Geologic Map of the Needles NE 7.5' Quadrangle, Mohave County, Arizona

Phillip A. Pearthree

DIGITAL GEOLOGIC MAP DGM-53 v 2.0

August 2018

Arizona Geological Survey

azgs.arizona.edu | repository.azgs.az.gov

Arizona Geological Survey

Phil A. Pearthree, State Geologist and Director

Manuscript v 2.0 approved for publication in August 2018
Printed by the Arizona Geological Survey
All rights reserved

For an electronic copy of this publication: www.repository.azgs.az.gov

For information on the mission, objectives or geologic products of the Arizona Geological Survey visit azgs.arizona.edu.

This publication was prepared by a unit of the University of Arizona. The University of Arizona, or any unit thereof, or any of their employees, makes no warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed in this report. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the University of Arizona.

This geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program, award no. 05HQAG0078. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Recommended Citation. Pearthree, P.A., 2018, Geologic Map of the Needles NE 7.5' Quadrangle, Mohave County, Arizona. Arizona Geological Survey Digital Geologic Map, DGM-53 v2.0, 14 p., map scale 1:24,000 (1 sheet).

Note. First released as v 1.0 in Feb. 2007

THE UNIVERSITY OF ARIZONA
College of Science

Introduction

The Needles NE 7 ½' Quadrangle includes the modern and historical floodplain of the Colorado River and part of the western piedmont of the Black Mountains. This quadrangle is completely covered with late Cenozoic surficial deposits laid down by the Colorado River or its tributaries. Deposits range in age from modern to several million years old, 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. This map and report describe the physical characteristics of deposits of different ages and sources, the mapped extent of various deposits, and potential geologic resource and geologic hazard implications of this mapping.

This mapping continues efforts by Arizona Geological Survey and the Nevada Bureau of Mines and Geology to map the rapidly developing Mohave Valley area, and complements geologic mapping of quadrangles to the north (Davis Dam; Faulds et al., 2001; Mt. Manchester; House et al., 2004; Davis Dam SE; Pearthree and House, 2005) and the quadrangle to the east (Boundary Cone; Spencer et al., 2007) (See Figure 1). This mapping was done under the joint State-Federal STATEMAP program, as specified in the National Geologic Mapping Act of 1992, and was jointly funded by the Arizona Geological Survey and the U.S. Geological Survey under STATEMAP Program Contract award no. 05HQAG0078.

Mapping Methods

Surficial deposits of the Needles NE 7 1/2' quadrangle were mapped primarily using aerial photographs and other remote sensing information. The principal imagery utilized are 1:24,000-scale color and false-color infrared aerial photos taken in 1979 for the Bureau of Land Management and false-color digital orthophotoquads taken in 2004 for the U.S. Geological Survey. Quartz-rich Colorado River 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 lower piedmont area in the northern part of the quadrangle 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 – these areas are depicted with a secondary pattern on the geologic map. In the remainder of the map, numerous field observations were made between fall 2004 and fall 2006. The physical characteristics of Quaternary alluvial surfaces (channels, terraces, alluvial fans, and floodplains) and associated deposits evident on remote-sensing imagery and in the field were used to differentiate them by age. Surficial deposits of the map area were then correlated with map units in adjacent quadrangles and regional deposit – soil chronosequences (Gile et al, 1981; Machette, 1985; Bull, 1991) to roughly estimate their ages. Mapping was compiled in a GIS format over the digital orthophotoquad base, 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

