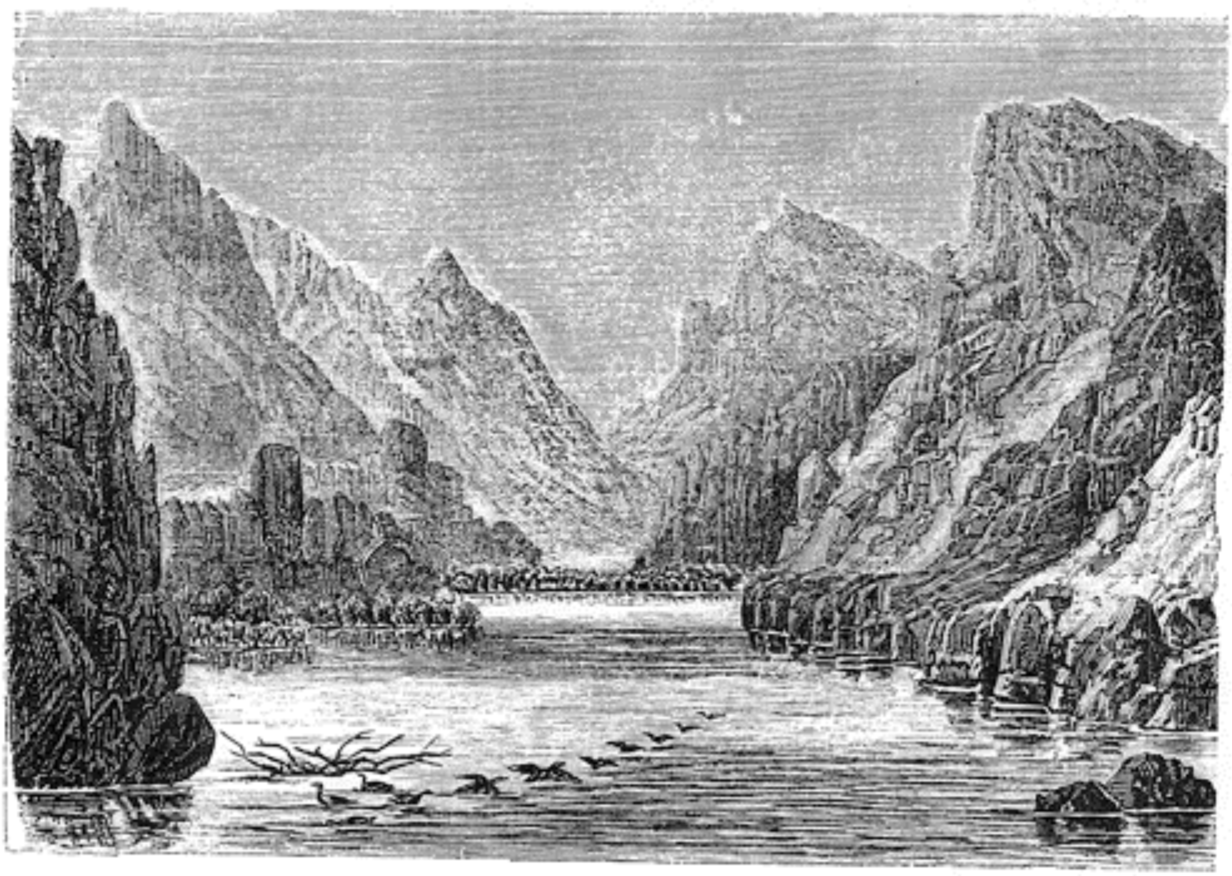
Geologic Map of the Topock 7.5´ Quadrangle, Arizona and California

By Keith A. Howard, Barbara E. John, Jane E. Nielson, Julia M.G. Miller, and Joseph L. Wooden

Pamphlet to accompany

Scientific Investigations Map 3236



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Front cover: View downstream into Topock Gorge ("Head of Mojave Cañon") as pictured in the Report upon the Colorado River of the West (fig. 16 of Ives, 1861). Miocene rocks on the skyline dip steeply to the right (west) in hanging-wall blocks above the Chemehuevi Detachment Fault and Devils Elbow Fault.

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Abstract

The Topock quadrangle exposes a structurally complex part of the Colorado River extensional corridor and also exposes deposits that record landscape evolution during the history of the Colorado River. Paleoproterozoic gneisses and Mesoproterozoic granitoids and intrusive sheets are exposed through tilted cross-sectional thicknesses of many kilometers. Intruding them are a series of Mesozoic to Tertiary igneous rocks including dismembered parts of the Late Cretaceous Chemehuevi Mountains Plutonic Suite. Plutons of this suite in Arizona, if structurally restored for Miocene extension, formed cupolas capping the Chemehuevi Mountains batholith in California. Thick (1–3 km) Miocene sections of volcanic rocks, sedimentary breccias, conglomerate, and sandstone rest nonconformably on the Proterozoic rocks and record the structural and depositional evolution of the Colorado River extensional corridor. Four major Miocene low-angle normal faults and a steep block-bounding fault that developed during this episode divide the deformed rocks of the quadrangle into major structural plates and tilted blocks in and east of the Chemehuevi Mountains core complex. The low-angle faults attenuate crustal section, superposing supracrustal and upper crustal rocks against gneisses and granitoids originally from deeper crustal levels. The transverse block-bounding Gold Dome Fault Zone juxtaposes two large hanging-wall blocks, each tilted 90°, and the fault zone splays at its tip into folds in layered Miocene rocks. A synfaulting intrusion occupies the triangular zone where the folded strata detached from an inside corner along this fault between the tilt blocks. Post-extensional upper Miocene to Quaternary strata, locally deformed, record post-extensional landscape evolution, including several Pliocene and younger aggradational episodes in the Colorado River valley and intervening degradation episodes. The aggradational sequences include (1) the Bouse Formation, (2) fluvial deposits correlated with the alluvium of Bullhead City, (3) the younger fluvial boulder conglomerate of Bat Cave Wash, (4) the fluvial Chemehuevi Formation and related valley-margin deposits, and (5) fluvial Holocene deposits under the river and the valley floor. These fluvial records of Colorado River deposition are interspersed with piedmont alluvial fan deposits of several ages.

Introduction

The Topock 7.5-minute quadrangle exposes geologic relations that splendidly illustrate notable processes of igneous intrusion, extensional tectonics, and fluvial geomorphology. The geologic map of the quadrangle and digital database document regionally significant aspects of Proterozoic, Cretaceous, and Miocene intrusion; of Miocene tectonic extension; and of evolution of the post-Miocene Colorado River. This report analyzes and interprets the geology and also gives brief accounts of the historical significance of the quadrangle, mineralization and mineral exploration, fossil materials, and ion-probe U-Pb dating.

The informal stratigraphic term Anthropocene has come into use in recent years for the geologic record of the time interval in which Earth history has been heavily affected by human activity, commonly referring to the time since the industrial revolution. As used on this geologic map, Anthropocene designates Holocene map units deposited during the 20th century. Geologic mapping of the quadrangle (fig. 1) is based on the 1970 topographic base map; younger sedimentation and flooding have since continued to evolve along the Colorado River corridor. Stages of carbonate soil development, reconnoitered for some surficial units, refer to the classification of Machette (1985). Major faults and intrusions in the quadrangle are named on figure 2 (map sheet). Localities mentioned in this report refer to surveyed sections.

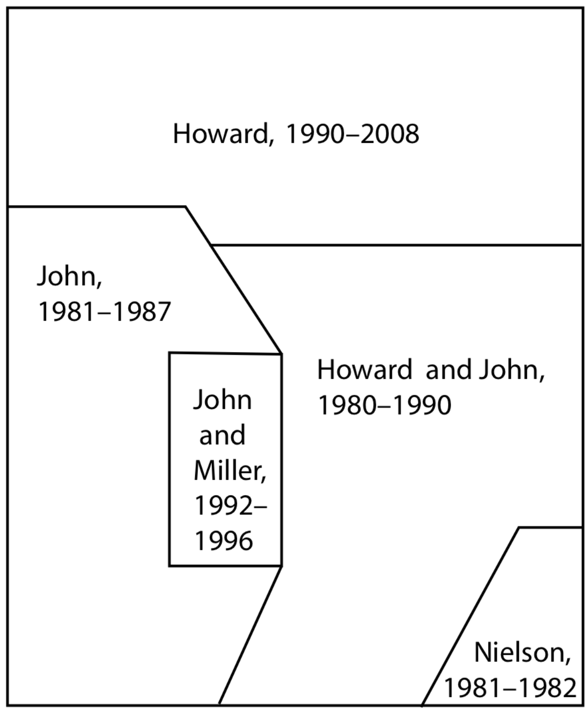


Figure 1. Map showing geologic mapping responsibilities in the Topock quadrangle.

Acknowledgments

Vicki Hansen, Martha Pernokas, Lindee Glick, Mary Squires, Geoffrey Phelps, Daniel Malmon, Zachary Anderson, and Linda Thorbarn contributed to the field observations and (or) geologic mapping. We thank Bob Simpson for geophysical perspectives and Ernie Anderson for additional structural observations, perceptive critiques, and detailed alternative interpretations of the mapping and structure. The map and report benefited from additional in-depth reviews by Sue Beard, James Faulds, Daniel Malmon, and Kyle House. John Nakata performed K-Ar dating on rocks in the quadrangle, Phillip Gans performed $^{40}Ar^{39}Ar$ dating, and Samuel Mukasa performed some of the U-Pb dating. Susan Priest, Sebastian Roberts, Zachery Anderson, and Tracey Felger entered the mapping into a Geographic Information System and patiently and expertly made needed revisions. Susan Priest designed the map layout and set up the metadata, which Kyle House reviewed. The mapping was done with the cooperation of the Bureau of Land Management, Bureau of Mines, University of California, Fish and Wildlife Service, National Science Foundation, and Bureau of Reclamation.

Geography

The quadrangle straddles the California-Arizona border along the Colorado River and includes rugged parts of the eastern Mojave and western Sonoran Deserts (figs. 3, 4). The quadrangle includes

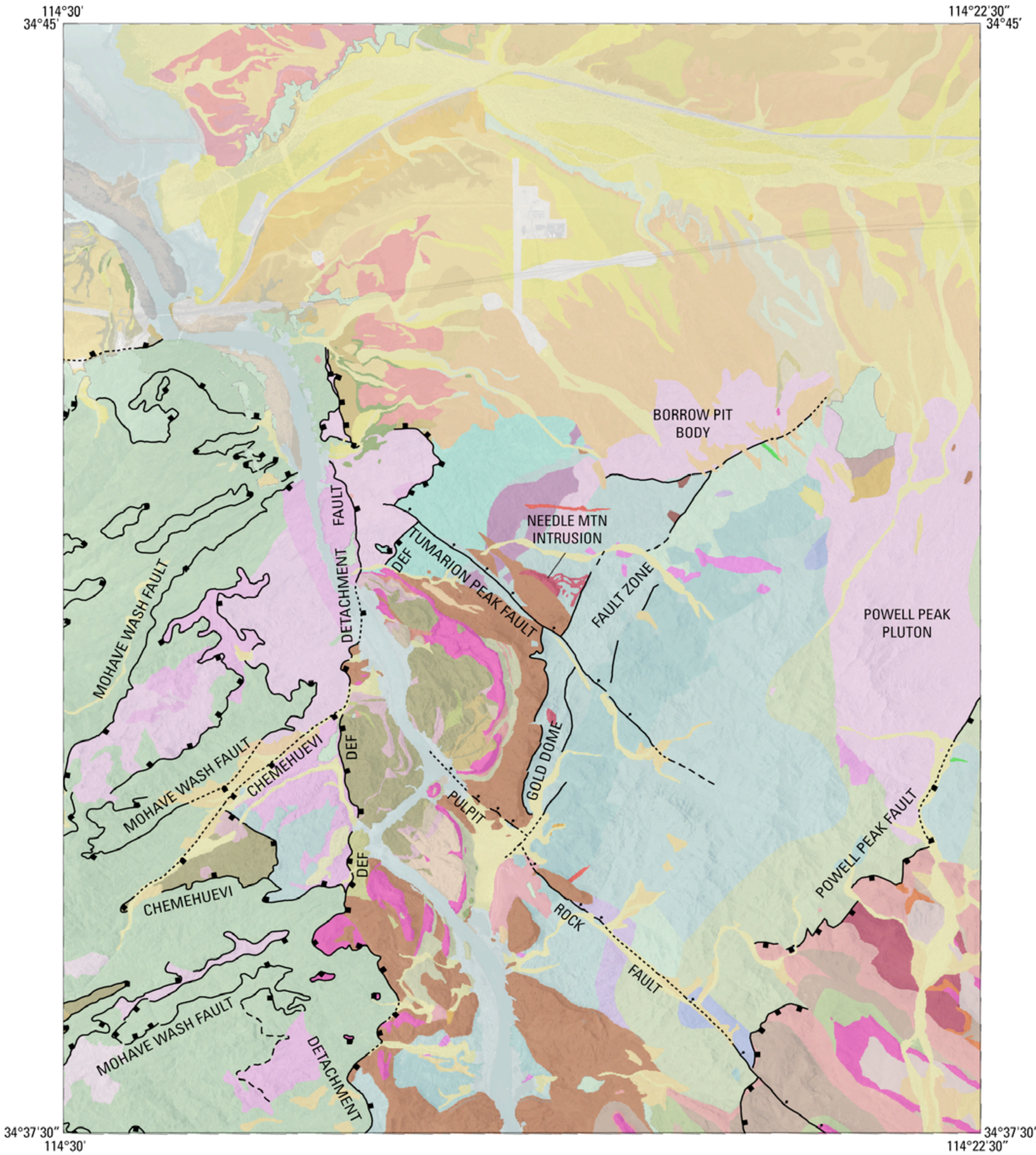


Figure 2. Map showing Topock quadrangle geology and major structures draped over hillshade derived from 30-m digital elevation model. Devil's Elbow Fault (DEF). (Full figure on map sheet.)

580 m of relief. Much of the western part of the quadrangle is in the Chemehuevi Mountains, in San Bernardino County, Calif. Much of the eastern part including The Needles is within the Mohave Mountains, in Mohave County, Ariz. The northern part of the quadrangle includes parts of Mohave

Cañon”. The now slow-moving river here forms the upstream part of Lake Havasu reservoir, impounded behind Parker Dam. Intermittent tributaries include small dry washes and the major Sacramento Wash, which drains a large western Arizona catchment area.

The narrow river valley at Topock in the northern part of the quadrangle offers a natural transportation corridor across the river (fig. 3), traversed by the Atcheson, Topeka, and Santa Fe Railroad, historic National Old Trails Road and old U.S. Route 66, Interstate Highway I-40, and three pipelines carrying natural gas to California from Texas and New Mexico. Other gas pipelines carry gas northward through the quadrangle from this corridor. The river and its shores are part of Havasu National Wildlife Refuge. The Chemehuevi Mountains and much of the refuge south of I-40 are designated wilderness areas. Impoundment of Lake Havasu reservoir in 1938 behind the Bureau of Reclamation’s Parker Dam led to flooding of an upstream area that became Topock Marsh in southern Mohave Valley.

Historical Significance

Mohave Valley is the ancestral home to a large concentration of Native Americans of the Mohave (Aha Macave). The Chemehuevi (or Nuwu), a branch of the Southern Paiute, also occupied part of the quadrangle area. Late nineteenth-century encounters between the Mohave and Chemehuevi are recounted in Kroeber and Kroeber (1973).

Terraces near Topock were the sites of prehistoric intaglios (ground figures), as large as 30 m, and also of a large area of scraped windrow patterns known as the “Topock Maze” or “Mystic Maze” (figs. 3, 5: Thompson, 1929; Reynolds and others, 2007). Musser-Lopez (2011) reviewed controversies over the origin of the maze and marshaled evidence that gravel quarrying for the railway in the 1880s by tribal members likely produced it, in contrast to the older ground figures. Both features were damaged during railroad and later freeway construction, but large remnants of the maze may be visited on surfaces of the intermediate-age piedmont alluvium (Qa2) 0.5 km northwest of Bat Cave, 1.5 km west of Topock.

The Needles were named in 1854 by Lt. A.W. Whipple in his U.S. Army expedition to explore a transcontinental railway route near the 35th parallel. The party had already endured many difficulties crossing New Mexico Territory, but the terrain south of The Needles awed Lt. J.C. Tidball as “if possible, the worst yet. It was a confused mass of gorges, precipices, and serrated crests several thousand feet high * * *.” (Tidball, 2004*).* He exaggerated the heights of the crests but the rugged nature of the terrain is not much overstated.

