before the arrival of the Colorado River and during the early Pliocene aggradation of the river. Deposits typically are poorly sorted to very poorly sorted, including angular to subangular cobbles, pebbles, sand and boulders, with minor silt and clay. Deposits typically are moderately indurated and form steep faces where they have been undercut by recent erosion.

Ttw Late Miocene Tuff of Wolverine Creek – White to buff-colored, very fine-grained airfall tuff bed exposed in Secret Pass Canyon (southern part of Map Sheet 5), interbedded with typical fanglomerate derived from the Black Mountains (unit Tfb). Tuff beds are found in one stratigraphic horizon but are discontinuous and vary in thickness from 1 cm to ~0.5 m. Samples from the tuff have been geochemically correlated with the Tuff of Wolverine Creek, which was erupted from the Heise volcanic field in the Snake River Plain in Idaho at 5.59±0.05 Ma (House et al., 2008;).

Colorado River Deposits

Qc_{r2} Historical abandoned river channel and floodplain deposits – Sand, silt, and gravel deposits associated with the historical flood channels and the floodplain of the Colorado River. Preserved floodplain surfaces typically are undulating, but most have been smoothed by agricultural activity and more recently by urban development. Prior to human alteration, historical floodplain areas included flood channels and abandoned channels and recently cut-off channel meanders, all of which may have been subject to inundation in large Colorado River floods. Floodplain surfaces typically are covered with fine-grained floodplain deposits, but relict gravel bars and lenses are common. Vegetation consisting of small to medium trees, shrubs and grasses is lush where not altered by agricultural activity. Qc_{r2} terraces are less than 10 feet above the active channel.

Qc_{r1} Late Holocene river floodplain deposits – Sand, silt, and gravel deposits associated with low terraces along the margins of the historical floodplain and point bars on the insides of abandoned channel meanders. Terrace surfaces typically are quite smooth (most have been altered by agricultural activity) and are less than 20 feet above the active channel. Terrace surfaces typically are fairly smooth and covered with fine-grained floodplain deposits, but relict gravel bars and lenses are common in the lateral accretion deposits on old point bars. Vegetation consisting of small trees and shrubs is fairly lush. These surfaces may have been inundated by large floods on the Colorado River prior to dam construction.

Qc_2 Latest Pleistocene to early Holocene river terrace deposits – Sand and gravel deposits associated with an inset terrace found along the flank of the historical Colorado River floodplain. Terraces surface are 20 to 40 feet above the active river channel, and are mantled with lightly varnished river pebbles and cobbles and quartz-rich sand; some relict channel features are preserved locally. Soil development is weak and vegetation cover is very sparse.

Qc_1 Younger late Pleistocene river terrace deposits – Sand and gravel deposits associated with an intermediate terrace found along flank of historical Colorado River floodplain. Terrace surfaces and eroded slopes are commonly mantled with river gravel and sand, but deposits consist of gravel, cross-bedded sands, silt and clay. Soil development consists primarily of discontinuous to continuous carbonate coatings on gravel clasts where terraces are well preserved. Vegetation cover is very sparse. Terrace surfaces are 50 to 70 feet above the modern river channel.

Qch Older late Pleistocene river deposits – Clay, silt, sand and minor gravel deposits associated with a major phase of late Quaternary aggradation along the Colorado River (Lundstrom et al., 2008; Malmon et al., in review). Terrace surfaces at or near the top of this unit are extensive in this quadrangle and are bounded on the east by erosional scarps cut into older river and piedmont deposits. Terraces are fairly flat or slope gently toward the river, but terrace surfaces are deeply dissected by tributary drainages. Deposits typically are sandy to gravelly at the surface but deeper exposures indicate that the deposits are dominated by silt and clay. Qch terrace surfaces range from about 200 to 350 feet above the active river channel. Lower terraces in this range are probably primarily erosional features cut into these river deposits.