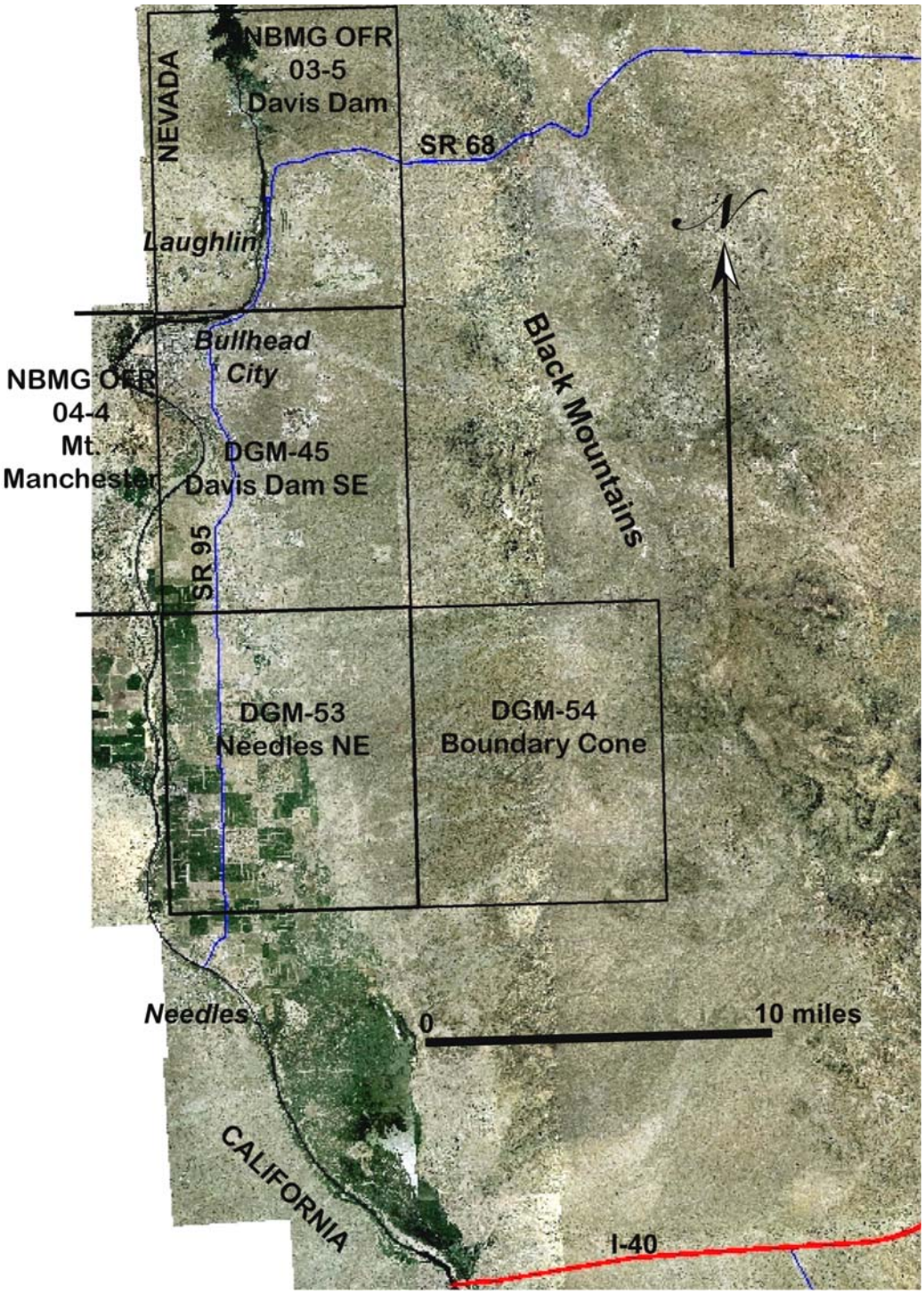

Figure 1. Location of Needles NE and adjacent mapped 7 1/2'quadrangles in Mohave Valley.

gravel is the primary factor used to differentiate Colorado River deposits from piedmont deposits. 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.

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 are typically have some very darkly varnished patches, but overall are somewhat lighter in color because erosion has exposed more underlying 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 braided (splitting and rejoining) or distributary (branching downstream) channel patterns; 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).

Geologic History

The geology of the Needles NE quadrangle reflects the complex interaction of the Colorado River and Black Mountain piedmont drainages over the past few million years. In the middle and late Miocene, Mohave Valley was likely internally drained with a depositional center in the southern part of the valley. Southern Mohave Valley is a deep sedimentary basin, with estimated depth to bedrock being at least 1600 feet in all of the quadrangle and as great as 8000 feet in the