The Army’s Colorado River expedition about four years later under Lt. J.C. Ives surveyed the Colorado River for its navigability and natural history, with Dr. John Strong Newberry investigating the geology (Ives, 1861). Ives described his impressions as his group navigated the small steamboat *Explorer* up Topock Gorge, then known as Mojave Cañon (fig. 4):

> “Entering the foot hills of the Mojave Range, the channel was again tortuous, and after traversing a narrow pass the Needles came in view directly in front. As we approached the mouth of the canon through the Mojave mountains, a roaring noise ahead gave notice that we were coming to a rapid, and soon we reached the foot of a pebbly island, along either side of which the water was rushing, enveloped in a sheet of foam * * *.
>
> A low purple gateway and a splendid corridor, with massive red walls, formed the entrance to the canon. At the head of this avenue frowning mountains, piled one above the other, seemed to block the way. An abrupt run at the base of the apparent barrier revealed a cavern-like approach to the profound chasm beyond. A scene of such imposing grandeur as that which now presented itself I have never before witnessed. On either side majestic cliffs, hundreds of feet in height, rose perpendicularly from the water. As the river wound through the narrow enclosure every turn

developed some sublime effect or startling novelty in the view. Brillient tints of purple, green, brown, red, and white illuminated the stupendous surfaces and relieved their sombre monotony. Far above, clear and distinct upon the narrow strip of sky, turrets, spires, jagged statue-like peaks and grotesque pinnacles overlooked the deep abyss (Ives, 1861)."

Commercial steamboats plied the river in the last part of the nineteenth century. The early name "Mellen," for the community that later became Topock, honored the Colorado River steamboat captain Jack Mellon (Geneology Trails History Group, 2006).

The historic transcontinental Atlantic and Pacific Railroad was built in 1881–1883 across the north-central edge of the quadrangle. Its old railroad grade, en route northwest to a former long bridge

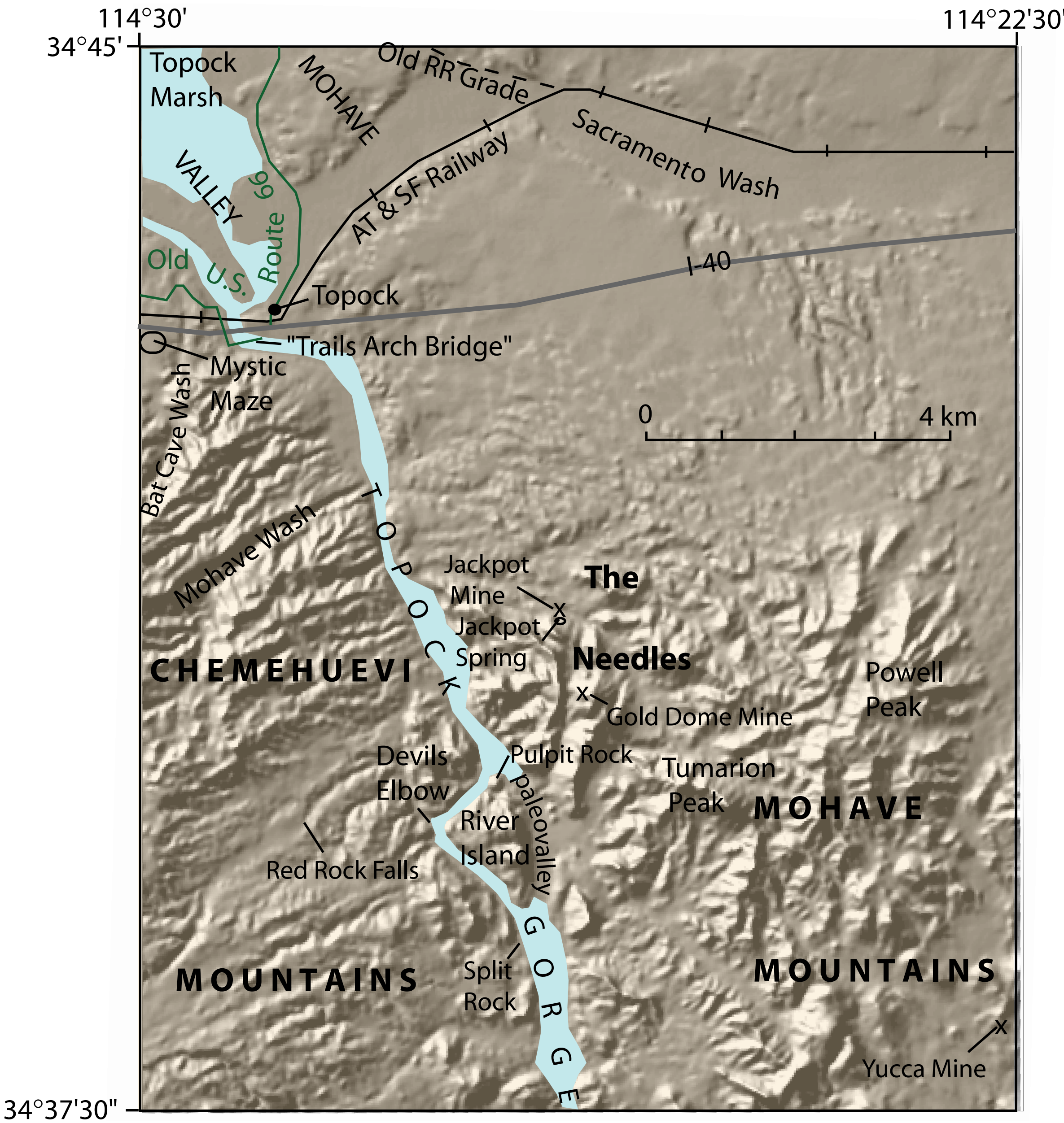


Figure 3. Map showing some geographic features in the Topock quadrangle. Old U.S. Route 66 follows the National Old Trails Highway. Old RR grade is abandoned historic Old Railway grade of Atlantic and Pacific Railway. AT & SF Railway, Atcheson, Topeka, and Santa Fe Railroad. Paleovalley of the ancestral Colorado

River shown near River Island; stratigraphic evidence for an unrelated, older (early Miocene) paleovalley (not labeled) near The Needles is discussed in the text.

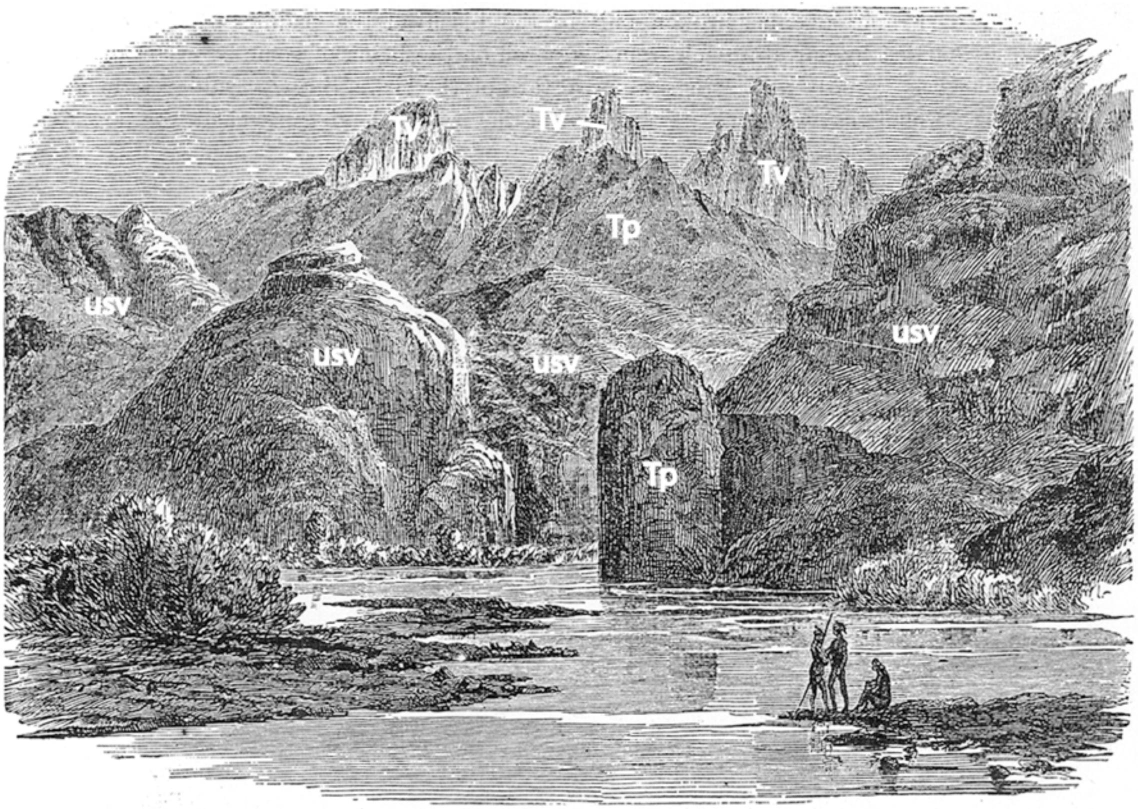


Figure 4. View northeastward up Topock Gorge (Mojave Cañon) from near Devils Elbow as rendered in the Report upon the Colorado River of the West (Ives, 1861). As annotated here, the lower volcanic sequence (Tv) forms the jagged Needles in the background. The Peach Spring Tuff (Tp) forms the dip slope of a plunging syncline making up the high background ridge in front of The Needles, and the tuff also underlies Pulpit Rock pinnacle, rising from the river in the right foreground. Other foreground hills expose conglomerate and breccia subunits of the upper sedimentary and volcanic sequence (usv).

across Mohave Valley, is partly preserved as artificial fill (map unit af) raised above the intermittently active Sacramento Wash and in cuts through Pliocene and Pleistocene sediments. The old railroad grade (fig. 3) was abandoned in 1890 when the railway was rerouted south to a new bridge over the Colorado River at Topock that was less prone to flood damage. The Atlantic and Pacific railroad became the Santa Fe Pacific in 1897, and then the Acheson, Topeka, and Santa Fe Railroad in 1902, here shortened to Santa Fe Railroad. The Santa Fe Railroad's historic water tower rises above the railway at Topock.

Much has been written about the history of bridges across the Colorado River at Topock (for example, Myrick, 1963; Jackson, 1988; Kuna, 1991; http://www.theroadwanderer.net/RT66coloriver.htm). In the early 20th century, wagons and automobiles traversing the National Old Trails highway were ferried across the river here. Starting in 1914, wagons and autos used the 1890 railroad bridge, between trains, until the one-lane Trails Arch highway bridge (fig. 3) was built in 1916 as the then-largest hinged arch bridge. This bridge, which once carried immigrants from the dust bowl to Calif., now supports a gas pipeline instead of a roadway. The National Old Trails highway and its successor, historic U.S. Route 66 (fig. 3), attract many history enthusiasts to the Topock area.

Figure 5. Photo showing part of the Mystic Maze (Topock Maze). The normally flat desert-pavement surface of the intermediate-age piedmont alluvium (Qa2) has been scraped into windrow-like features. See figure 3 for location.

Previous Geologic Investigations

Early geologic descriptions of the area were presented by J.S. Newberry (in Ives, 1861), Lee (1908), Darton and others (1916), and Thompson (1929). Coonrad and Collier (1960a,b) recognized and mapped low-angle faults in the Chemehuevi Mountains. Since then, the geology has been studied by many groups. Metzger and Loeltz (1973) outlined a stratigraphy of upper Miocene and younger deposits, interpreted drill logs for subsurface occurrences of the Bouse Formation and deposits of the Colorado River and its tributaries, and analyzed the water resources of the area. Investigative reports have been published on the Cretaceous plutons (John, 1988; John and Mukasa, 1990; John and Wooden, 1990), structural evolution and geochronology (Howard and others, 1982; John, 1987a; Howard and John, 1987, 1997; Foster and others, 1990; Nakata and others, 1990; John and Foster, 1993; Foster and John, 1999; Campbell-Stone and John, 1996; Carter and others, 2006), Miocene rocks and their paleomagnetism (Miller and John, 1988, 1993, 1999; Wells and Hillhouse, 1988; Hillhouse and Wells, 1991), and upper Miocene to Quaternary stratigraphy and geomorphology (Metzger and Loeltz, 1973; Howard and Malmon, 2007; Malmon and Howard, 2007; Howard and others, 2008; Pearthree and others, 2009; Malmon and others, 2011). See Pearthree and others (2009) for other mapping interpretation and further subdivision of surficial deposits in the northwestern part of the quadrangle. Malmon and others (2010) discussed backwaters formed after the impoundment of Lake

Havasu behind Parker Dam. Hydrogeological studies and drilling have been conducted for groundwater remediation west of Topock (DTSC, 2010; Department of the Interior, 2010).

This map revises preliminary geologic maps of parts of the area by John (1987b), Howard and others (1997b), and Miller and John (1999). Areas adjacent to the quadrangle were mapped by John (1987b), Howard and others (1999), Miller and John (1999), Malmon and others (2009), and Pearthree and others (2009) (fig. 6). Field guides to parts of the quadrangle and its environs were presented by Nielson (1986), Howard and others (1987, 1994), and John and Howard (1994).

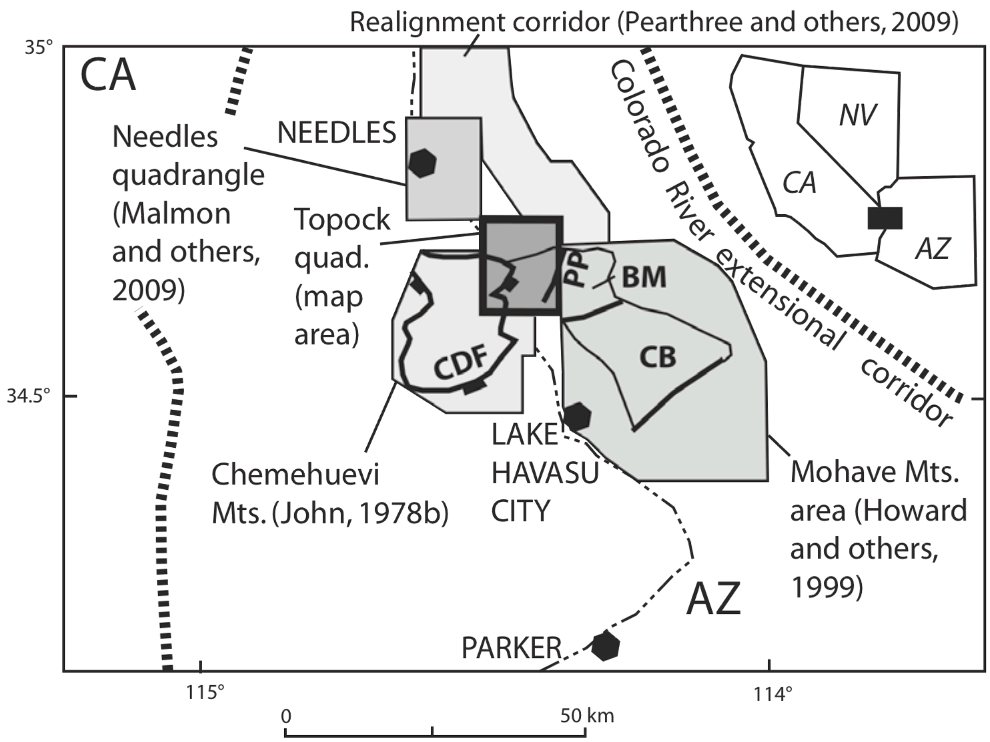
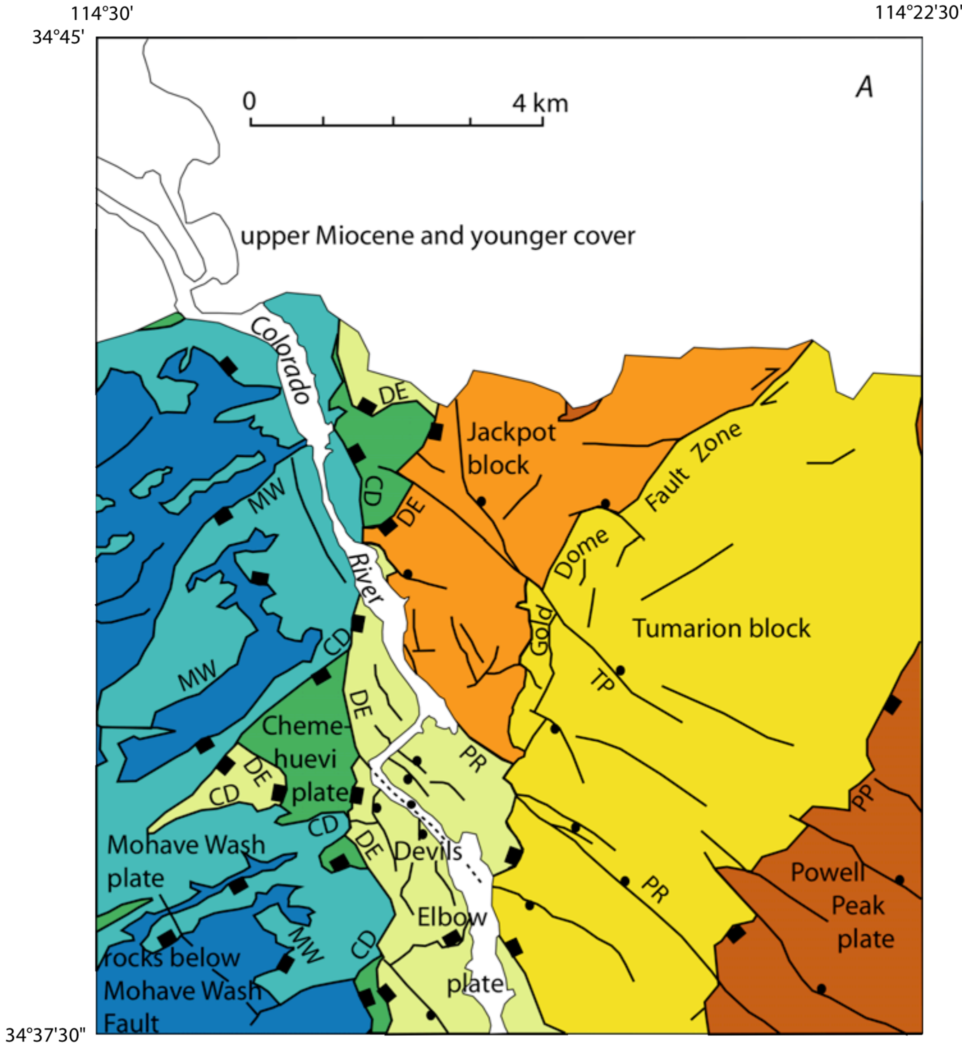


Figure 6. Map showing the Topock quadrangle in relation to adjacent geologic map areas and the Colorado River extensional corridor. Major structural features in and near the map area include the Chemehuevi Detachment Fault (CDF; John, 1987a), the Powell Peak plate-Boulder Mine area (BM) of numerous fault slices above the Powell Peak Fault (PP), and the large tilted Crossman block (CB; Howard and others, 1999).