Qcn Early to middle Pleistocene river deposits – Early to middle Pleistocene river sand, rounded to subangular gravel, silt and clay deposits exposed in the lower part of the piedmont. Deposits are generally similar to older river deposits of unit Tcb, but probably contain more fine-grained beds. Qcn deposits locally interfinger with early Pleistocene alluvial fan deposits of unit Qo. An early Pleistocene mammoth was found in this unit just outside the map area (House et al., 2005).

Tcb Pliocene river deposits – A thick sequence of Colorado River deposits that consist of river sand, gravel and silt with a substantial component of tributary sand and gravel. These deposits are informally named "Bullhead alluvium" (House et al., 2005). They are extensively exposed in some parts of the piedmont and minimally exposed on other areas, but they likely underlie most of the middle and lower piedmont. Deposits are variably indurated and are typically gray in color, but are locally oxidized. River sands typically are fairly coarse and cross bedding is common. Exposures reveal abundant minor unconformities, but no strong buried soils or other evidence of major depositional hiatuses was observed. In the middle and lower piedmont below about 1100 ft above sea level (asl), this unit consists primarily of Colorado River deposits.

Above that level, piedmont deposits predominate, but locally Colorado River sand and gravel can be found as high as 1300 ft asl. River deposits and tributary alluvium are clearly interfingered in some locations.

Tsc Pliocene fine-grained deposits - Very fine sand and silty sand, locally calcareous, and very poorly lithified. Fine sand and silt grades upward over 15 m into, and is interbedded with, pebble to cobble conglomerate. This unit may represent a transgressive sequence, deposited subaqueously in a lake associated with the Bouse Formation, with a coarser nearshore facies outboard of alluvial fan terminus prograding over fine-grained offshore facies. Alternatively, it may represent deposition marginal to the Colorado River floodplain at the time of maximum river aggradation in the early Pliocene, with progradation of tributary fan deposits onto the floodplain at the top of the sequence.

Tbo Latest Miocene to early Pliocene limestone and fine clastic deposits of the Bouse Formation – One- to 20-m-thick, pale white to buff-colored, very fine marl and silty to sandy marl, siltstone, clay, and sandstone, weakly to moderately consolidated. Outcrops predominantly consist of white to buff marl or calcareous sandstone that is less than 2 m thick. Thicker outcrops in the southern part of the map and in Secret Pass Canyon in the northern part of the map consist of tan to buff clay, silt and sand deposits. Where base of the Bouse deposits is exposed in these areas, the lowermost part of the section is white calcareous siltstone or sandstone. Generally this unit is intercalated within and locally interbedded with local fan deposits (unit Tfb [Black Mountains piedmont] or QTf [Mohave Mountains piedmont]).

Sacramento Wash Deposits

Qyr_2 Modern channel and low terrace deposits – Very young deposits in channels of Sacramento Wash. Channel deposits typically consist of sand, pebbles, cobbles and occasional small boulders. Channel patterns are variable, including large single channels and linked anastamosing smaller channels.

Qyr_1 Late Holocene floodplain and terrace deposits - Young deposits associated with low terraces of Sacramento Wash. Deposits typically are moderately sorted, consisting sand, silt, pebbles, and few small boulders. Bar and swale topography is common where deposits are gravelly. Soil development is weak, with minimal soil structure and minor carbonate accumulation, but gravelly surfaces appear darker brown than younger Qyr_2 surfaces due to incipient to moderate rock varnish accumulation.

Qir_3 Younger late Pleistocene terrace deposits – Younger intermediate deposits associated with terraces along Sacremento Wash. Deposits typically are moderately sorted mixtures of silt, sand, pebbles and cobbles, with few small boulders. Surfaces are moderately dissected by tributary drainages that head on the surfaces and through-going distributary channels. Local surface topographic relief varies from about 1 to 5 m. Soil development is weak, with no clay accumulation and weak (stage I) calcic horizon development with fine filaments and discontinuous clast coatings. Desert pavement development typically is moderate to strong, and rock varnish is brown to dark brown.