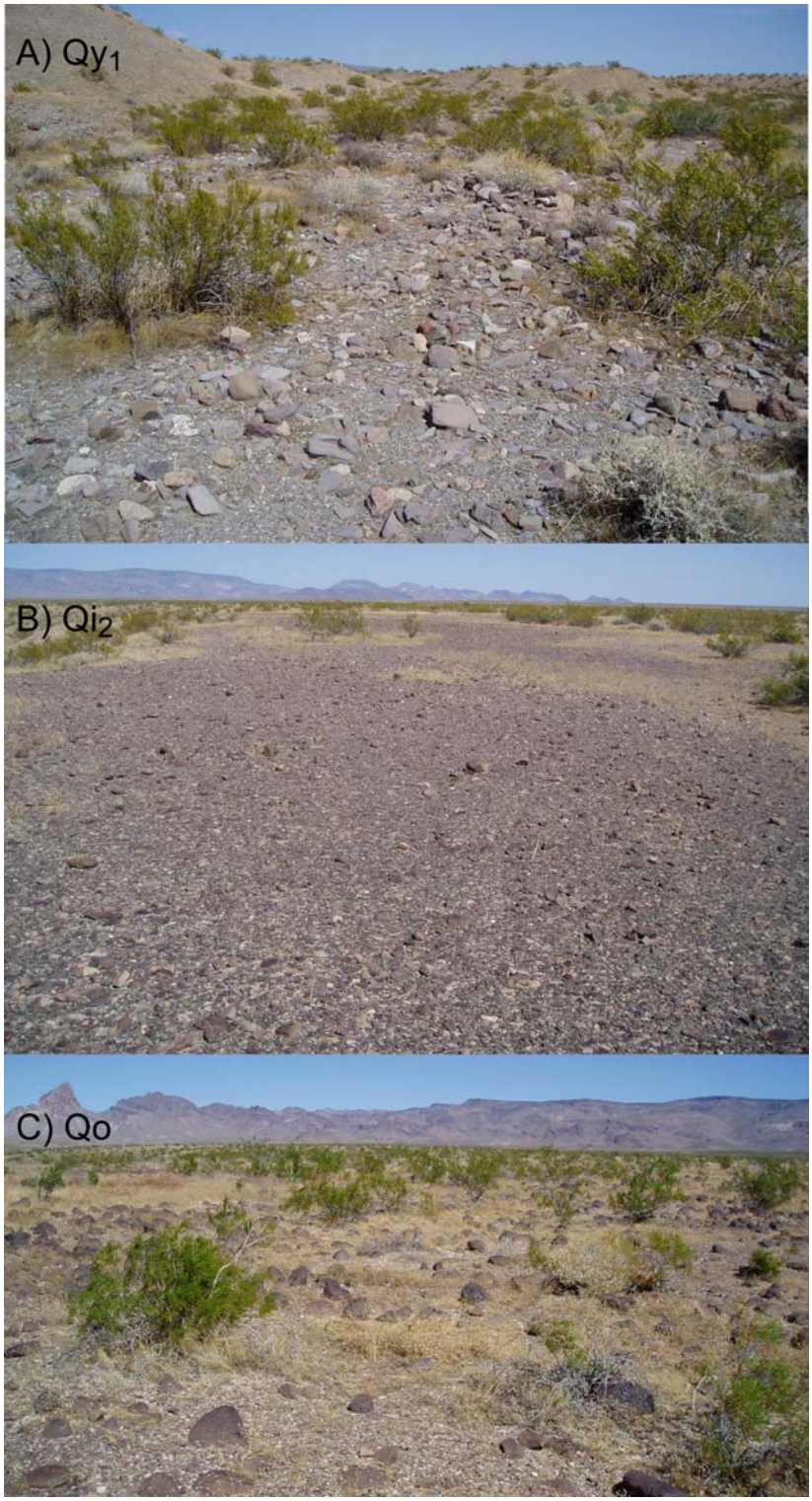

Figure 2. Ground photos of Holocene (Qy_1), late Pleistocene (Qi_2), and early to middle Pleistocene (Qo) piedmont surfaces. Holocene surfaces are fairly rough and lightly varnished; late Pleistocene surfaces are smooth and darkly varnished; older Pleistocene surfaces have some very darkly varnished surface clasts but are lighter in color overall because of exposure of carbonate soil fragments.

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_c, Qy_2) are lightest in color and have complex branching channel patterns; late Pleistocene fans and terraces are darkest and only moderately dissected by local tributary channel networks (Qi_3, Qi_2); older Qi_1 alluvial surfaces are much 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. The bold white bar indicates one mile on the photo.

western part of the quadrangle (Richard et al., 2007). Presumably, much of this sediment is quite fine-grained but no late Miocene or older deposits are exposed in the quadrangle.

The history of the Colorado River in this general area begins with the influx of water and sediment from the north after 5.5 Ma (House et al, 2005). The first deposits associated with the arrival of the Colorado River contain only locally-derived sediment from the northern margin of Mohave Valley. 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). The deposits that record the initial entry of the river into this area are not exposed in the Needles NE quadrangle, but are exposed farther north in Mohave Valley (House et al, 2005), on the western and southern sides of Mohave Valley (Metzger and Loeltz, 1973), and along the flanks of the Black Mountains to the east (Spencer et al, 2007). Outcrops of Bouse Formation range in altitude from about 500 to 1800 feet above sea level (asl) record the presence of a deep body of water in Mohave Valley. 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; Figure 4) interfingered with tributary gravel and sand (Black Mountain fanglomerate, unit Tfb) (Pearthree and House, 2005; House et al., 2005). The maximum level of river aggradation at the latitude of the Needles NE quadrangle was about 1300 feet asl and was attained by about 4 Ma. The estimated age of maximum river aggradation is based on an extensive exposure of the ~ 4 Ma Lower Nomlaki tephra interbedded with distal tributary alluvial fan deposits and overlain by the highest levels of Bullhead alluvium in the Boundary Cone quadrangle to the east (House et al, 2005; Spencer et al., 2007). As a result of this major phase of river aggradation, much of the lower Black Mountains piedmont is underlain by Pliocene river sand and gravel.

Figure 4. Photo of sand and silt beds of the alluvium of Bullhead City. Medium to coarse sand beds typically are light-colored, moderately indurated and exhibit planar to trough cross-bedding. Fine sandy and silty beds that dominate the right part of the exposure are less well-indurated. Tributary gravel at the top of the ridge was deposited above an erosion surface cut onto the older river deposits.

The Colorado River had begun to incise into the valley fill by 3.3 Ma, when tributary alluvium was deposited above an erosion surface cut across the uppermost part of the old river deposits (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 level by the early Quaternary. 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; Lundstrom et al, 1998; Lundstrom et al., in press) and reached about 800 feet asl in this area (Figure 5). There were periods of aggradation earlier in the Quaternary as well (House et al., 2005; Figure 5). 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 record periods of more minor river aggradation. The historical river floodplain widens fairly dramatically from about 2 miles at the northern edge of the quadrangle to about 5 miles in the central and southern parts of the quadrangle (the western edge of the floodplain is off the quadrangle).