Tectonic Block Diagram

To set the stage for discussion of the geology, figure 7 presents a geologic-map-based tectonic map and block diagram displaying the major Miocene structural architecture of the quadrangle. The Chemehuevi plate and higher fault plates and blocks show evidence of >18 km of relative northeastward Miocene transport above the Chemehuevi Detachment Fault and as much as 70–100° of tilting down to the southwest. The displacement and these tilt rotations form a major basis for geologic interpretations of the rock units and structures.



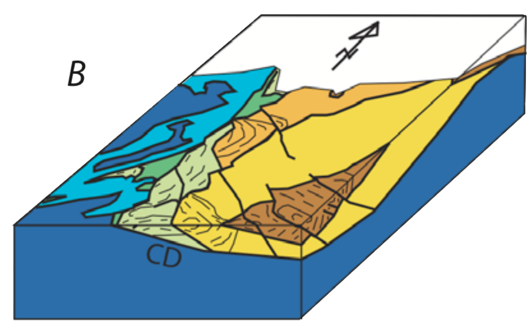


Figure 7. *A*. Interpretive tectonic map of the Topock quadrangle showing major faults and named structural blocks and plates (each a different color). Hanging walls are indicated for normal faults (ball) and low-angle normal faults (rectangles); arrows indicate strike-slip separation. Colors distinguish the structural blocks. The Mohave Wash Fault (MW) carries the Mohave Wash plate over a deeper footwall. The structurally higher and younger large-displacement Chemehuevi Detachment Fault (CD) carries the Chemehuevi and higher plates. The Chemehuevi Detachment Fault truncates the higher Devils Elbow Fault (DE), which carries the Devils Elbow plate. The dextral, mostly steep Gold Dome Fault Zone separates the Jackpot and Tumarion tilt blocks, which are higher parts of the Devils Elbow plate. The Powell Peak Fault (PP) carries the Powell Peak plate (Boulder Mine area of Howard and others, 1982, 1999) over the Tumarion block. The Tumarion Peak Fault (TP) and Pulpit Rock Fault (PR) cut the Tumarion and Jackpot blocks. *B*. Interpretive tectonic block diagram of the quadrangle. Rocks that are in the Chemehuevi plate (dark green) and higher plates typically are tilted to the southwest as indicated by stratal dips and dips of diabase sheets. Thin form lines indicate layering in Miocene volcanic and sedimentary rocks. CD, Chemehuevi Detachment Fault.

Proterozoic Rocks

Paleoproterozoic gneisses in the east half of the quadrangle above the Chemehuevi Detachment Fault form an assemblage dominated by metamorphosed granitic rocks (Xg, Xag, Xgl, Xgp), which enclose small bodies of amphibolite (Xga) and metasedimentary gneiss and quartzite (Xgs). Most rock units are likely to be 1.7 Ga or older based on resemblance to dated rocks in nearby regions (Wooden and Miller, 1990; Chamberlain and Bowring, 1990; Wooden and Dewitt, 1991; Bryant and Wooden, 1991, 2008). Metamorphic foliations in the Tumarion block and in the Gold Dome Fault Zone define a girdle indicative of a southwestward-plunging axis of folding (fig. 8). This axis would plunge northeastward if restored for steep Miocene southwestward tilting (see Miocene Extensional Structure). Similar patterns of both mapped foliation and tilt-restored foliation were observed in the Crossman and the Buck Mountains blocks 20 km to the southeast (Howard and others, 1982). Paleoproterozoic augen gneiss (Xag) forms an elongate pluton in the Tumarion block and resembles rocks dated as 1.64 Ga in the Bill Williams Mountains by Wooden and Miller (1990). The mapped outline of this pluton would represent the cross section of a thick dike-like body as much as 6 km high, deeper toward the northeast, if 90° of southwestward Miocene tilting were restored. Phanerozoic mylonitic fabric overprints Paleoproterozoic gneiss and migmatite below the Chemehuevi Detachment

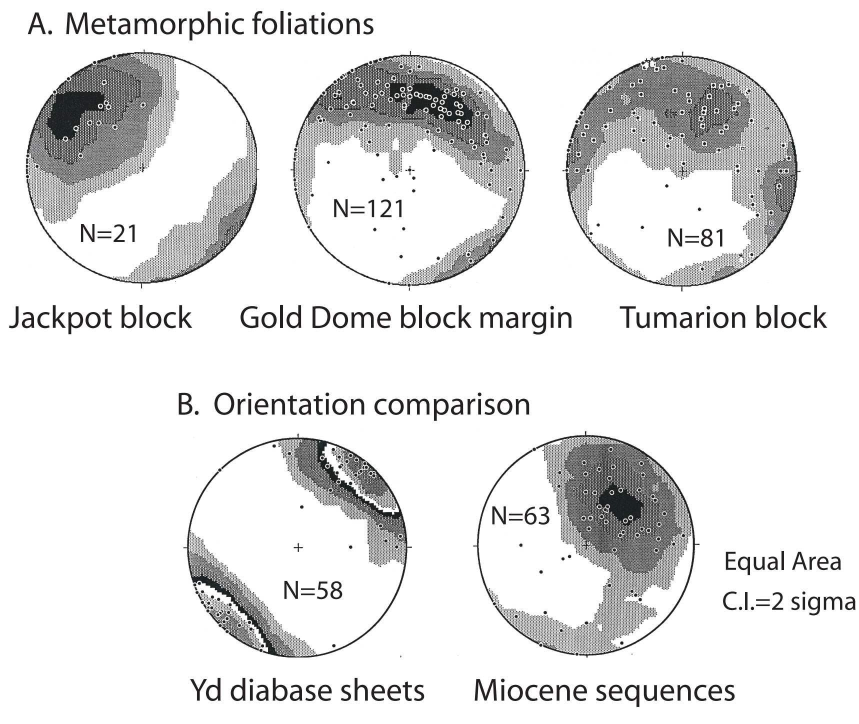


Figure 8. Contoured orientation data (poles, lower hemisphere equal-area projection) for areas in the Topock quadrangle east of the Colorado River. *A.* Metamorphic foliations in three domains—the Jackpot and Tumarion blocks and the Gold Dome Fault Zone between them (fig. 7). *B.* Comparison of orientations of Mesoproterozoic diabase sheets with bedding in middle and lower Miocene rocks in the Tumarion and Jackpot blocks (east part of quadrangle, from John and Howard, 1994). The diabase sheets are mostly near vertical and strike northwest. The oldest Miocene rocks subparallel this steep orientation, consistent with pre-tilt subhorizontal orientations for the diabase sheets. Spread in orientations in Miocene rocks reflects younger parts of the Miocene section dipping less steeply than older parts (see also Miller and John, 1999).

Fault in the western part of the quadrangle, forming a map unit of mylonitic rock (Xgm) that represents a deeper crustal level than the rocks exposed in the eastern part of the quadrangle.

The Paleoproterozoic metamorphic rocks in the central part of the quadrangle are intruded by a northeast-elongate pluton of granite (Yg) assigned to the Mesoproterozoic based on similarity to 1.4-Ga rocks in the region (Anderson and Bender, 1989). Emplacement of this pluton possibly was responsible for steep southeastward-dipping metamorphic foliations mapped in adjacent older rocks (in the Jackpot block; figs. 7, 8*A*). The granite and older rocks, in turn, are intruded by steep diabase sheets (Yd) that are correlated lithologically with 1.1-Ga diabase widespread in Arizona and California that consistently reconstructs as originally subhorizontal intrusive sheets (Howard, 1991). In the Tumarion and Jackpot blocks, the sheets dip steeply and strike northwest (fig. 8*B*) and were interpreted to restore to pre-Miocene subhorizontal orientations (before Miocene tilting; John and Howard, 1994; Howard and John, 1997). A similarly steep, northwest-striking orientation for the sheets where they occur in the Chemehuevi plate west of Devils Elbow (fig. 7) was likewise interpreted to reflect 70–90° southwestward tilting there (John and Foster, 1993).

Mesozoic Intrusions

Granitoids of the Chemehuevi Mountains Plutonic Suite record Late Cretaceous plutonism and deformation (John, 1987b, 1988; John and Wooden, 1990; John and Mukasa, 1990). Diorite (Kd) is also dated as Late Cretaceous, and other, undated rocks such as the diorite of Topock (Kt) may also be Cretaceous.

The Chemehuevi Mountains Plutonic Suite forms a laccolith-shaped batholith in the Chemehuevi Mountains, here called the Chemehuevi Mountains batholith (lower part of fig. 9; John, 1988). It includes several nested granitoid phases (including Kcg, Kcb, Kcc), exposed mostly west of the quadrangle, and is inferred to represent initially deeper levels to the east-northeast because of 10–20° tilting down to the west-southwest. Northeastward-elongate extensions of the suite prominent in the west part of this quadrangle were interpreted as feeder dikes (John, 1988). Cross section A–A′ speculates a concealed northeastward extension of the larger biotite granodiorite feeder dike in Arizona, at the site of a subtle aeromagnetic anomaly mapped by Mariano and Grauch (1988). Biotite granodiorite (Kcb) and hornblende-biotite granodiorite (Kcb, Kch) assigned to the Chemehuevi Mountains Plutonic Suite also form the Powell Peak pluton in the Tumarion structural block, and biotite granodiorite (Kcb) also forms the smaller Borrow Pit body in the Jackpot structural block, both in Arizona. If these two bodies are restored for 90° of Miocene tilting and for >20 km of Miocene northeastward movement along the underlying detachment faults (John, 1987a), they occupy upward-elongate cupola positions above the now-beheaded Chemehuevi Mountains batholith (fig. 10). As reconstructed with these cupolas in figure 10, the batholith had an aspect ratio of roughly 1:1, a flat, sill-like lower portion fed from below by dikes, and irregular upward protrusions into Proterozoic rocks.

The porphyritic hornblende-biotite granodiorite (Kcg) of that suite commonly hosts a mylonitic foliation, as does Paleoproterozoic mylonitic gneiss and migmatite (Xgm) that floor the Chemehuevi Mountains batholith. The mylonitic fabric includes a gently southwest-plunging lineation that shows top-to-northeast shear sense where the foliation dips gently or sinistral shear sense where the mylonitic foliation is steep in the northwestern part of the quadrangle (John and Mukasa, 1990). The gently dipping mylonitic foliation is modestly folded parallel to the lineation (John, 1987b). As the younger biotite granodiorite (Kbg) and Chemehuevi Peak Granodiorite (Kcc) of the same suite do not exhibit the mylonitic fabric, John and Mukasa (1990) concluded that the mylonitic fabric records regional top-to-northeast contractional ductile shearing of about 75 Ma age, between the time of emplacement of older and younger members of the Chemehuevi Mountains Plutonic Suite. Miocene mylonitization

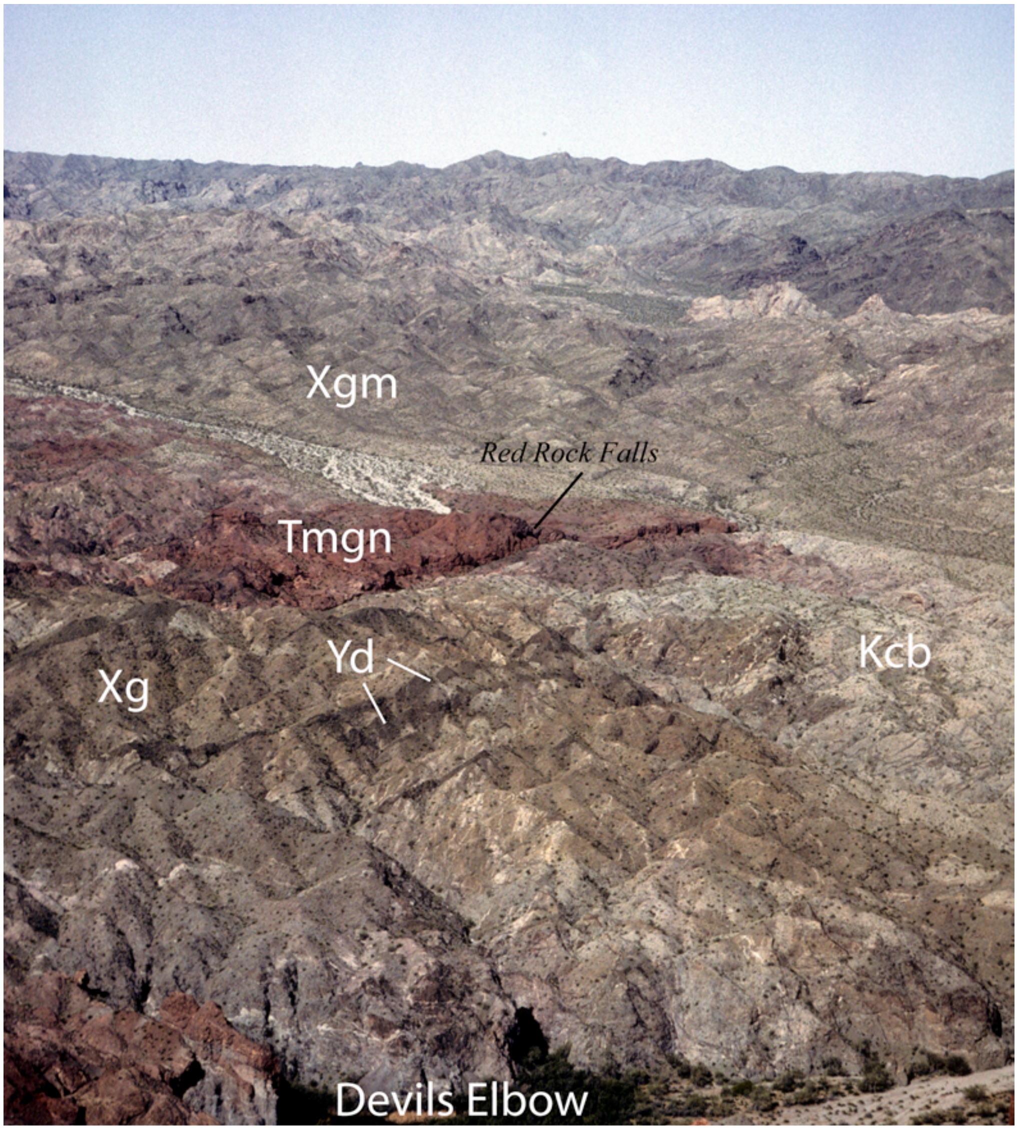


Figure 9. Photo showing view west into the Chemehuevi Mountains in the southwest part of the Topock quadrangle. An extensional klippe of reddish gneiss-clast megabreccia (Tmgn) of the Devils Elbow plate is structurally superposed on gneiss (Xg) crosscut by diabase sheets (Yd, dark) and biotite granodiorite (Kcb, light) in the Chemehuevi plate. Both plates in turn are structurally superposed on rocks below the Chemehuevi Detachment Fault, including mylonitic gneiss and migmatite (Xgm).

along the northern front of the Chemehuevi Mountains is indicated by Miocene intrusive ages for some mylonitized parts of the quartz monzonite unit (TKwq).