Qir_2 Older late Pleistocene terrace deposits – Intermediate-age deposits associated with high terraces of Sacramento Wash. Deposits are poorly sorted, including sand, pebbles, cobbles, and boulders, with minor silt and clay. Qir_2 surfaces are drained by incised tributary drainage networks. Surfaces are moderately to deeply dissected, with local topographic relief varying from about 2 to 10 m. Original depositional topography typically is modified by erosion along incised valleys, but surfaces commonly are quite smooth between valleys. Well-preserved surfaces are typically dark brown due to darkly varnished, tight pebble-cobble pavements. Soils have weak clay accumulation and slight reddening in the upper 30 cm beneath the surface, and calcic horizons typically are stage II with continuous coatings on gravel clasts and some whitening of the soil matrix.

Qir_1 Middle Pleistocene terrace deposits – Gravel, sand and silt deposits associated with the highest preserved terraces of Sacramento Wash. Terrace surfaces range from about 80 to 120 feet above the active channel. Soils are moderately developed with stage III calcic soils and moderate reddening. Surface gravel clasts are moderately to darkly varnished and desert pavements vary from tightly packed and smooth to loose gravel lag, depending on local erosion.

Qir Pleistocene terrace deposits, undifferentiated.

QTr Pliocene or Pleistocene deposits – Thicker gravel, sand and silt deposits with mixed lithologies underlying several levels of terraces along Sacramento Wash. Gravel fraction includes substantial granitic rock, presumably derived from Sacramento Valley and possibly the Mohave Mountains to the south. Gravel clasts are typically moderately well-rounded to subangular.

Miscellaneous Surficial Units

Qe Holocene eolian sand deposits - Well-sorted, fine to medium, quartz-dominated sand deposits with minor silt and fine lag gravel forming low, elongate dunes.

Qls landslide deposits – Mapped only in Secret Pass Canyon, deposits consist of blocks of moderately indurate fanglomerate (unit Tfb) that have slid downslope over fine-grained Bouse deposits.

Qtc hillslope colluvium and talus - Very poorly sorted, angular to subangular, locally derived, weakly bedded, moderately to steeply dipping slope deposits associated with bedrock hills.

d profoundly disturbed areas - Surface areas substantially disturbed by mines, tailings or ponds, urban areas, and sizable paved roads.

Bedrock Units

Trx Phenocryst-rich Rhyolite lava (Miocene) – Phenocryst-rich rhyolite lava containing ~25% phenocrysts of feldspar, quartz and biotite.

Tb Basalt lava (Miocene) – Basaltic and andesitic basalt lava with up to 10% 1-3mm mafic phenocrysts.

Tt Nonwelded felsic tuff (Miocene) – Nonwelded, massive to thick-bedded felsic, sparse lithic lapilli tuff.

Tdx Phenocryst-rich dacitic lava (Miocene) – South of Times Gulch only. Phenocryst-rich plagioclase, biotite phyric dacitic lava typically with dark vitric matrix.

Trp Phenocryst-poor rhyolite lava (Miocene) – South of Times Gulch only. Phenocryst-poor lava containing <7% feldspar, quartz, and sparse biotite phenocrysts.

Tqk Quartz feldspar porphyry dikes (Miocene) - Porphyry dikes containing 2-10% subhedral to euhedral feldspar phenocrysts up to 2cm and trace to 2% anhedral quartz phenocrysts (2-5mm) in a light green to tan aphanitic groundmass. Dikes of this unit intrude feldspar porphyry dikes of unit Tk.

Tm Mafic dikes (Miocene) - Porphyry dikes containing 5-15% feldspar phenocrysts up to 1cm (rarely 2cm) and >5% altered mafic minerals in a medium to dark green aphanitic groundmass. At least some of the feldspar is plagioclase, but some of the larger phenocrysts appear to be K-feldspar. Altered mafic minerals form 1-3mm aggregates and include chloritized biotite and epidote. Traces of blebby, anhedral, 1-5mm quartz are locally present. Dikes of this unit intrude feldspar porphyry dikes of unit Tk.