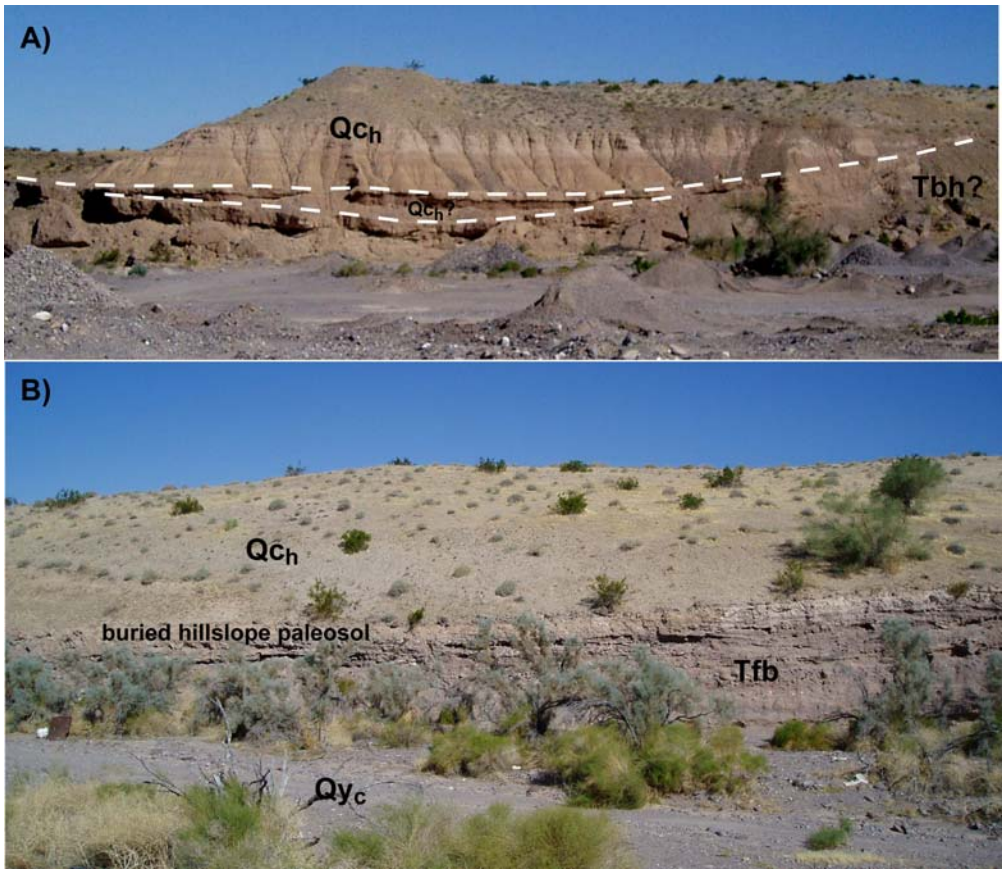

Figure 5. Exposures of tan, fine-grained late Pleistocene Colorado River deposits (unit Qch). A) Clay/silt beds fill a broad paleovalley, with a fairly well-developed calcic paleosol marking the unconformity (upper white line). Fine-grained deposits below the paleosol record an earlier episode of partial valley filling. All of these deposits are inset into older Colorado River deposits. B) Similar late Pleistocene river deposits 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 a hillslope formed on older fan deposits. Qch deposits are capped by several feet of sand.

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 annual 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 channel migration and abandonment was preserved in the 1938 aerial photos of the floodplain (Figure 6A). 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 6B). The modern channel is quite narrow (it is just west of the quadrangle) and most of the historical channel (unit Qc_{r3}), recently abandoned channels and floodplain area (unit Qc_{r2}), and slightly older floodplain area (unit Qc_{r3}) has been altered by urban development or agricultural activity.

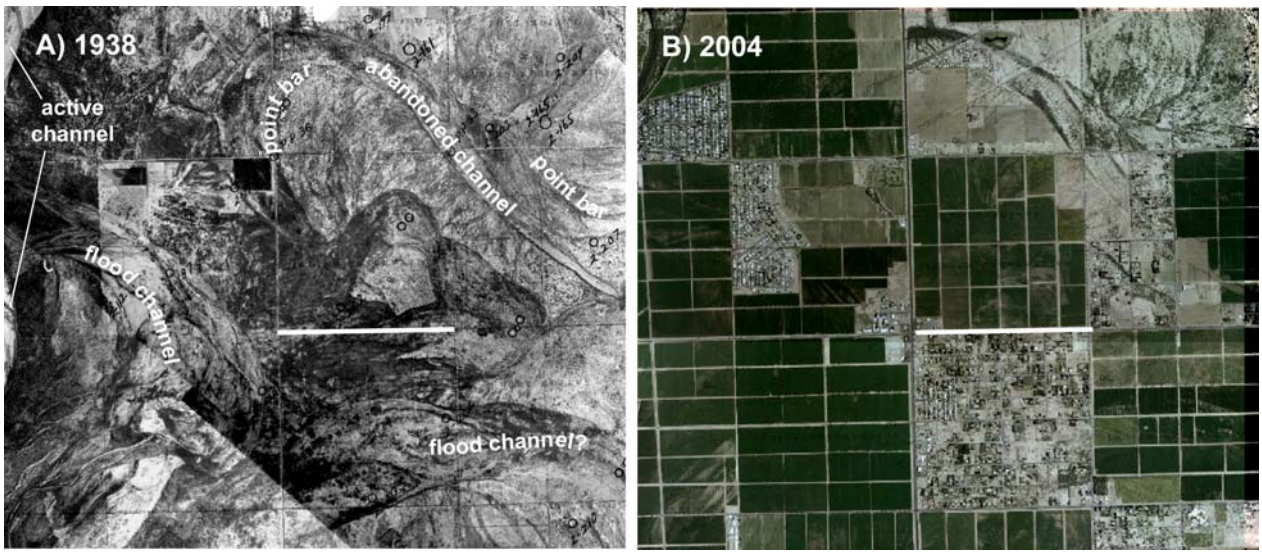

Figure 6. Comparison of the modern and historical Colorado River floodplain. The aerial photograph from 1938 reveals a dynamic floodplain, with abundant evidence of shifts in channel position in the latest Holocene. Large dams on the river limit modern flood inundation and anthropogenic activity has masked most of the floodplain. The bold white lines are 1 mile in length and in the same geographic position in each photograph.