A swarm of northeast-striking lamprophyre dikes (TKl) of Late Cretaceous or Tertiary age cuts the Powell Peak pluton and nearby eastern parts of the quadrangle, and similarly oriented mafic dikes are present farther west as part of the dike swarm of Chemehuevi Mountains (TKcd). (Northwest-striking members of the dike swarm of Chemehuevi Mountains, Tcd, are assigned here to the Miocene.) If the lamprophyre dikes (TKl) predate 90° of Miocene tilting of the Tumarion structural block, their prevailing 75° west-northwest dip would restore to vertical, with an east-northeast strike. These dikes are suspected to be of latest Cretaceous or early Tertiary age because the restored orientation resembles that of Late Cretaceous- to early Tertiary-age dikes in many parts of Arizona

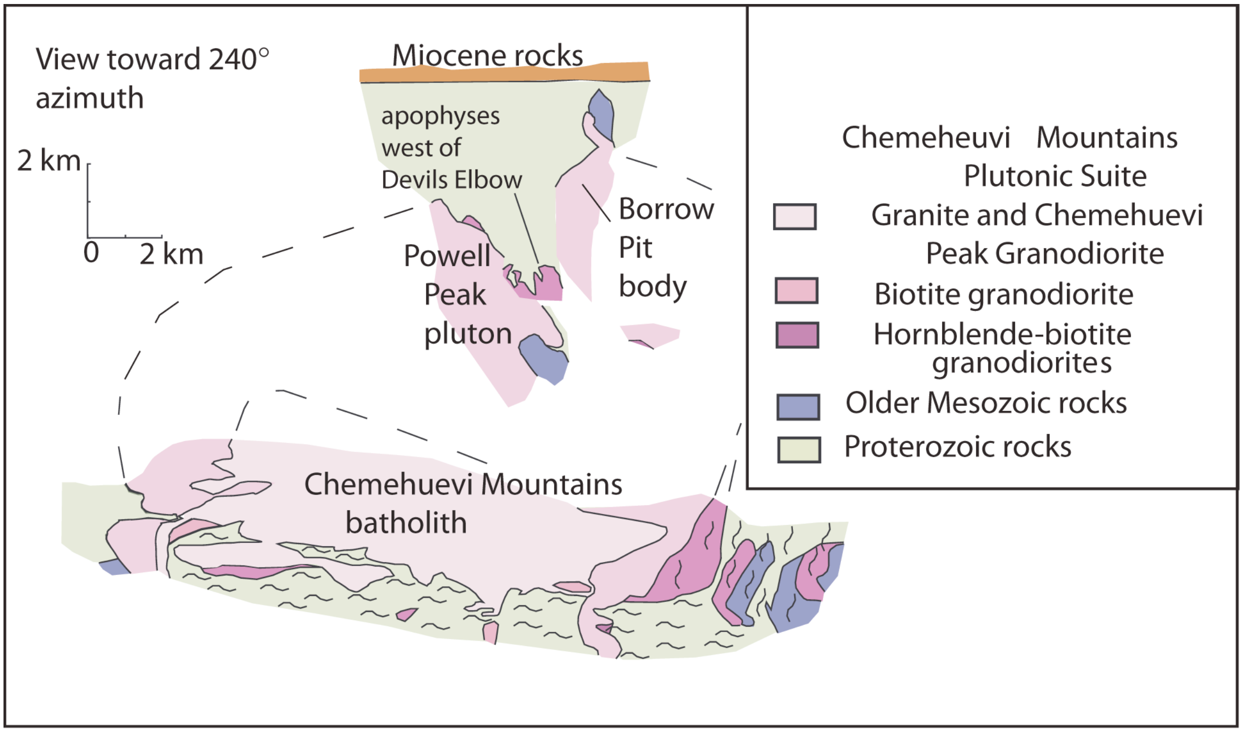


Figure 10. A reconstructed pre-extension cross-sectional shape of the Chemehuevi Mountains Plutonic Suite, viewed south-southwestward. Reconstructed before Miocene tilting, by combining separate down-dip views of map patterns in four structural plates and blocks, with unexposed parts represented by uncolored areas on the figure. The lower part (modified after John, 1988) projects the lower part, floor, and feeder dikes of the Chemehuevi Mountains batholith as exposed in the footwall of the Chemehuevi Detachment Fault in and west of the quadrangle, assuming the batholith is tilted 15° WSW.; the depth shown assumes that the exposed batholith was at early Miocene depths ≥10 km (after Foster and John, 1999). The shape is inferred to be representative, although the plutons are not likely to be cylindrical as assumed for the projections. The upper part of the reconstruction restores the Powell Peak pluton in the Tumarion block and the Borrow Pit body in the Jackpot block back above the Chemehuevi Mountains batholith, assuming they each tilted 90° SW. as it translated >20 km relatively NE.; apophyses of granodiorites exposed near Devils Elbow and another small patch of granodiorites to the right in the projection (both in the Chemehuevi plate) are placed at arbitrary depth. If the early Miocene depth for the Chemehuevi Mountains batholith was <10 km, the two major parts of the reconstruction would be closer together.

(Rehrig and Heidrick, 1976; Livacarri, 1991). The restored dike orientation may reflect stress orientations during northeast-southwest-directed contraction in the Laramide orogeny. Irregular bodies and dikes of quartz porphyry (TKq) and of fine-grained granite (TKf) may be either Late Cretaceous or Tertiary in age.

Sub-Miocene Unconformity

Lower Miocene rocks in the quadrangle nonconformably overlie Proterozoic rocks. The nonconformity characterizes this as part of the Kingman uplift, where uplift in the Sevier or Laramide orogenies led to deep pre-Miocene erosional stripping of regional Cambrian to Triassic marine and younger Mesozoic continental sequences (Stone and others, 1983; Bohannon, 1984; Faulds and others, 2001; Beard and others, 2010). The region of uplift is hundreds of kilometers long and wide.

Miocene Rocks Related to Tectonic Extension

Volcanic and sedimentary rocks of Miocene age overlie and are faulted against the pre-Miocene rocks. The deformed Tertiary rocks are divided into three major lithologic sequences, from oldest to youngest: (1) a lower volcanic sequence and sedimentary rocks, (2) the 18.5-Ma Peach Spring Tuff (Tp), and (3) an upper sedimentary rock and volcanic sequence (fig. 11). The laterally variable Miocene section includes 0.5–1 km of volcanic rocks and as much as 2 km of detrital rocks. Most of the faulted Miocene sections in the region around the Chemehuevi and Mohave Mountains are dated between 22 and 14 Ma (Howard and John, 1987; Nielson and Beratan, 1990; Nakata and others, 1990; Nielson, 1993; Nielson and Beratan, 1995; Miller and John, 1993, 1999).

Lower Miocene Volcanic and Sedimentary Rocks

Thin arkose and conglomerate (Tac) derived from underlying Proterozoic rocks occur at and interfingered near the base of the Tertiary section, as in many other areas in the region (Lucchitta and Suneson, 1993; Howard and others, 1997a, 1999). The mostly overlying lower volcanic sequence, locally dated as 20.5±0.7 Ma, is well exposed in the southeastern and central parts of the quadrangle. The laterally variable volcanic rocks in this sequence include andesitic lahar agglomerate low in the

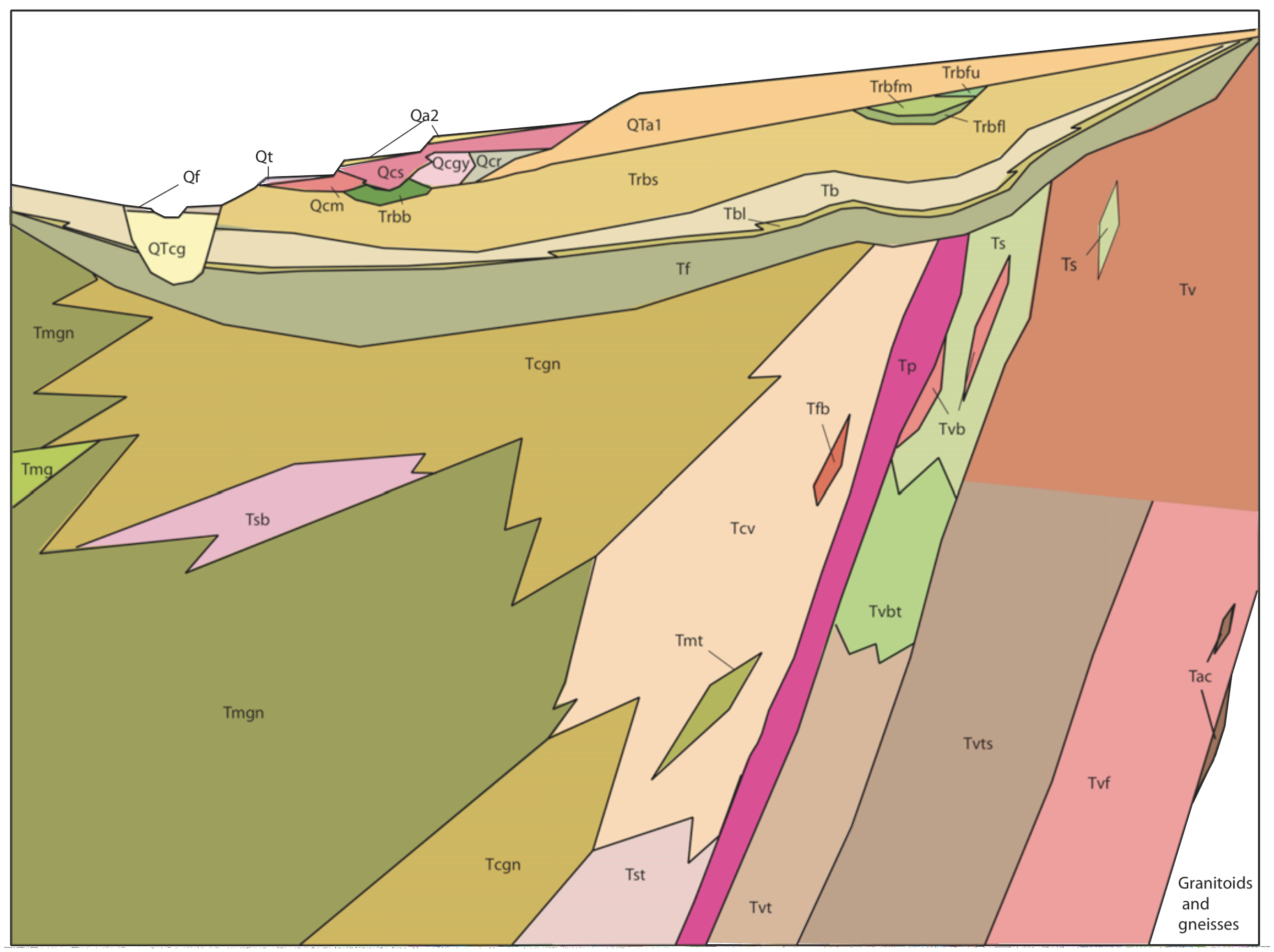


Figure 11. Conceptual diagram showing stratigraphic relations among Cenozoic sedimentary and volcanic units in the Topock quadrangle.

sequence, which thins out to the north near the Gaging Station on the Colorado River. Mafic and intermediate-composition flows dominate middle levels of the lower volcanic sequence, and they are overlain by a sequence of tuffs that interfinger abruptly with tuffaceous conglomerate and sandstone. Dikes and sills thought to be cogenetic with the flows invade parts of the volcanic section. Upper parts of the lower Miocene section include basalt, tuff, and conglomerate (Tvbt) and basalt flows (Tvb) intercalated with a sandstone and conglomerate unit (Ts). That sedimentary unit (Ts; fig. 12) thickens and outlines a paleovalley near The Needles (Gold Dome Mine area), as does the overlying Peach Spring Tuff (Tp). This distinctive tuff crops out prominently as an important stratigraphic marker and is a regionally widespread ignimbrite dated as 18.5±0.2 Ma by Nielson and others (1990). At its northern exposures in the quadrangle, the tuff laps northward across the lower volcanic sequence and onto Proterozoic granite. An angular unconformity on top of the tuff coincides with a transition upward from dominantly volcanic environments to dominantly detrital deposition.

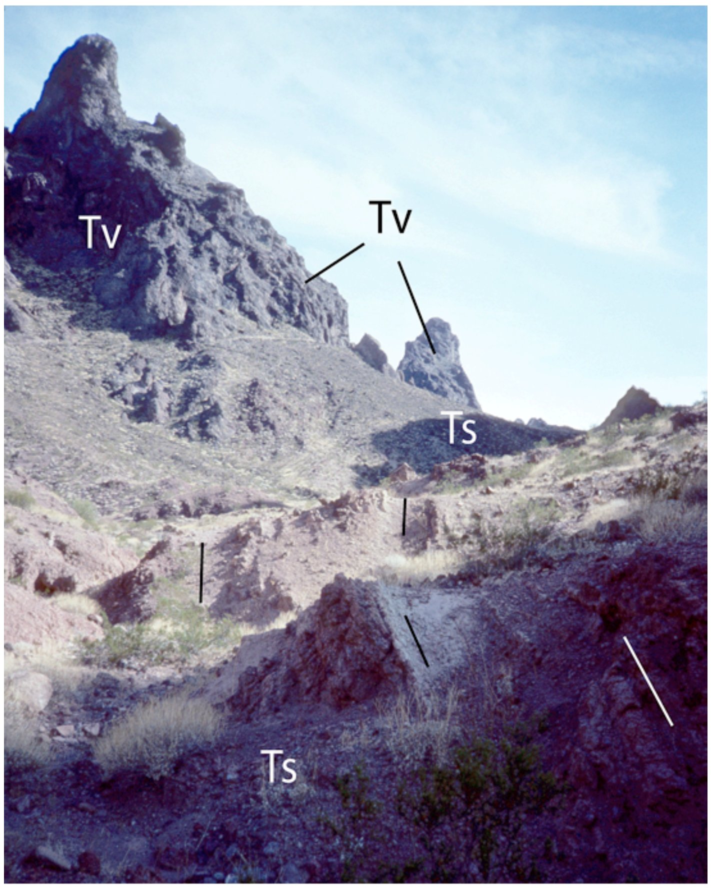


Figure 12. Photo showing steeply dipping Miocene rocks of the sandstone and conglomerate unit (Ts, here including unlabeled basalt interlayers) in the Gold Dome Mine and The Needles area overlying flows of the lower volcanic sequence (Tv).

Miocene Intrusions

The quartz monzonite unit (TKwq) includes mylonitic granodiorite and quartz monzonite along the north front of the Chemehuevi Mountains that are dated here as 19–19.4 Ma (table 1). They record early Miocene intrusion and extensional shearing at mid-crustal depths.

Table 1. Isotope-ratio and age data for zircon grains determined by sensitive high-resolution ion microprobe–reverse geometry (SHRIMP–RG).