Tk Feldspar porphyry dikes (Miocene) - Porphyry dikes containing 5-15% euhedral K-feldspar phenocrysts (2-10mm), traces of anhedral quartz phenocrysts (1-3mm), and trace to 2% mafic minerals (<<1mm), in an aphanitic groundmass that ranges from light gray to tan to white. These dikes are commonly bleached, altered, and iron-oxide stained.

Tg Monzonite and quartz monzonite porphyry (Miocene) – Felsic porphyry containing ~5% 2-6mm euhedral feldspar with fine-grained granitic matrix and sparse, typically hematite altered mafics. Contact zones with younger rocks are commonly argillic altered, silicified, and hematite stained.

Tgm Monzodiorite porphyry (Miocene) – Quartz monzodiorite to quartz monzonite containing15-30% mafic minerals and characterized by greenish gray color. The texture ranges from fine-grained and plagioclase-porphyritic to medium-grained and approaching equigranular. Greenish gray, euhedral plagioclase forms phenocrysts 5-20 mm long and constitutes up to 50% of the rock. Mafic minerals are in part altered, but typically include some fresh, euhedral, 1-2 mm biotite. The mafic phase is intruded by more felsic quartz monzonite (Tg) of the main phase of the Moss Porphyry.

Tr Rhyolite lava (Miocene) – Phenocryst-poor rhyolite lava typically containing ≤5% feldspar phenocrysts with sparse quartz and biotite. To the north, in the massif near Union Pass phenocryst content is up to 10% and rarely up to 20%.

Tps Peach Springs Tuff (Miocene) - Moderately phenocryst-rich, 1-5mm, 2 feldspar, 1-3mm biotite ash-flow tuff. Potassium feldspar is typically more abundant than plagioclase (<1-2mm) and larger (up to 5mm). Matrix is typically light gray to lavender and the tuff is strongly indurated, although not always obviously densely welded. Pumice content is highly variable ranging from <<5% to 25%. Lithics, consisting of coarse-grained, potassium feldspar porphyritic granite, dacitic and andesitic lava, and dark, variably volcaniclastic argillaceous sandstone and conglomerate constitute from 0 to 50%. Zones containing blocks larger than 1m making up more than ~25% of the unit are generally, but not always, differentiated as lithic megabreccia (Tpsb).

Tpsb Peach Springs Tuff megabreccia (Miocene) - Zones within the Peach Springs Tuff containing lithic blocks larger than 1m, and making up ~25% or more of the tuff. Blocks, ranging up to several hundred meters, consist of coarse-grained, potassium feldspar porphyritic

granite, dacitic and andesitic lava, and dark, variably volcaniclastic argillaceous sandstone and conglomerate.

Tpsd Peach Spring Tuff dacitic megabreccia (Miocene) – Zones within the Peach Springs Tuff containing monolithic dacitic (Td) lithic blocks larger than 1m, and making up ~25% or more of the tuff. In many areas, lithic blocks are larger than several hundred meters. Equivalent in part to member 5 of Thorson's (1971) Alcyone Formation.

Tpsc Peach Spring Tuff conglomeratic megabreccia (Miocene) - Zones within the Peach Springs Tuff containing monolithic conglomeratic (Tso) lithic blocks larger than 1m, and making up ~25% or more of the tuff. In many areas, lithic blocks are larger than several hundred meters. Equivalent in part to member 4 of Thorson's (1971) Alcyone Formation.

Tpsg Peach Spring Tuff granitic megabreccia (Miocene) – Zones within the Peach Springs Tuff containing monolithic granitic lithic blocks (YXg) larger than 1m, and making up ≥25% or more of the tuff. In many areas, lithic blocks are larger than several hundred meters. Equivalent in part to member 2 of Thorson's (1971) Alcyone Formation.

Tmv Mafic to intermediate lava complex (Miocene) – A sequence of thin (<20m thick) phenocryst-poor, generally fine-grained, dark gray matrix andesitic lavas typically containing <5%, <2mm plagioclase ± sparse hornblende and or pyroxene phenocrysts. Lavas are complexly interbedded with thin volcaniclastic sandstone and mostly nonwelded felsic to intermediate ash-flow tuff and ash-fall tuff.