Tributary washes have responded to the variations in base level imposed by the Colorado River and climate changes during the past 5 million years or so. As the river aggraded early during this period, tributary drainages deposited alluvial fans that interfingered with the Colorado River deposits (unit Tfb). Near the Black Mountains in the Boundary Cone quadrangle to the east, deposits of this period are exclusively tributary, the lower piedmont is underlain primarily by Pliocene Colorado River deposits (unit Tcb), and the middle piedmont contains both river and tributary deposits. Pliocene river and tributary deposits are exposed only along the southeastern fringe of the Needles NE quadrangle, but are much more extensively exposed in the Boundary Cone quadrangle to the east. As the river began to incise after 4 Ma, tributary alluvium 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 above an erosion surface cut across the highest level of late Quaternary river deposits (unit Qc_c), and thus must also be late Quaternary in age. Several younger late Pleistocene and Holocene piedmont units are graded to the younger river terraces or the modern floodplain (units Qi_3 and Qy_1). In the southeastern 1/4 of the quadrangle, late Pleistocene to Pliocene deposits on the piedmont are moderately to deeply dissected and modern washes are entrenched far below surrounding remnants of older deposits. The northeastern 1/4 of the quadrangle is dramatically different. Here, 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.

Geologic Hazards

Flooding. Flooding hazards in the Mohave Valley area may be subdivided into those associated with the Colorado River and with smaller tributary washes draining the piedmont of the Black Mountains. Large floods on the Colorado River uniformly occur in the spring and early summer as a result of abundant snowmelt runoff. The largest historical flood, which occurred in 1884, had a flood peak of about 300,000 ft^3/sec in Grand Canyon (Pope et al., 1998). The construction of Hoover and Glen Canyon dams on the Colorado River greatly decreased flood peaks. Even during the exceptional snowmelt year of 1983, the peak flood release from Hoover Dam to the lower Colorado River was about 50,000 ft^3/sec. Smaller tributaries that drain the Black Mountains and the adjacent piedmont are subject to flash floods. Large floods on these drainages result from intense, localized thunderstorms that usually occur during the summer or early autumn, and water levels rise and fall rapidly during floods.

Surficial geologic mapping reveals a long history of flood inundation that can be used in conjunction with hydrologic and hydraulic modeling to assess the extent and character of flood hazards, including alluvial-fan flooding. Because the construction of dams has profoundly altered the Colorado River flood regime, the existence of very young river deposits mantling the broad river floodplain does not have any direct relationship to flood hazards in the modern environment. Mapping of deposits of different ages on piedmonts outlines the extent of areas that may be prone to flooding, however. Much of the piedmont in this quadrangle is covered by Holocene alluvial deposits, and thus has been subject to significant inundation and associated erosion and deposition during the past 10,000 years. Areas of subject to widespread, generally shallow flooding (sheetflooding and/or alluvial fan flooding) are characterized by extensive young deposits (units Qy_c, Qy_2, and depending on local relief, Qy_1) and minimal channel incision. Unentrenched distributary channel networks are indicative of active fan areas (Figure 7). Other piedmont drainages have incised distributary channel systems, where much of the area between channels is composed of surfaces that are tens to hundreds of thousands of years old. The older surfaces are almost always topographically higher than adjacent channels and young terraces, and their presence indicates that the distributary channels are relatively stable; greater topographic relief implies increasingly stable channel positions. Finally, many piedmont drainage networks are stable, incised tributary systems where flood inundation is confined to valley bottoms or portions of valley bottoms by Pleistocene and older deposits (Figure 8).

The distribution of young deposits on the piedmont provides evidence of areas that may be prone to flooding. In the northern part of the piedmont, Holocene deposits are quite extensive,

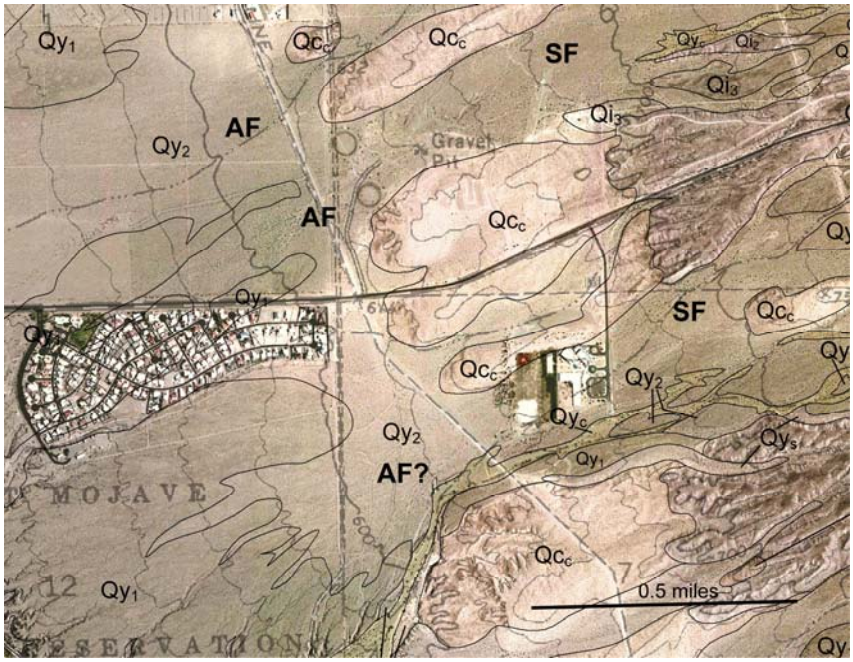

Figure 7. Active alluvial fan and sheetflood areas in the northern part of the Needles NE quadrangle. Active fan areas are indicated by extensive Qy_2 deposits and downstream-branching distributary drainage networks (labeled AF). Locally, recent channel incision may have isolated late Holocene fans from inundation (labeled AF?). Areas farther upslope that are likely subject to sheetflooding are labeled SF.