[Analyst: J.L. Wooden. Sample locality coordinates in NAD 1927]

Spot name	U (ppm)	Total $^{238}U/^{206}Pb$	Error (%)	Total $^{207}Pb/^{206}Pb$	Error (%)	^{207}Pb corrected $^{206}Pb/^{238}U$ age (Ma)	1σ error (Ma)
SAMPLE H12T0-1 (map unit Kd), lat 34.7014° N., long 114.3925° W., 72.7±0.9 Ma							
H12T0-1.1	130	83.82	2.4	.0495	7.0	76.3	1.9
H12T0-2.1	205	82.47	2.1	.0475	5.9	77.7	1.7
H12T0-3.1	315	85.13	1.9	.0513	4.4	74.9	1.4
H12T0-4.1	171	88.23	2.2	.0530	6.1	72.2	1.6
H12T0-5.1	243	84.71	1.7	.0467	4.0	75.7	1.3
H12T0-6.1	194	86.05	1.8	.0474	4.5	74.5	1.3
H12T0-7.1	97	90.56	2.1	.0489	6.4	70.7	1.5
H12T0-8.1	220	90.25	1.7	.0473	4.4	71.0	1.2
H12T0-9.1	114	93.64	2.0	.0442	6.2	68.7	1.4
H12T0-10.1	237	90.72	1.8	.0503	4.1	70.4	1.3
H12T0-11.1	219	87.78	1.7	.0478	4.4	73.0	1.3
H12T0-12.1	221	89.05	1.7	.0482	4.6	71.9	1.2
H12T0-13.1	127	87.81	2.0	.0481	5.6	72.9	1.4
H12T0-14.1	304	86.27	1.6	.0483	3.7	74.2	1.2
H12T0-15.1	349	85.96	1.6	.0482	3.4	74.5	1.2
H12T0-16.1	240	89.62	1.7	.0471	4.2	71.6	1.2
H12T0-17.1	150	86.92	1.9	.0476	5.3	73.7	1.4
H12T0-18.1	208	89.21	1.8	.0502	4.4	71.6	1.3
SAMPLE H89MH-47 (map unit Kcb) lat 34.6996° N., long 114.4267° W.; 74.6±1.1 Ma							
H89MH-47-1.1	135	3.91	1.7	.1073	1.2	1440.8	24.6
H89MH-47-2.1	527	84.92	1.7	.0479	3.5	75.4	1.3
H89MH-47-3.1	75	85.27	2.3	.0524	7.0	74.7	1.7
H89MH-47-4.1	241	95.70	1.8	.0493	4.2	66.8	1.2
H89MH-47-5.1	209	87.04	1.8	.0498	4.6	73.4	1.3
H89MH-47-6.1	198	83.03	1.8	.0472	6.2	77.2	1.4
H89MH-47-7.1	84	82.37	2.2	.0486	6.9	77.7	1.7
H89MH-47-8.1	396	87.86	1.6	.0478	3.3	72.9	1.2
H89MH-47-9.1	319	93.32	1.6	.0478	5.8	68.7	1.1
H89MH-47-10.1	567	87.80	1.5	.0458	2.8	73.2	1.1
H89MH-47-11.1	623	85.64	1.5	.0476	2.7	74.8	1.1
H89MH-47-12.1	152	85.47	1.9	.0513	5.2	74.6	1.4
SAMPLE H12WM-10 (map unit TKwq) lat 34.7106° N., long 114.4964° W.; 19.4±0.4 Ma							
H12WM-10.1	88	315.55	4.7	.0440	17.7	20.5	1.0
H12WM-10.2	73	341.95	3.6	.0535	13.6	18.7	0.7
H12WM10.3	142	314.26	2.7	.1217	11.7	18.6	0.6
H12WM-10.4	66	361.73	3.9	.0561	14.6	17.6	0.7
H12WM-10.5	152	330.92	2.7	.0466	10.0	19.4	0.5
H12WM-10.7	137	331.60	2.8	.0458	10.7	19.4	0.6
H12WM-10.6	146	302.14	2.6	.1390	6.0	18.9	0.5
H12WM-10.8	82	329.60	3.5	.0481	13.8	19.5	0.7
H12WM-10.9	152	358.63	2.8	.0580	10.4	17.7	0.5

H12WM-10.10	45	253.00	3.8	.2736	15.3	18.4	1.5
H12WM-10.11	8454	253.00	3.8	.0613	5.7	25.0	1.0
H12WM-10.12	374	324.34	2.0	.0462	6.6	19.9	0.4
H12WM-10.13	120	332.54	3.0	.0410	12.6	19.5	0.6
H12WM-10.14	92	326.61	3.3	.0570	11.9	19.5	0.7
H12WM-10.15	246	318.02	2.3	.0495	7.9	20.2	0.5
H12WM-10.16c	86	353.02	3.5	.0530	13.2	18.1	0.7
H12WM-10.16r	60	323.12	4.1	.0573	15.7	19.7	0.8
H12WM-10.17	159	343.53	2.7	.0523	9.8	18.6	0.5
SAMPLE H12WM-9[1] (map unit TKwq) lat 34.7094° N., long 114.5189° W.; 19.0±0.3 Ma							
H12WM-9.1	162	322.51	3.6	.0585	11.5	19.7	0.7
H12WM-9-2.1	225	354.48	2.4	.0464	9.7	18.2	0.5
H12WM-9-3.1	271	348.95	2.3	.0530	7.6	18.3	0.4
H12WM-9-4.1	129	328.66	2.9	.0530	10.4	19.4	0.6
H12WM-9-5.1	119	342.99	3.0	.0484	11.9	18.7	0.6
H12WM-9-6.1	194	336.65	2.5	.0457	9.5	19.1	0.5
H12WM-9-7.1	192	343.20	2.5	.0502	9.0	18.7	0.5
H12WM-9-8.1	194	347.75	2.6	.0516	9.2	18.4	0.5
H12WM-9-9.1	262	323.42	2.2	.0479	7.5	19.9	0.5
H12WM-9-10.1	126	350.24	3.2	.0463	13.3	18.4	0.6
H12WM-9-11.1	255	321.41	2.5	.0500	7.9	19.9	0.5
H12WM-9-12.1	571	335.50	1.9	.0459	5.6	19.2	0.4

[1]Sample site is 1.7 km west of Topock quadrangle.

The dike swarm of Chemehuevi Mountains is centered on the Chemehuevi Mountains batholith in the footwall of the Chemehuevi Detachment Fault. Part of this swarm, consisting of northwest-striking dikes (Tcd), is thought to mainly be of Miocene age. Other Miocene dikes crop out in the eastern part of the quadrangle, in higher structural blocks.

An approximately 16-Ma Miocene hypabyssal intrusion complex of intermediate composition (part of unit Ti), towers in pinnacles over adjacent land near the center of the quadrangle (fig. 13*A*; see fig. 2 for location) The complex intrusion, called the Needle Mountain intrusion by Howard and John (1997), includes numerous satellite sills (concordant to Proterozoic host-rock foliation) and dikes (fig. 13*B*). Crush zones representing strands of the block-bounding Gold Dome Fault Zone are exposed around and on the east side of the intrusion. The intrusion is partly faulted and brecciated but less than adjacent Proterozoic gneisses, a relation consistent with emplacement during Miocene deformation along the Gold Dome Fault Zone.

Synextensional Sedimentary Rocks

The upper sedimentary and volcanic sequence unconformably overlies the Peach Spring Tuff with an angular discordance of 0° to 13°. The sequence includes conglomerate, sedimentary breccia, landslide breccia, sandstone, tuff, and a few interbedded basalt flows (Miller and John, 1988, 1993; Nielson and Beratan, 1990; Nielson, 1993; John and Howard, 1994; Howard and others, 1999). These rocks were deposited during extensional tilting and faulting (Miller and John, 1988, 1993, 1999). In Topock Gorge, they are as thick as 2 km. Correlative rocks in the southeastern part of the quadrangle are exposed as more than 80 m of conglomerate-rich sedimentary rocks and tuff (unit Tst).

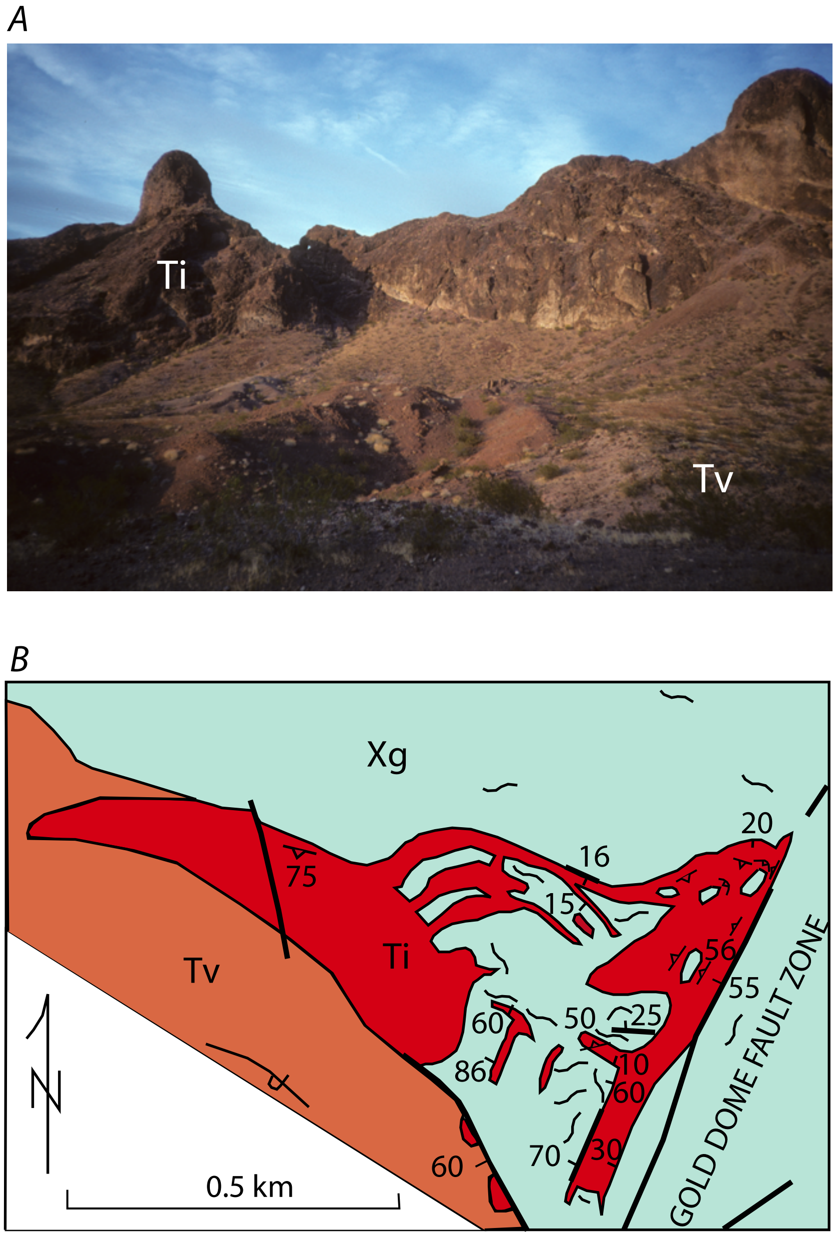


Figure 13. *A*. Photo showing cliff-forming rocks of the Needle Mountain intrusion (Ti) that rise above less resistant rocks of the lower volcanic sequence (Tv) in the foreground. Note "Eye of the Needle" (Darton and others, 1915) to the right of the pinnacle. *B*. Detailed map of the Needle Mountain intrusion (Ti) and its host rocks of the lower volcanic sequence (Tv, steeply dipping volcanic agglomerate) and brecciated gniess (Xg, containing crush zones). The intrusion is located on figure 2 (on map sheet). Magmatic foliation in the dacitic intrusion (indicated by strike and dip symbols) defines a steeply plunging syncline at the northeast end of the intrusion. Dip amounts measured on intrusive contacts and faults also shown. Foliation in gneiss indicated by form lines.

The thick sections along Topock Gorge include both conglomerate (Tc and subunits Tcgn and Tcv) and landslide megabreccia deposits (Tm and subunits Tmg, Tmgn, and Tmt). The subdivision of these deposits according to clast content indicates a reverse stratigraphy that suggests an unroofing sequence in the source terrain, where volcanic debris generally was shed early, then gneiss debris from Proterozoic rocks, and finally debris of originally deeper Cretaceous granitic rock and of chloritic breccia and cataclasite associated with denuded detachment faults (Miller and John, 1988, 1999). The inferred source-terrain section—volcanic rocks above Proterozoic rocks in turn above Cretaceous granitoids—agrees with the reconstructed structural sections in the Jackpot and Tumarion blocks and lower rocks in the footwall of the Chemehuevi Detachment Fault. Current directions and clast compositions suggest that the debris was largely derived from active fault scarps to the west (Miller and John, 1999).

Miocene Extensional Structure

Miocene tectonic extension of the Colorado River extensional corridor is recorded by mylonitic fabric deforming 19-Ma middle-crust plutonic rocks and by large offsets along northeast-dipping brittle low-angle normal faults, often called detachment faults (Howard and John, 1987). These faults cut gently down-section in the northeast direction of tectonic transport from a breakaway fault zone 50 km west of the Topock quadrangle (Howard and John, 1987). Detachment faults exposed around the Chemehuevi Mountains and other domal core complexes in the central part of the extensional corridor (John, 1987a,b) record extensional faulting that also produced tilting of upper crustal sections and other structural disruptions.

Cumulative slip on the low-angle fault system increases to the northeast across the Colorado River extensional corridor and totals an estimated 40–75 km, so that the corridor's width is 1.7 to 4 times its original width (Howard and John, 1987; Hillhouse and Wells, 1991). Regional field relations indicate that the lowest exposed detachment faults cut initially to depths of 10 to 15 km, which corresponds to the pre-tilt thickness of the hanging-wall Crossman tilt block in the Mohave Mountains to the southeast (Howard and others, 1999; fig. 6). The detachment fault system roots 30–50 km east of the Topock quadrangle under the little-deformed Hualapai Mountains and Colorado Plateau (Howard and John, 1987). Miocene extension in this region, therefore, occurred along an east-rooted, asymmetric shear system in the upper and middle crust (Howard and John, 1987).

Low-angle Normal Faults

The Powell Peak Fault in the southeastern part of the quadrangle is the structurally highest of four major gently dipping extensional faults (fig. 7). The other three stacked low-angle normal faults dip east from the Chemehuevi core complex in the western part of the quadrangle: the Devils Elbow Fault, the deeper and youngest Chemehuevi Detachment Fault, and the structurally deepest Mohave Wash Fault. The interpretive tectonic diagram (fig. 7) includes within the Devils Elbow plate a low-angle fault plate that straddles the river in the southern part of the quadrangle; we interpret this subplate to pinch out northward in the subsurface.

The Devils Elbow Fault and higher faults carry upper plates that include steeply southwest-tilted blocks in the eastern part of the quadrangle (fig. 7). Slip on the Devils Elbow Fault was several kilometers, with the top to the east-northeast (John, 1987a). The Chemehuevi Detachment Fault, the master fault, accommodated at least 18 km of top-to-northeast slip. The Mohave Wash Fault accommodated approximately 2 km of top-to-northeast slip (John, 1987a). Rocks that form the footwalls of the Chemehuevi and Mohave Wash faults are largely granitoids and gneiss that resided in the middle crust prior to extension. Mylonitic fabric in dated 19-Ma plutonic rocks along the north front of the Chemehuevi Mountains may record an early stage of shear on the Chemehuevi Detachment Fault before the fault was uplifted into a brittle regime of deformation.

Rocks in the hanging wall of the major Chemehuevi Detachment Fault represent tilted oblique sections across a range of Miocene upper crustal depths. The Chemehuevi Detachment Fault superposes upper crustal rocks onto rocks from deeper crustal levels. These deeper rocks are denser on average (Simpson and others, 1990; McCarthy and others, 1991; Campbell-Stone and John, 1996). A

12-mgal gradient from higher to lower gravity values eastward across the central part of the quadrangle near the Colorado River (Mariano and others, 1986) implies that the fault system may steepen eastward for some distance from ≤15° at surface exposures beneath the hanging wall, as interpreted on cross section B–B´, based on a northward gravity gradient in the northern part of the quadrangle (Mariano and others, 1986).

Northeast-striking corrugations characterize both the exposed Chemehuevi Detachment Fault and Mohave Wash Fault. The fault-surface corrugations have amplitudes of 30 m to 400 m and wavelengths of 200 m to 10 km and have been described as primary grooves that cut rather than mimic any folding of the mylonitic foliation in the footwalls (John, 1987a). Elongate exposures of allochthonous (structural upper-plate) Miocene rocks in the southwestern part of the quadrangle southwest of Red Rock Falls prominently express two of the grooves in the bounding Chemehuevi Detachment Fault.

In some outcrops, the Chemehuevi Detachment Fault exhibits a porpoising surface resembling grande roche moutoneés. The fault locally exhibits a laminated, flinty ultracataclasite 2–3 cm thick. Breccia and gouge are conspicuous along the Devils Elbow Fault. Rock between the Chemehuevi Detachment Fault and the underlying Mohave Wash Fault commonly is shattered or crossed by many unmapped faults and likely represents an extensional duplex. The shattered zone is affected by greenschist-facies retrogressive metamorphism characterized by abundant chlorite and epidote. A similar chloritic breccia zone underlies the Mohave Wash Fault.