Txd Heterolithic breccia (Miocene) – Breccia composed largely of coarse-grained, 2-feldspar phenocrst-rich porphyry clasts of mixed derivation, including varieties with apparent hypabyssal (with evenly distributed, euhedral phenocrysts) and extrusive (with unevenly distributed, subhedral to euhedral phenocrysts) textures. Principal clast types include:

Td Dacitic lava (Miocene) – A composite unit of phenocryst-rich dacitic lava flows containing 20-40% 1-6mm euhedral plagioclase, 0-5% 1-4mm euhedral biotite and 0-5% 1-6mm typically chloritic altered mafic phenocrysts. The lavas are typically dark colored with variably vitric to fine-grained crystalline matrix. Flow boundaries are characterized by zones of autobreccia with minor amounts of pyroclastic and volcaniclastic sedimentary interbeds.

Tcc Tuff of Cook Canyon (Miocene) – Dacitic tuff that underlies the Peach Springs tuff and may be genetically related to it (Gaudio et al., 2003).

Tso Sandstone and conglomerate (Miocene) – Medium- to thick-bedded and rarely thin-bedded poorly-sorted argillaceous sandstone, pebbly sandstone and cobble-pebble, rarely boulder conglomerate and breccia interbedded with subordinate black mudstone, and ripple cross-laminated siltstone and fine-grained sandstone. Clasts are dominantly heterolithic intermediate volcanic and granitic, and the matrix for the sandstone and conglomerate is dark green and argillaceous.

Tfl Tertiary lava flows, sills, tuffs and sedimentary rocks – Commonly altered mafic to silicic lava flows and sills interbedded with sandstone and tuff beds. Includes andesite, tuff, rhyolite porphyry flows, and basalt dated at about 18 to 21 Ma (Howard et al., 2000). Deposits include arkosic conglomerate.

TKqp Tertiary or Cretaceous quartz porphyry dikes – Light-colored, northeast-trending dikes intruding biotite granodiorite. Quartz porphyry dikes with phencrysts of sphene,

hornblende, biotite, alkali feldspar, quartz, and plagioclase.

TKl Tertiary or Cretaceous biotite lamprophyre dikes – Dark, northeast-trending dikes with chilled margins against granodiorite unit. Conspicuous biotite phenocrysts, with plagioclase phenocrysts and alkali feldspar groundmass.

Kbg Cretaceous biotite granite – Light gray, equigranular, medium-grained sphene-biotite granodiorite and monzogranite. Inferred to be part of a single pluton, dated at 72 Ma (Howard et al., 2000).

Ydb Diabase dikes (Proterozoic) – Dark gray to black dikes that commonly weather to olive brown. Ophitic to subophitic, locally metamorphosed and foliated. Rocks contain 40-50 percent plagioclase laths set in a matrix of hornblende and augite. Dikes are 1 to 20 m thick.

YXg Coarse-grained granite (Proterozoic) - Coarse-grained, potassium feldspar-porphyritic and megacrystic, 10-20% biotite, locally weakly foliated granite.

YXgn Fine- to medium-grained granite and gneissic granite (Proterozoic) – Foliated to weakly foliated, fine- to medium-grained granite containing less than 15% mafics (mostly biotite).

Xgd Granitic augen gneiss (Early Proterozoic) – Medium to coarse-grained augen gneiss to equigranular gneiss of granodiorite or monzogranite composition, with biotite and hornblende. Cut by isoclinally folded pegmatite dikes and ophitic diabase dikes.

Xg Gneiss (Early Proterozoic) – May include leucocratic, pegmatite, amphibolite, metasedimentary, and biotite gneiss.

Xgp Pegmatite and granitic rock (Early Proterozoic) – Medium-grained, light-colored, foliated monzogranite and pegmatite. Monzogranite includes biotite, muscovite, or garnet.

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