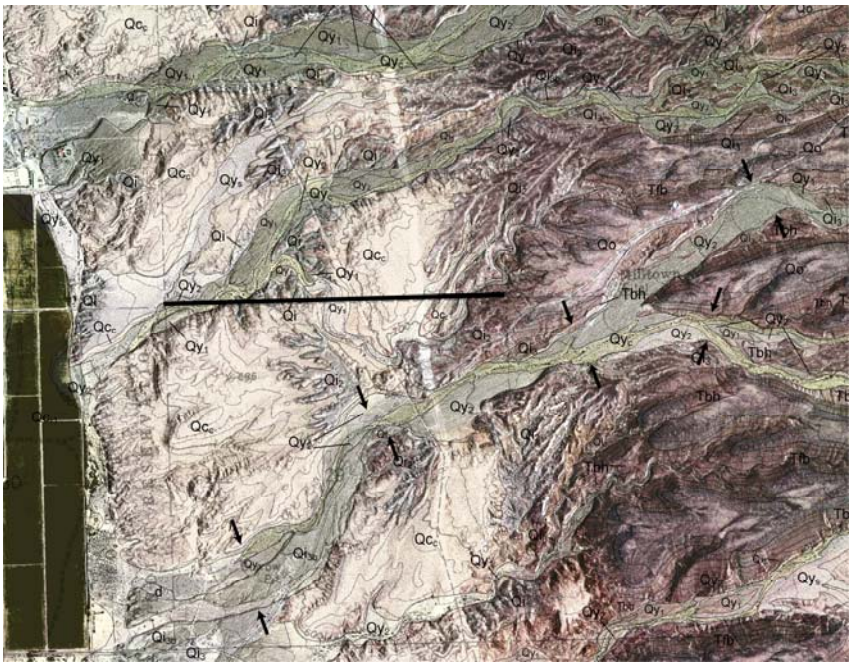

Figure 8. Large, incised tributary drainages in the southeastern part of the Needles NE quadrangle. In this area, significant flooding is restricted to portions of the bottoms of relatively wide valleys cut into older river and tributary deposits. Black arrows show approximate limits of flood inundation along an incised drainage. Bright-colored areas are covered by late Pleistocene Colorado River deposits. The bold black bar indicates one mile on the photo.

channel patterns commonly are anastomosing and locally are distributary, and topographic relief between active channels and adjacent Holocene and late Pleistocene alluvial surfaces is typically 6 feet or less. Sheetflooding is certainly extensive in this area, and where topographic relief is minimal portions of late Pleistocene surface remnants may be inundated in large floods. Active alluvial fans exist in a few areas where piedmont washes debouch onto the historical river floodplain or onto the margins of late Pleistocene to Holocene river terraces (Figure 7). Farther south along the eastern margin of the quadrangle, flooding is confined to broad valley bottoms by topography associated with older deposits (Figure 8). All of the sizable washes in this area have deposited relatively small active alluvial fans where they debouch onto the margin of the historical Colorado River floodplain.

Quaternary Faulting. A series of low scarps that are formed on late Pleistocene alluvial fan deposits in the far southeastern corner of the Needles NE quadrangle may record late Quaternary surface faulting (Figure 9). The scarps are very subtle; total surface displacement is less than 0.5 m. Several older, higher surface remnants terminate downslope in the general area of the fault scarps, but this is also the approximate altitude of the maximum late Quaternary Colorado River aggradation so it is possible that these higher scarps were partially or completed formed by lateral river erosion. The total length of the scarps observed on aerial photographs and in the field is about 2.5 km. These scarps are formed on Qi_2 fan surfaces that are somewhat younger than the maximum late Pleistocene Colorado River aggradation, and Holocene to late Pleistocene terrace deposits inset into valleys in this area are not displaced, so the most-recent surface displacement must be late Pleistocene in age.

The possible fault scarps in the Needles NE quadrangle may well be associated with the more extensive faults and folds of the Needles graben and related structural and geomorphic features. The Needles graben is formed in an early to middle Pleistocene alluvial fan surface about 10 km southeast of the scarps mapped on the Needles NE quadrangle. It was first recognized in the 1970's (Metzger and Loeltz, 1973; Purcell and Miller, 1980). Reconnaissance geomorphic analyses indicate that the fault zone has had recurrent Quaternary movement and the youngest displacement event occurred in the late Pleistocene (Pearthree et al., 1983). Faulting has generated a fairly low fault scarp on the northeast side of the structure and smaller scarps on the southwest side of the structure, 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, whereas they are less than 2 m high on an adjacent middle to late Pleistocene alluvial fan. Holocene and younger late Pleistocene deposits are not displaced. More recent reconnaissance investigations have identified a moderately large monocline located about 1.5 km west of the Needles and extending about 5 km to the northwest (observations by Keith Howard, in House et al., 2005). The same early to middle Pleistocene alluvial fan surface that hosts the Needles graben is down-dropped to the southwest by at least 25 m across this monocline, and there may be a small thrust fault west of the monocline. The amount of Quaternary displacement across the monocline suggests that it is the primary structure in this area and that the Needles graben is a minor, related feature.