The Mohave Wash and Chemehuevi faults were interpreted from thermochronologic, structural, and stratigraphic arguments to have dipped gently initially (John, 1987a; Miller and John, 1999; John and Foster, 1993; Foster and John, 1999). On the other hand, the highly tilted orientations of rocks in the superposed Chemehuevi plate and higher blocks, described below, imply rotational tilting on initially steep faults, such as the Devils Elbow Fault that fed displacement into the Chemehuevi Detachment Fault. The Chemehuevi Detachment Fault cuts the Devils Elbow and Mohave Wash faults and high-angle faults, showing that it had the latest movement.

The structurally higher Powell Peak Fault in the east part of the quadrangle bounds the east side of the Tumarion block and dips ≤20°–40° east under a series of shingled fault slivers (extensional allochthons) in the Boulder Mine area to the east (fig. 6; Howard and others, 1982; 1999). The fault's low dip and relation to the Tumarion tilt block (see Tilted Fault Blocks and the Transverse Gold Dome Fault Zone) suggests that this fault represents a tilted and warped normal fault that originally was steep and subparallel in strike to the northwest-southeast tilt axis. The age of the fault relative to tilting is uncertain. If a south-plunging anticline at the fault's southern tip is viewed down-plunge, its shape suggests a now-rotated down-to-northeast normal fault (fig. 3C of Howard and John, 1997), which cuts the tilted block and ends at a tip in draped Miocene cover (2 km west of the southeast corner of the quadrangle). The lower volcanic unit where strung out along the fault shows attenuation along bedding-parallel faults. We interpret this to indicate that flexural slip helped accommodate folding and thinned the fault-parallel limb.

Tilted Fault Blocks and the Transverse Gold Dome Fault Zone

Miocene tectonic extension in the Colorado River extensional corridor produced tilting and structural disruption in addition to large movement on the low-angle faults (fig. 7). John (1988) suggested that the Chemehuevi Detachment Fault and its footwall are tilted 10°–20° to the southwest. Hanging-wall normal faults and tilt axes in hanging-wall fault blocks typically strike northwest-southeast, about 60° oblique from the inferred east-northeast slip direction and strike of corrugations of the deeper Chemehuevi Detachment Fault. This obliquity may relate to vertical-axis rotations in hanging-wall slabs (Wells and Hillhouse, 1988) or temporal variations in the extensional stress orientation (Campbell-Stone and others, 2000).

Compared to the footwall of the Chemehuevi Detachment Fault, hanging-wall Miocene volcanic and sedimentary deposits and their basement substrate of Proterozoic and Cretaceous metamorphic and intrusive rocks above the Chemehuevi Detachment and Devils Elbow faults experienced much greater tilting and fault disruption. Their steep (~90°) southwestward tilt in the eastern part of the quadrangle is deduced from the steep to locally overturned dips of southwest-facing, nonconformably overlying lower Miocene rocks (where not faulted) and on the persistently near-vertical dip and northwest strike of Proterozoic diabase sheets that intrude underlying basement gneisses (fig. 8*B*), approximately parallel to basal Miocene rocks in the same structural blocks. The uniform orientations of the diabase sheets suggest that basement blocks are tilted uniformly approximately 90° to the southwest (compare to Howard and others, 1982, 1999, and Campbell-Stone and others, 2000, for adjacent areas). The top of basement rocks in the Jackpot structural block is marked by steeply dipping to overturned, southwest-facing volcanic agglomerate of the lower volcanic sequence (Tv). At the southwest side of the tilted Tumarion block, considered here as the top of the block, the arkose and conglomerate (Tac) and lower volcanic sequence (Tv subunits) similarly nonconformably overlie but are commonly faulted against Proterozoic basement rocks.

Because of the steep tilting, the map patterns in pre-Miocene rocks above the Chemehuevi Detachment Fault, including in the Jackpot and Tumarion blocks, display natural cross sections of plutons and dike swarms (fig. 9). A possible contradiction to our structural interpretation is the observation in the Tumarion block of amygdules in lamprophyre dikes (TKl) north of Powell Peak and vesicles in an unmapped vesicular dike of plagioclase-phyric jackstraw andesite porphyry 2 km east-northeast of the Jackpot Mine that lithologically resembles flows in the lower Miocene section. From their locations we would reconstruct the dikes' early Miocene paleodepths as 7–8 km and 4–5 km, respectively. Typically, shallower depths and lower pressures are expected for magmas to degas and form vesicles.

The interpreted steep tilting implies that rocks experienced horizontal-axis tilting while being lowered onto the deeper Chemehuevi Detachment Fault from listric feeder faults. Proterozoic rocks in the subplate of the Devils Elbow plate on both shores of the river in the southern part of the quadrangle underlie moderately south-dipping rocks of the Miocene lower volcanic sequence (Tv), appear to be moderately tilted, and contain variously oriented diabase sheets. The subplate contains augen gneiss (Xg) more or less along the projected trend of augen gneiss (Xag) to the northeast in the Tumarion block, which could be consistent with little structural disruption between basement rocks in that block and the subplate.

The Gold Dome Fault Zone separates the steeply tilted Jackpot and Tumarion tilted fault blocks in the eastern part of the quadrangle, above the projected Devils Elbow Fault (fig. 7; Howard and John, 1997). The Gold Dome Fault Zone within basement rocks is a northeast-striking system of moderately to steeply dipping transfer faults showing dextral separation (John and Howard, 1994). Strands of the southern part of the fault zone place volcanic rocks over Proterozoic rocks and dip moderately to gently, similar to the Powell Peak Fault, which they crudely mirror. Many more faults than are here mapped are undoubtedly present along both sides of the Gold Dome Fault Zone. We interpret the Gold Dome Fault Zone to end southward at a complex fault tip in the Split Rock area. It is possible, but not so interpreted on figure 7, that the Powell Peak plate or something like it extends westward to include common moderate- to low-angle fault superpositions of the lower volcanic sequence onto basement rocks around both the southwest corner of the Tumarion block and the nearby subplate to the southwest.

Dips tend to decrease up section in Miocene rocks. The sedimentary rocks unit (Ts) may accommodate much relative strain between tilted basement and folded cover rocks. Locally within the large southwest-plunging syncline near The Needles, dips decrease from 60°–70° in the lowest part of the overlying Peach Spring Tuff to ~35° in a nearby upper part of the tuff, even though the tuff is a single cooling unit. This observation suggests the possibility that some fanning of dips accommodates strain, even within a single ash-flow tuff. Some of the orientation of compaction foliation in the tuff, measured on flattened pumice clasts (fiamme), possibly in addition reflects molding of the tuff to underlying paleotopography. In contrast, fanning dips in the overlying middle Miocene upper sedimentary and volcanic sequence and an angular unconformity at its base more clearly reflect sequential deposition during extensional tilting (Miller and John, 1999).

Other Normal Faults

The Pulpit Rock, Tumarion Peak, and other northeast-dipping normal faults cut the tilt blocks, and some cut the Gold Dome Fault Zone and related folds (fig. 7). The moderately northeast-dipping Tumarion Peak Fault accommodates 425 m of northeastward heave (horizontal separation), where it cuts the Gold Dome Fault Zone and the syncline related to that fault zone. Along fault strike to the northwest, the heave on the Tumarion Peak Fault decreases to 300 m, as >100 m of heave is accommodated by a northward fault splay. Farther south in the quadrangle, the similarly northwest-striking Pulpit Rock Fault coincides with a major kink in the orientation of Miocene rocks at Pulpit Rock on the Colorado River. The estimated heave of this fault is 60 m in the western part of the Tumarion block and 10 m where it offsets the Powell Peak Fault in the southeastern part of the quadrangle. The moderate dips of these faults are consistent with the faults postdating most of the tilting. None of this type of fault is known to cut the Chemehuevi Detachment Fault. Instead the faults seem to represent brittle stretching of the upper plates while that detachment fault was still active.

Folds

The Topock quadrangle is one of several areas in the southern Basin and Range Province that display plunging folds of layered cover rocks above steep-fault offsets in deeper unstratified rocks. John and Howard (1994) and Howard and John (1997) interpreted these folds as fault-propagation features, forced above growing faults at the edges of basement blocks as the blocks tilted and segmented above deeper detachments during the progression of tectonic extension. Simplified down-plunge restoration by Howard and John (1997) assumed a variable plunge and assumed steep dips for the Gold Dome Fault Zone, not fully accounting for shallow dips for the fault segments that separate volcanics from basement gneiss in the southern part of the Gold Dome Fault Zone.

The cover of Miocene sedimentary and volcanic rocks drapes over and around the fractured, tilted, and much thicker basement rocks at both the southern and western corners of the Tumarion block (Howard and John, 1997). The results are a complexly faulted, south-plunging anticline in the Miocene rocks at the south corner of the block (2 km west of the southeast corner of the quadrangle) and a faulted southwest-plunging anticline at the west corner of the block (south and southeast from Split Rock). The folding of cover units contrasts with the homoclinal tilt of underlying basement implied by the uniform orientation of diabase sheets. Massive volcanic flows, lahars, and breccias of the lower volcanic sequence are either folded with overlying rocks or (adjacent to the Gold Dome Fault Zone) are segmented into many fault slices, indicating a more brittle behavior than overlying strata. Depositional contacts in this lower part of the cover sequence are commonly sheared. Bedding-parallel faults attenuate the limbs of folds that are structurally above both the Powell Peak Fault and the Gold Dome Fault, indicating that flexural slip helped accommodate folding. A west- to southwest-plunging syncline in the Miocene section overlies the inside corner formed where the Tumarion and Jackpot blocks are juxtaposed along the Gold Dome Fault Zone (near Pulpit Rock). The syncline plunges 70°–80° in the sedimentary rocks that underlie the Peach Spring Tuff; higher in the section it plunges less. The Peach Spring Tuff (Tp) and underlying sandstone and conglomerate of the sedimentary rocks unit (Ts) and basalt flows (Tvb) wrap smoothly around this syncline. Structural accommodation in the sedimentary rocks unit (Ts) may explain the deformational contrast between these smoothly folded rocks and the underlying more faulted rocks of the lower volcanic sequence. Small unmapped reverse faults offset the folded Peach Spring Tuff and indicate contraction caused by bunching in the interior of the syncline. The south limb of the syncline curiously thickens in the Pulpit Rock-River Island area.

A second style of folding, represented by gently plunging southeast-striking synclines in the Miocene rocks, relates to other normal faults, to be described next. The most prominent of these synclines, 1–2 km northwest of the southeast corner of the quadrangle, lies in the hanging wall of a down-to-the-northeast normal fault. The southwest-facing limb of this syncline is viewed as the cap of a small tilted block; the steeper northeast-facing limb is viewed as a result of drag on the underlying fault.

Intrusion Shape and Dike Orientations

The Needle Mountain intrusion describes a south-southwest-plunging synformal shape, most apparent from internal foliations at its northeast end (fig. 13*B*). This shape and the intrusion's position at and near the base of the folded volcanic cover and at the inside corner between the Jackpot (to the northwest) and Tumarion (to the southeast) tilt blocks led to its interpretation as filling a Miocene triangular gap or triangle zone below the partly delaminated syncline formed where the Gold Dome Fault Zone propagated upward from basement to cover rocks during tilting (John and Howard, 1994; Howard and John, 1997). This model for the intrusion ignores mapped complexities in the intrusion and its partial transection of the Proterozoic-Miocene nonconformity.

Northwest-striking dikes indicative of northeast-southwest inflation and extension are common in Miocene dike swarms in the central part of the Colorado River extensional corridor (Spencer, 1985; Howard and others, 1999; Pease and others, 2005; Campbell-Stone and others, 2000). Miocene dikes mapped in the quadrangle mostly strike northwest, but some are subhorizontal, including dikes in the Chemehuevi plate 3 km southeast of Topock and also (unmapped) west of Devils Elbow (John and Foster, 1993) that are mapped here as northwest-striking dikes of the dike swarm of Chemehuevi Mountains (Tcd). Likely counterparts are mapped as units Tdl and Tdm in the Tumarion and Jackpot blocks (fig. 7). The subhorizontal dikes in the Chemehuevi plate and in the Tumarion block would reconstruct as steep northwest-striking dikes if steep southwest tilting were restored.

Post-extension Deposits

A series of little-deformed sediments unconformably overlie the synextensional sequences and record the landscape evolution from late Miocene to historical times, after the extensional tectonism had ceased. These deposits include piedmont alluvial-fan deposits, quiet-water limestone and mud of the Bouse Formation, ancient and modern river deposits of the Colorado River and Sacramento Wash, and windblown sands. The deposits record late Miocene filling of an internally drained ancestral Mohave Valley, its subsequent early Pliocene flooding associated with the arrival of Colorado River water, and younger degradational and aggradational episodes as the river incised and aggraded multiple times. The deposits include a stratigraphic record of interactions between the river and the large tributary, Sacramento Wash, during aggradational episodes. This report builds on a stratigraphic framework of the Bouse Formation and younger deposits related to the Colorado River valley that was outlined by Metzger and Loeltz (1973).

Deposits Predating the Colorado River

The oldest of the post-extension units is Miocene fanglomerate (Tf) consisting of locally derived, poorly sorted angular alluvial deposits. This deposit represents alluvial fans that filled local basins before the lower Colorado River arrived and dissected the area. Where exposed 1 km northeast of Topock, the fanglomerate consists largely of greenish granitic clasts containing epidote and chlorite, characteristics of rocks that occupy the footwall of the Chemehuevi and Mohave Wash detachment faults. The presence of clasts derived from the footwall of the Chemehuevi Detachment Fault, together with northward-directed current imbrication, indicates that the fanglomerate was deposited on fans emanating from the Chemehuevi Mountains into a basin depocenter that is east of the axis of modern Mohave Valley. Because bedrock highlands crop out south of this position where they would block any southeastward external drainage, we interpret the fanglomerate as deposited in an internally drained basin, which was not drained through any predecessor of Topock Gorge.

The lower Pliocene Bouse Formation (Tb) succeeds the fanglomerate (Metzger and Loeltz, 1973). The Bouse Formation in the quadrangle consists of a basal white limestone (Tbl) as thick as 3–4 m and thicker, overlying deposits (Tb) of interbedded greenish and yellowish clay and silt and pale-orange-gray sand (fig. 14). At least a 15 m thickness of these beds is exposed in the quadrangle. Subsurface thicknesses of 57 and 77 m were interpreted from logs from two drill holes between Sacramento Wash and I-40 (at NE¼SW¼NW¼ sec. 14 and SE¼SW¼SW¼ sec. 11, T. 16 N., R. 20½ W., Metzger and Loeltz, 1973). Outcrops of the formation reach elevations at least as high as 457 m in the adjacent Franconia quadrangle to the east (Howard and others, 1999; Howard and Malmon, 2007), and the elevation range suggests that, if the formation is little deformed, its depositional thickness may exceed 335 m. House and others (2005, 2008, 2011) presented evidence at the north end of Mohave Valley that a boulder-carrying erosive flood immediately preceded quiet-water deposition of the Bouse Formation, and they proposed that this flood represents catastrophic failure of a natural dam upstream. Various authors have considered the Bouse Formation to represent deposition either in a brackish estuary associated with the proto-Gulf of California or in lakes. Intraformational deltaic sand beds were considered to have been deposited prior to ~4 Ma from the entry of earliest Colorado River sediments into this quiet water (Metzger, 1968; Buising, 1990; Turak, 2000; Spencer and others, 2008; House and others, 2005, 2008; McDougall, 2008). The model of Spencer and others (2008) interpreted the Bouse Formation sediments as deposited in a lake fed by this initial Colorado River and dammed behind bedrock in the area that later became Topock Gorge. Wave reworking in the water body likely explains well-sorted, crossbedded gravel in the fanglomerate unit where it immediately underlies the limestone of the Bouse Formation.

Pliocene to Pre-Late Pleistocene Alluvium and Its Relation to Degradation and Aggradation of the Colorado River

Overlying and inset into the Bouse Formation on an erosional unconformity exposed adjacent to the Topock quadrangle are ancestral Colorado River and related deposits that we equate to unit B of older alluviums of Metzger and Loeltz (1973). The deposits include Pliocene quartz-rich sandstone and conglomerate (Trbs) correlated to the alluvium of Bullhead City of House and others (2005), which records ~250 m of aggradation before 4.1±0.5 Ma (House and others, 2005, 2008; see also Howard and others, 2008; Pearthree and others, 2009). This unit in the quadrangle typically exhibits fluvial crossbedding, rounded quartz sand grains, and rounded pebbles of chert, quartzite, and limestone derived from hundreds of kilometers upstream—clear signs of deposition by the Colorado River. The fluvial deposits indicate a major fluvial aggradational episode following deep initial Colorado River incision into the Bouse Formation (Metzger and Loeltz, 1973; House and others, 2005, 2008; Howard and others, 2008).