Soil Problems. Several types of soil/substrate problems may be encountered in the Needles NE quadrangle. Parts of the historical floodplain of the Colorado River may be susceptible to soil compaction or collapse upon wetting or loading (hydrocompaction). Hydrocompaction is a reduction in soil volume that occurs when susceptible deposits are wetted for the first time after burial. Deposits that are susceptible to hydrocompaction are typically relatively fine-grained, young sediments that are deposited in a moisture-deficient environment. Potential soil problems

in piedmont areas consist of low infiltration rates and hard substrate. All piedmont soils contain substantial calcium carbonate. Soils associated with units Qi_1 and Qo typically have cemented calcium carbonate and silica hardpans in the shallow subsurface. Excavation may be difficult and near-surface infiltration rates low on these piedmont units.

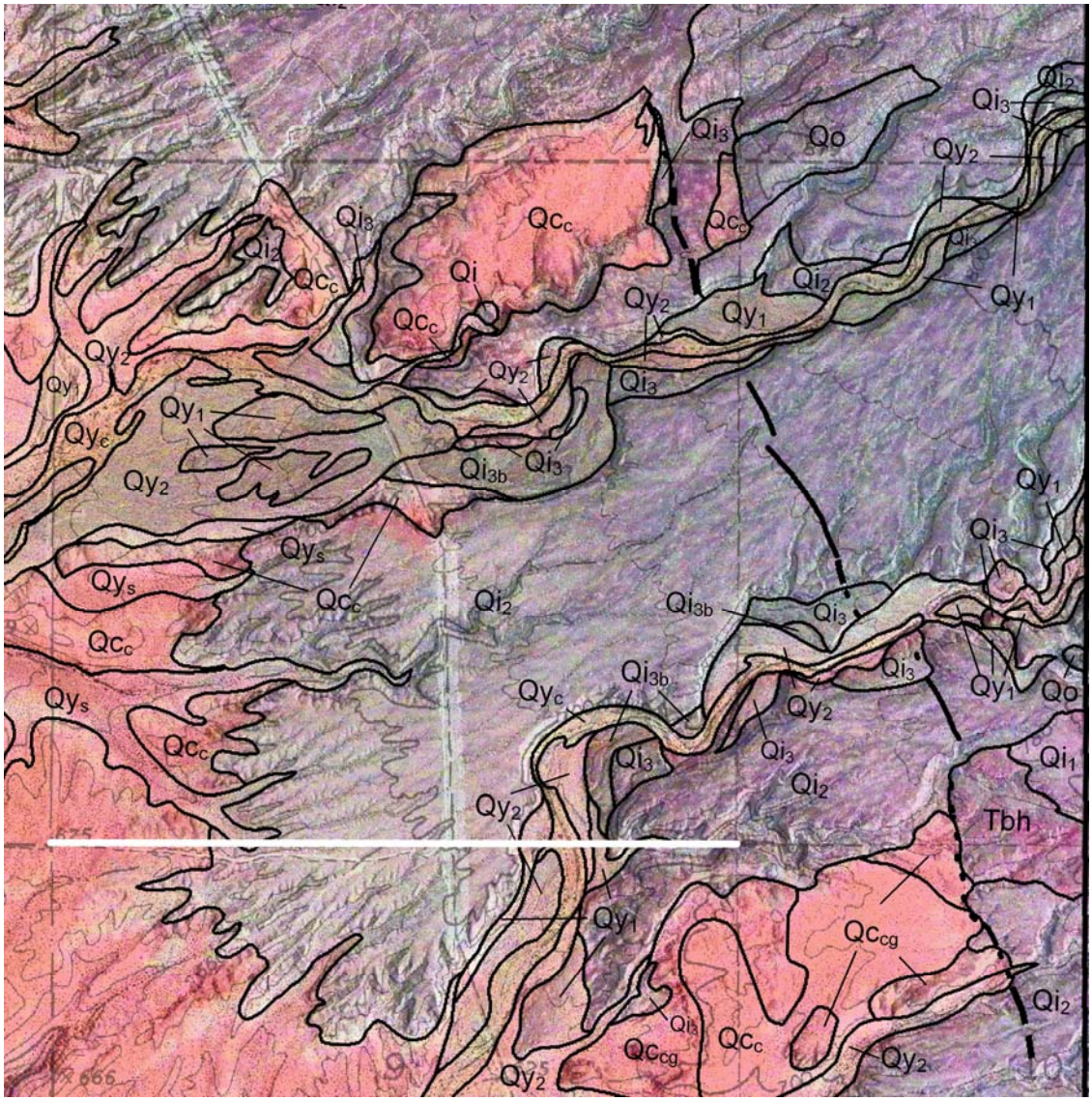

Figure 9. Low fault scarps formed on Qi_2 surfaces are shown by heavy black lines. Vertical displacement of Qi_2 surfaces is less than 0.5 m down to the west. Qi_3 and younger surfaces are not displaced, and older surfaces such as Qi_1 and Qo do not cross the fault zone. The bold white bar indicates one mile on the photo. Late Quaternary Colorado River deposits show up as pink in this image; Holocene to late Pleistocene tributary deposits appear as various shades of brown, and older late Pleistocene tributary fans appear purple.

Geologic Resources

Late Cenozoic Colorado River deposits in the Needles NE quadrangle are potentially an abundant source of aggregate for construction. At this time, small to moderately large aggregate operations are extracting gravel and sand from early Holocene and latest Pleistocene gravelly river terrace deposits (units Qc_1 and Qc_2) along the margins of the historical river floodplain. 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 Bullhead City area to the north, much larger aggregate operations are mining extensive and thick Pliocene Colorado River deposits (alluvium of Bullhead City, unit Tcb). Similar deposits are exposed in the southeastern corner of the Needles NE quadrangle and probably underlie much of the lower piedmont. Thus, the eastern part of this quadrangle likely has significant potential aggregate resources.

Acknowledgments. The Bureau of Land Management, the Bureau of Reclamation and the U.S. Geological Survey supplied most of the aerial photographs used in these mapping efforts. Remote sensing data provided by Simon Hooke of the Jet Propulsion Laboratory and Sarah Robinson of the U.S. Geological Survey were vital in identifying and mapping old Colorado River deposits on the piedmont. Kyle House of the Nevada Bureau of Mines and Geology and Keith Howard of the USGS provided valuable insights into the geology of this area. Assistance in map preparation was provided by Joe Cook and Todd Shipman. Map layout was done by Stevan Gyetvai.

References

Amoroso, Lee, 2006, Age calibration of carbonate rind thickness in late Pleistocene soils for surficial deposit age estimation, Southwest USA: Quaternary Research, v. 65, p. 172-178.

Birkeland, Peter W., 1999, Soils and Geomorphology (3rd Ed.): Oxford University Press, New York, 429 pp.

Bull, W.B., 1991, Geomorphic Response to Climatic Change: Oxford University Press, New York, 326 p.

Faulds, J.E., House, P.K., Ramelli, A.R., Bell, J.W., and Pearthree, P.A., 2001, Preliminary geologic map of the Davis Dam Quadrangle, Clark County, Nevada, and Mohave County, Arizona: Nevada Bureau of Mines and Geology, Open File Report 03-5, 1:24,000.

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the basin and range area of southern New Mexico -- guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources Memoir 39, 222 p.

House, P.K., Howard, K.A., Bell, J.W., and Pearthree, P.A., 2004, Preliminary geologic map of the Arizona and Nevada parts of the Mt. Manchester Quadrangle: Nevada Bureau of Mines and Geology Open-File Report 04-04, 1:24,000.

House, P.K., Pearthree, P.A., Howard, K.A., Bell, J.W., Perkins, M.E., Faulds, J.E., and Brock, A.L., 2005, Birth of the lower Colorado River—Stratigraphic and geomorphic evidence for its inception near the conjunction of Nevada, Arizona, and California, in Pederson, J., and Dehler, C.M., eds., *Interior Western United States: GSA Field Guide 6*, p. 357-387.

Lundstrom, S.C., Mahan, S.A., and Paces, J., 1998, Late Pleistocene sedimentation and erosion of the lower Colorado River, Nevada and Arizona: possible evidence for catastrophic floods: Geological Society of America Abstracts with Programs, v. 30, p. 31, A-14.

Metzger, D.G., and Loeltz, O.J., 1973, Geohydrology of the Needles area, Arizona, California, and Nevada: U.S. Geological Survey Professional Paper 486-J, 54 p.

Machette, M.N., 1985, Calcic soils of the southwestern United States: in Weide, D.L., ed., Soils and Quaternary Geology of the Southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

Reynolds, S.J., and DeWitt, Ed, 1991, Proterozoic geology of the Phoenix region, central Arizona, *in* Karlstrom, K.E., ed., Proterozoic geology and ore deposits of Arizona: Arizona Geological Society Digest 19, p. 237-250.

Pearthree, P.A., and House, P.K., 2005, Geologic map of the Davis Dam SE 7 1/2' quadrangle, Mohave County, Arizona, and Clark County, Nevada: Arizona Geological Survey Digital Geologic Map DGM-45, scale 1:24,000.

Pearthree, P.A., Menges, C.M., and Mayer, Larry, 1983, Distribution, recurrence, and possible tectonic implications of late Quaternary faulting in Arizona: Arizona Bureau of Geology and Mineral Technology Open-File Report 83-20, 51 p.

Purcell, C., and Miller, D.G., 1980, Grabens along the lower Colorado River, California and Arizona, in Fife, D.L., and Brown, A.R., eds., Geology and Mineral Wealth of the California Desert: South Coast Geological Society, p. 475, 484.

Richard, S.M., Shipman, T.C., Greene, L., and Harris, R.C., 2007, Estimated depth to bedrock in Arizona: Arizona Geological Survey Digital Geologic Map DGM 52, scale 1:1,000,000.

Spencer, J.E., and Patchett, J., 1997, Sr isotope evidence for a lacustrine origin for the upper Miocene to Pliocene Bouse Formation, lower Colorado River trough, and implications for timing of Colorado Plateau uplift: Geological Society of America Bulletin v, 109, p. 767-778.

Spencer, J.E., and Pearthree, P.A., 2001, Headward erosion versus closed-basin spillover as alternative caused of neogene capture of the ancestral Colorado River by the Gulf of California, in Young, R.A., and Spamer, E.E., eds., Colorado River Origin and Evolution: Grand Canyon Association, p. 215-219.

Spencer, J.E., Ferguson, C.A., Pearthree, P.A., and Richard, S.M., 2007, Geologic map of the Boundary Cone 7.5' Quadrangle, Mohave County, Arizona: Arizona Geological Survey Digital Geologic Map DGM-54, scale 1:24,000.