Clast imbrication in the Pliocene units in the quadrangle indicates varied current directions, including some down Sacramento Wash. The fluvial sandstone and conglomerate unit (Trbs) includes, in the northeastern part of the quadrangle, an arkosic facies that lacks far-traveled pebbles of chert, quartzite, and limestone and is inferred to record mostly deposition in an ancestral Sacramento Wash draining from the Hualapai and Black Mountains. Aggradation in this and other tributaries would have occurred in response to major aggradation of the valley axis by a buildup of sand and gravel transported down the Colorado River.

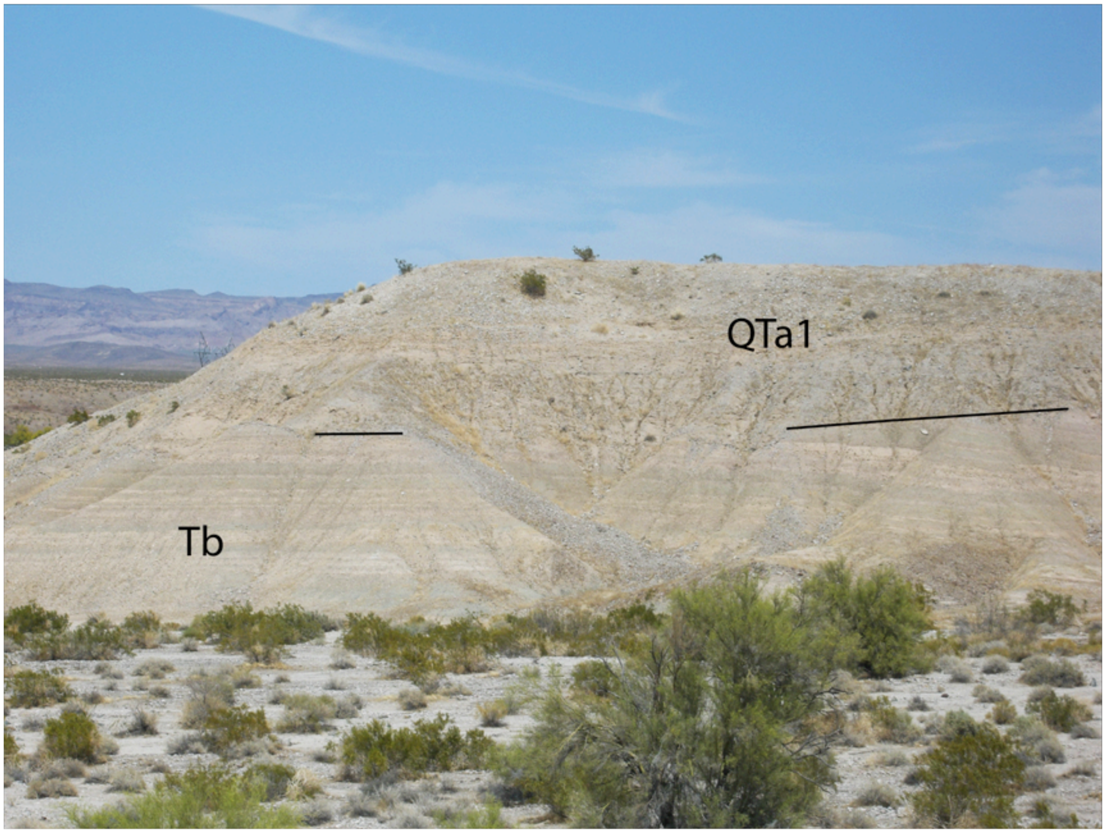


Figure 14. Photo showing bedded mud and sand of the Bouse Formation (Tb) and overlying older piedmont alluvium (QTa1) near Sacramento Wash in the northeast part of the quadrangle.

A varied set of deposits that we describe as the facies of Santa Fe Railway (Trbfl, Trbfm, Trbfu) overlies the sandstone and conglomerate unit and likely correlates to higher parts of the Bullhead City unit of House and others (2005). The facies contains river pebbles of quartzite and chert and displays fanning dips and internal angular unconformities that record progressive structural sagging during its fluvial deposition (fig. 15). Dipping beds of the facies of Santa Fe Railroad were photographed by Lee (1908) and described and sketched interpretively by Metzger and Loeltz (1973, their figure 12).

Inset into the sandstone and conglomerate unit is the boulder conglomerate of Bat Cave Wash (Trbb), a coarse fluvial unit mapped from west of Topock southeast and south to River Island (fig. 16). The boulder conglomerate of Bat Cave Wash locally overlies and locally contains blocks derived from the sandstone and conglomerate unit (Trbs), indicating that an erosional unconformity separates the Bat Cave Wash unit from older ancestral Colorado River deposits into which it is inset. The inset relation reflects deep incision before deposition of the boulder conglomerate, which in turn is inset by the Chemehuevi Formation. The Bat Cave Wash unit thus records a cycle of degradation-aggradation-degradation between early Pliocene time and the Late Pleistocene age of the Chemehuevi Formation. The Bat Cave Wash unit has a projected thickness of at least 30 m and lacks internal bedding, so it may represent a single depositional flood event (Howard and Malmon, 2011). The boulder conglomerate and clast imbrication within it define an abandoned, winding paleovalley that is subparallel to but crossed by the modern Colorado River (Howard and others, 2008). Some of the unit occupies a paleovalley on the east side of River Island that was later reoccupied during deposition of the Chemehuevi Formation. Large subrounded boulders in the boulder conglomerate include clasts derived from the Peach Spring Tuff, clasts of vesicular basalt resembling rocks in the Black Mountains bordering the east side of Mohave Valley, and clasts of mylonitic gneiss resembling rocks exposed in the Newberry, Dead, Sacramento, and Chemehuevi Mountains on the west side of the valley. These river-carried boulders are among the coarsest Colorado River deposits downstream of the Grand Canyon. The paleochannel they occupy is cut into varied substrates to a depth that is about 15 m above the historical pre-dam river grade and the lowest exposed sandstone and conglomerate unit (Trbs). Local sources for most of the boulders suggest that they may have been delivered to the river or its banks by debris flows. The deposit also includes boulders of quartzite derived from hundreds of kilometers upstream that record long-distance fluvial transport by a powerful stream.

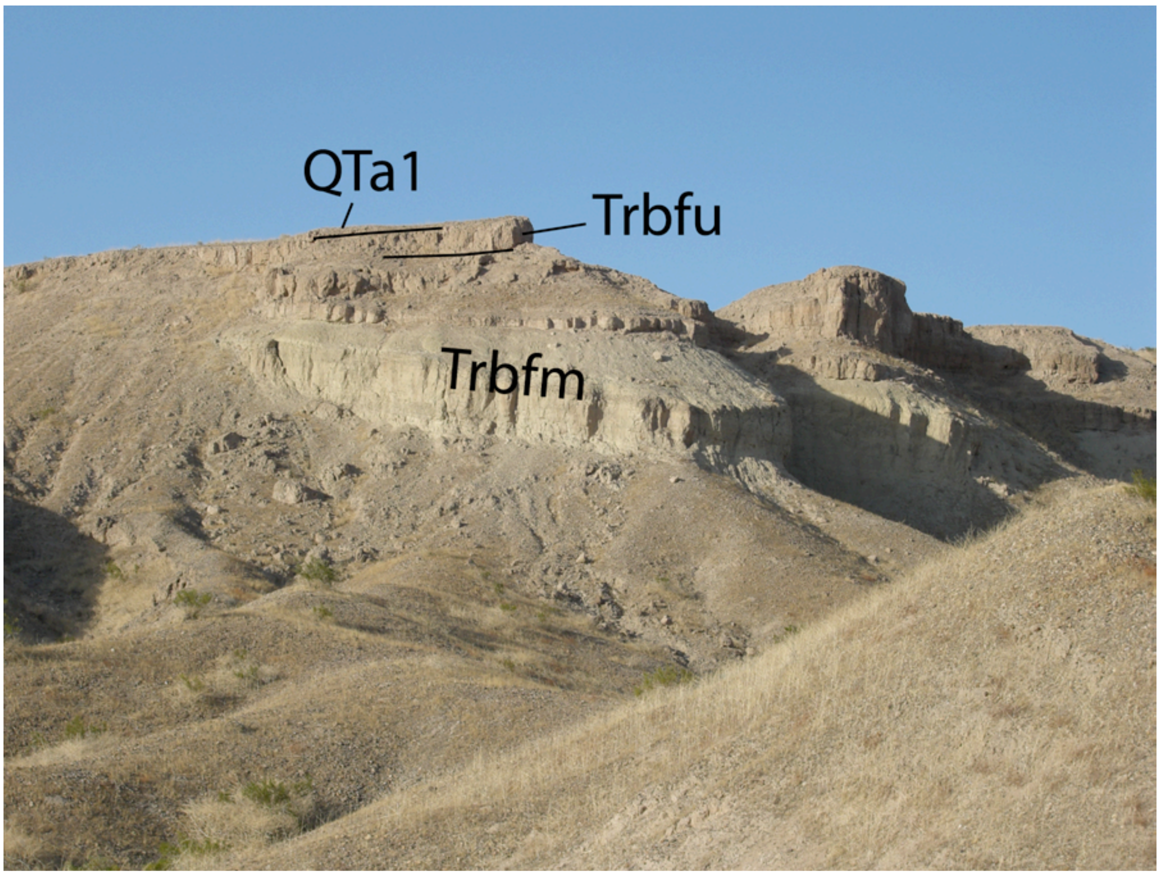


Figure 15. Photo showing fan dips in fluvial and related deposits of the facies of Santa Fe Railway (Pliocene). The lower beds, of the middle-part subunit of this facies (Trbfm), are overlain unconformably by the less deformed upper conglomerate subunit (Trbfu), which in turn is capped by undeformed deposits of reworked roundstone pebbles mapped as part of the older piedmont alluvium (QTa1).

A widespread, locally derived, piedmont alluvial deposit (QTa1, older piedmont alluvium) is inset into several of the ancestral Colorado River units. The older piedmont alluvium unit includes a fluvial facies (QTa1s) whose clast content and fluvial structures define it as deposits of an ancestral Sacramento Wash. Original depositional surfaces of these units are not preserved. Correlative deposits can be subdivided just north of the quadrangle into a succession of progressively lower and younger inset alluvial-fan lobes and terraces (Metzger and Loeltz, 1973, their unit C; House and others, 2005). Wilshire and Reneau (1992) found that correlative fan deposits (their unit QT1) record a thick depositional sequence that underlies pediments surrounding the nearby Mohave Mountains southeast of the quadrangle, into which are inset the Pleistocene Chemehuevi Formation and younger thin piedmont alluvium units (equivalent to Qa2, Qa3, and Qa4 in this quadrangle). This pre-Chemehuevi Formation stratigraphy indicates an extended period of alluvial-fan and tributary progradation and deposition on the piedmont valley sides as the Colorado River re-incised following earlier aggradational accumulation of ancestral Colorado River deposits.

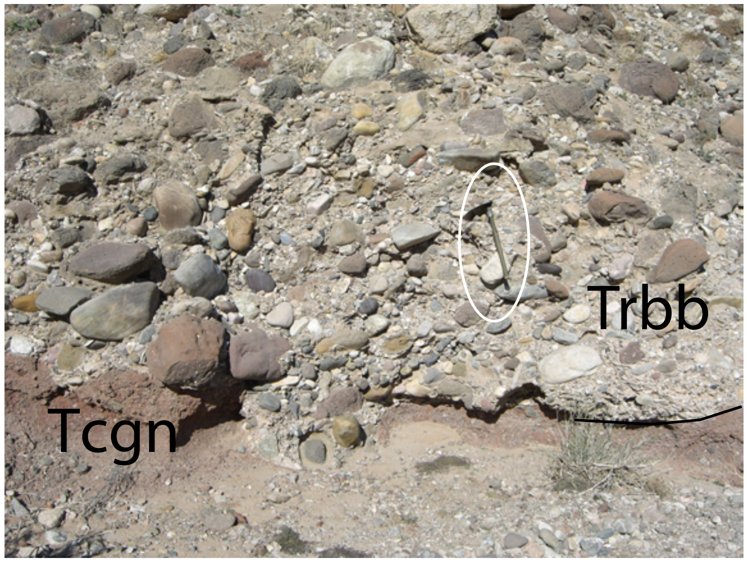


Figure 16. Photo showing boulder conglomerate of Bat Cave Wash (Trbb) resting unconformably on red Miocene gneiss-clast conglomerate (Tcgn), 1.8 km east-southeast of Topock. Trenching tool (circled) is 0.6 m long.

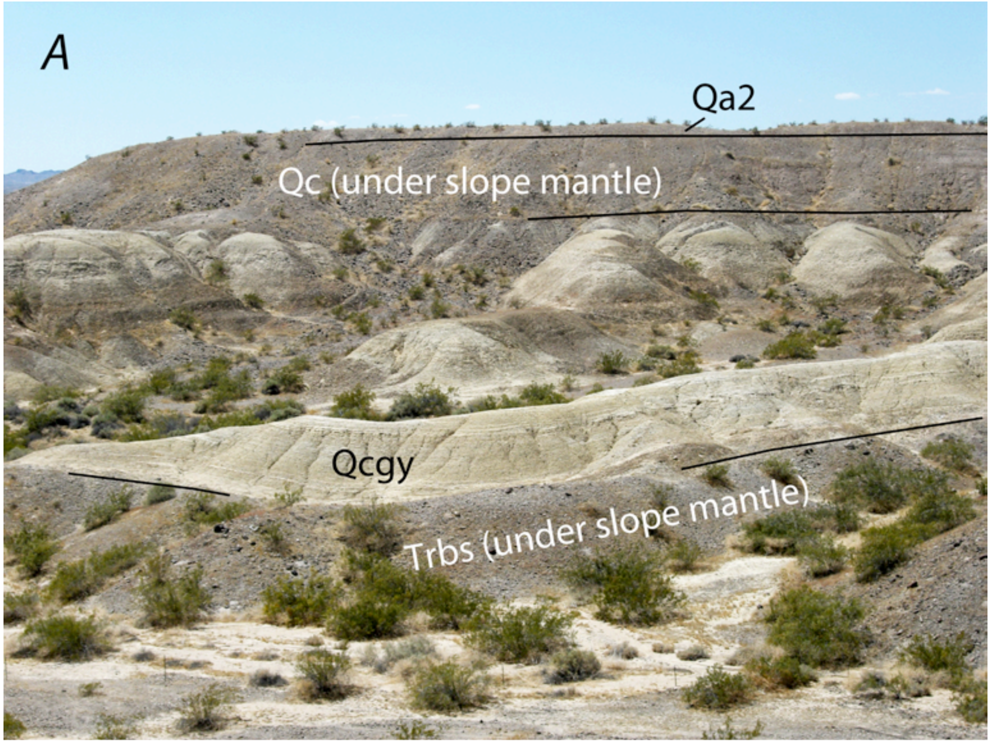
Late Pleistocene and Holocene Alluvium and Its Relations to Further Aggradations and Degradation of the Colorado River

Younger deposits record Late Pleistocene re-aggradation of the river valley. They include the Chemehuevi Formation (Longwell, 1936, 1963; Malmon and others, 2011), a fluvial unit that equates to units D and E of Metzger and others (1973) and Metzger and Loeltz (1973) and to the Chemehuevi beds of House and others (2005). The Chemehuevi Formation extends discontinuously along the Colorado River valley from upper Lake Mead to near Yuma, Ariz., a distance of over 550 km (Longwell, 1936, 1963, Malmon and others, 2011). The Chemehuevi Formation's Late Pleistocene age is based on multiple lines of evidence (Malmon and others, 2007, 2011; Lundstrom and others, 2008), including an internal tephra bed north of the map area that was suggested to correlate geochemically to about 72 ka (Malmon and others, 2011). Metzger and others (1973) considered the Chemehuevi Formation deposits to represent floodplain aggradation of as much as 100 m of fine-grained Colorado River mud (Qcm) followed by sand deposited during subsequent degradation (Qcs). An alternate model views the sands as channel sediment and the muds as floodplain sediment, both deposited by an aggrading river (Malmon and others, 2011). A gypsiferous mud facies (Qcg) is mapped in this quadrangle (fig. 17*A*) near Sacramento Wash, Warm Springs Wash, and other tributaries east of Topock. If the gypsum is primary, it may record evaporative backwaters and tributary deposits near the margins of the main floodplain (Malmon and others, 2011), possibly isolated from the river as a consequence of the river's floodplain aggradation (for example, Lundstrom and others, 2008). The backwaters may be analogous to modern ponds formed where bars on the edges of 20th century reservoirs in the river valley have dammed the mouths of tributary washes (Malmon and others, 2010). The Chemehuevi Formation in the quadrangle occurs between elevations of about 470 ft (143 m) and about 690 ft (210 m), where it embays erosional surfaces on the older piedmont alluvium (QTa1). In Topock Gorge (fig. 17*B*), the Chemehuevi Formation partly occupies the abandoned paleovalley east of River Island that had been earlier channelized and occupied by the boulder conglomerate of Bat Cave Wash (Trbb). This dry River Island paleovalley (Lee, 1908; Howard and others, 2008) contains a combined thickness of 70 m of the sand facies (Qcs) of the Chemehuevi Formation along with two interbeds of angular gravel (Qca). Some clasts in these angular gravel interbeds resemble chlorite-rich, altered granitic rocks exposed in the footwall below the Chemehuevi Detachment Fault in the Chemehuevi Mountains northwest across the Colorado River, so the angular alluvial gravel may record one or more local debris flows that flooded into the late Pleistocene Colorado River. Other riverlaid gravels in abandoned river paleovalleys, here mapped as terrace gravel and sand (Qtg), lie upstream from Devils Elbow across the Colorado River and downstream on the Arizona side of the river valley at the south edge of the quadrangle.

Muds of the Chemehuevi Formation on the north side of Sacramento Wash interfinger abruptly eastward with a facies mapped here as the deposits of old railway grade (Qcr; fig. 18). The old railway grade subunit consists of interbedded mud, Colorado River fluvial gravel, angular tributary gravel, paleosols, and sand containing root casts. The subunit is interpreted to represent depositional environments near the margin of an aggrading Colorado River valley, consisting of alternations of fringing marsh, locally derived alluvial fan, occasional excursions of Colorado River channels, and nondepositional episodes of soil formation. A fossil site whose reported position places it within these mapped deposits yielded freshwater and land snails (Taylor, 1983) and dentition from an extinct miniature pronghorn (*Capromerx* sp.) identified by C.A. Repenning in an internal 1968 U.S. Geological Survey report. Mammoth remains in similar-appearing deposits 1.5 km north of the map area were interpreted from a photograph as *Mammuthus meridionalis* (Irvingtonian mammal age, about 0.3–1.5 Ma; Agenbroad and others, 1992; L. Agenbroad, written commun., 1994). An early to middle Pleistocene paleontologic age would conflict with correlation to the Late Pleistocene Chemehuevi Formation.

Fluvial terrace gravel and sand (Qtg, Qtp) overlie the Chemehuevi Formation (Qc and subunits) and cap various terraces as high as 60 m above the present Colorado River within the quadrangle. Other terraces are formed of thin, locally derived, younger sidestream deposits mapped as the intermediate-age piedmont alluvium (Qa2), which interfingers with or overlies the terrace gravel and sand on a descending series of terraces. The Qa2 unit at successively lower terrace heights exhibits lower degrees of soil development, which may indicate that the terrace flights formed over a significant time interval. These terraces suggest staggered degradation of the river valley after the Late Pleistocene aggradation when the Chemehuevi Formation accumulated (Longwell, 1936; Metzger and others, 1973). Boulders in the terrace gravel and sand unit on the west flank of upper Topock Gorge include vesicular basalt, like that in the Black Mountains east of the river, and a clast of conglomerate derived from the ancestral Colorado River sandstone and conglomerate unit (Trbs). The boulders, therefore, may have been transported small distances by high-velocity late Pleistocene Colorado River floods that incorporated debris-flow material from the opposite bank. Younger units of piedmont alluvium generally form thin veneers on the thicker older piedmont alluvium (QTa1), just as Wilshire and Reneau (1992) reported for the Mohave Mountains area to the east. The youngest piedmont alluvial unit (Qa4) is material in historically active washes.

Holocene subsurface fluvial sediments that underlie the Colorado River and its floodplain near Topock (Metzger and Loeltz, 1973) record more than 15 m of radiocarbon-dated mid-Holocene aggradation (Howard and others, 2011), as do similar deposits tens of kilometers downstream near Blythe (Metzger and others, 1973). The 113-m elevation of the lowest dated Holocene subsurface



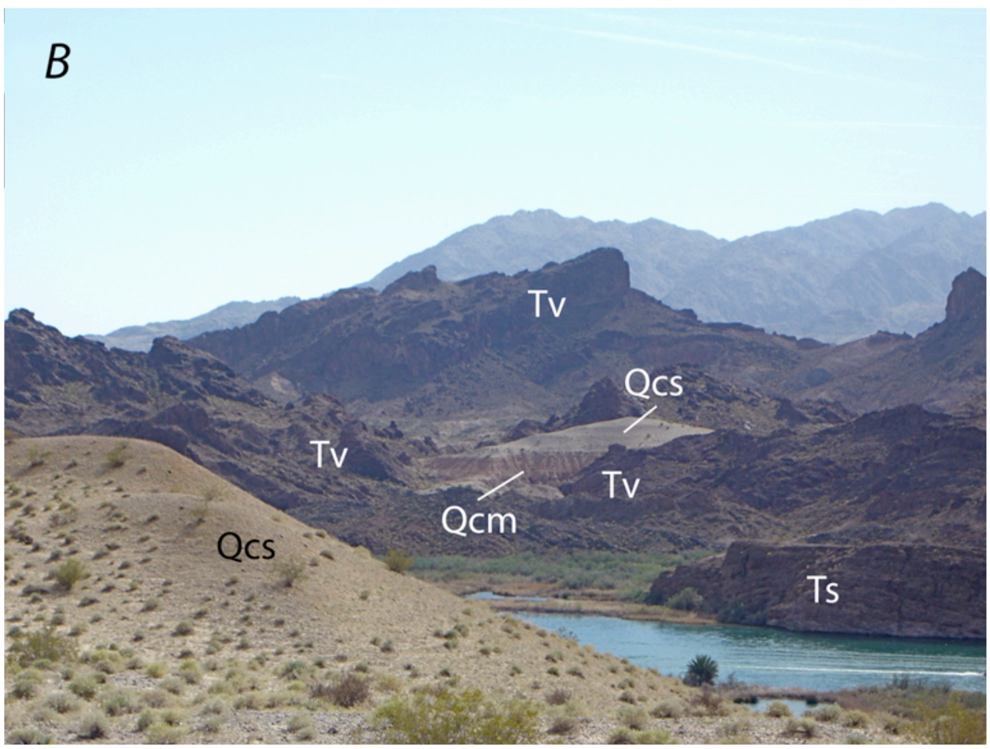


Figure 17. Photos showing outcrops of the Chemehuevi Formation. *A*. Pale-toned gypsiferous facies (Qcgy) draped unconformably (dips likely are compactional) onto poorly exposed and partly covered underlying sandstone and conglomerate (Trbs), 2.6 km north-northeast of Topock. *B*. View across Topock Gorge from Sand Dunes underlain by sand facies of the Chemehuevi Formation (Qcs) in paleovalley (fig. 3) near River Island. Southwestward across the Colorado River, typical Chemehuevi Formation exposures of bluff-forming dark mud (Qcm) overlain by lighter sand (Qcs) are inset into darker Miocene units including sandstone and conglomerate (Ts) and the lower volcanic sequence (Tv).

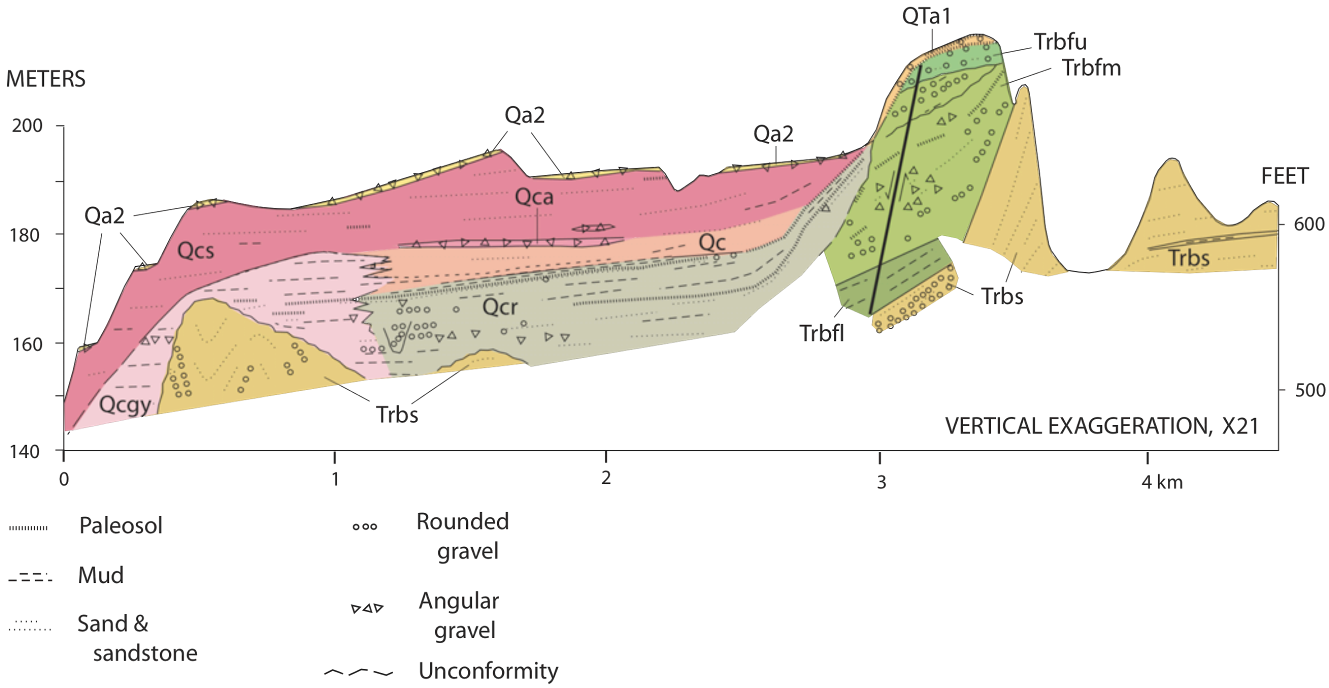


Figure 18. Sketch showing stratigraphic relations of Pliocene to Pleistocene deposits exposed on the northwest to north wall of Sacramento Wash northeast from Topock Marsh. Apparent dips greatly steepened by the 21x vertical exaggeration. The sandstone and conglomerate (Trbs) is overlain by facies of Santa Fe Railroad (Trbfl, Trbfm, and Trbfu), which are progressively less deformed higher in the stratigraphic succession; maximum dips are 20° in the lowest bed and 5° in the higher beds. These units are overlain in angular unconformity by older piedmont alluvium (QTa1, here containing abundant roundstone pebbles reworked from underlying deposits) and by inset deposits of old railway grade (Qcr), which locally dip as much as 5° mostly north, opposite in dip direction (despite apparent parallel dips on this projection) from south-dipping underlying facies of Santa Fe Railroad and underlying sandstone and conglomerate (Trbs). The deposits of old railway grade interfinger with gypsiferous mud (Qcgy) and sand and mud of the undivided Chemehuevi Formation (Qc), which is overlain by angular gravel (Qca) and sand (Qcs) of the Chemehuevi Formation. Intermediate-age piedmont alluvium (Qa2) overlies these deposits on terraces.

sediments near Topock indicates earlier incision of at least 98 m below the top of the Chemehuevi Formation. This incision and more than 18 m of younger Holocene and Anthropocene accumulated fluvial and deltaic sediments together define the youngest degradation-aggradation cycle of the river valley. The exposed floodplain and deltaic deposits postdate Parker Dam, which impounded Lake Havasu and flooded Topock Marsh. This flooding led to sedimentation that caused a gradual 8 m rise in grade in the upper part of Topock Gorge (Metzger and Loeltz, 1973). Unmapped sediments younger than the 1970 topographic base map on which the geologic map is based have accumulated extensively along the river shores as part of the continuing aggradation in Lake Havasu. Shorelines continue to evolve (Malmon and others, 2010), and more recent aerial imagery could be consulted to get up-to-date assessments of the riparian corridor.

Pliocene and Quaternary Deformation

The quadrangle is within a broad, relatively tectonically stable region of Arizona and California where units younger than middle Miocene rarely are deformed (Sonoran Fault Province of Howard and others, 1978; Carr, 1991). Local faults and folds in the upper Miocene, Pliocene, and Pleistocene units in the northern part of the quadrangle are therefore noteworthy, although not as conspicuous as the Quaternary Needles graben area 5 km north of the quadrangle (Pearthree and others, 1983, 2009). In the quadrangle, dips as steep as 15° can be found in the fanglomerate (Tf), the Bouse Formation (Tb), and overlying cemented old piedmont alluvium (Tao). South-plunging folds and small west-northwest-striking faults affect ancestral Colorado River deposits near the central north edge of the quadrangle, including a fan of dips (to 20°) that record structural sagging during deposition of the facies of Santa Fe Railway (as noted by Metzger and Loeltz, 1973, p. 14). Nearby overlying Upper Pleistocene deposits of old railway grade are folded to 5° northwest dips. The Chemehuevi Formation exhibits structural draping on an uneven substrate (fig. 16*A*) and locally (3 km east of Topock gaging station) exhibits tiny, 5-cm-displacement normal faults. Tectonic drivers for the Pliocene and Quaternary deformation are not known.

Paleontology

The Bouse Formation contains casts of vegetation fragments; ostracodes (*Cyprideis)* and reworked Cretaceous coccoliths were reported from an outcrop of the formation 2 km west of the Topock quadrangle (Smith, 1970; Winterer, 1975, table 6). Fossil material found in Pliocene and Pleistocene deposits related to the Colorado River in the Topock quadrangle include vertebrates, mollusks, and plants (table 2). A rib bone fragment 19 cm long (fig. 3b of Howard and Malmon, 2007), recovered by D.V. Malmon from the boulder conglomerate of Bat Cave Wash (Trbb) 3 km east-southeast of Topock, belonged to a small equine (R.E. Reynolds, written commun., 2006 in Howard and Malmon, 2007). The lower claystone and sandstone subunit of the facies of Santa Fe Railway (Trbfl) at the north edge of the quadrangle yielded remains of fish, pond turtle, rodent, and lizard, as well as bivalves and water reeds (R.E. Reynolds, written commun., 2008). The reported site of a mammoth tooth *(Mammuthus meridionalis*, L. Agenbroad, written commun., 1994; Agenbroad and others, 1992) was found in or near deposits that we map as artificial fill along the Arizona abutment for the Santa Fe Railway Colorado River bridge, so the tooth's original stratigraphic context is unknown. A mandible fragment from a miniature pronghorn, collected in 1968 by D.G. Metzger from the upper part of the unit that we map as deposits of old railway grade (Qcr), was identified in an internal 1968 U.S. Geological Survey report as *Capromerx* sp. by C.A. Repenning, who stated "Small antilocaprids comparable to this specimen have been found in rocks ranging in age from middle Pliocene (Hemphillian mammalian age) to late Pleistocene and have been assigned to several genera, based largely on the form of the horn cores. Most individuals of late Pleistocene age have only one lingual inflection on P_3 and, as the specimen from near Topock has two, it is more probable that it is older." Mollusks from the same locale were identified by Taylor (1983) as four extant species: the freshwater snails (which live locally), *Bakerilymnaea cubensis* (Pfieffer), *Pysa virgata* Gould, and the land snails, *Vertigo ovata* Say and a species of *Succinea(?*). Gastropods identified as *Succinea?* sp. in the region were more recently collected at or near the same site from the upper part of the deposits of old railway grade (Qcr). The Chemehuevi Formation also contains casts of plant roots and reeds, and its gypsiferous mud subunit yielded the gastropod, *Planorbela* sp., which is suggestive of a eutrophic aquatic environment (C. Powell, written commun. to D.V. Malmon, 2006; Malmon and others, 2011, p. 49).

Mineralization and Mineral Exploration

Miocene faulting and intense fracturing, accompanied in places by argillic alteration and copper and manganese mineralization, affects many of the rocks in the area (Hopkins and others, 1984; John and others, 1988). An area in California referred to as the area of the Quartz Queen prospect on the north side of Devils Elbow yielded anomalous values of base metal concentrations and was

Table 2. Fossil remains found in the Topock 7.5′ quadrangle, Arizona and California.

Map unit label	Material	Reference	General location	Comment
Tb	Vegetation fragments	This report	NW. of Powell Peak	
Trbb	Equine	R.E. Reynolds, written commun., 2006, in Howard and Malmon (2007, their fig. 3b).	3 km ESE. of Topock	Rib bone in cobble-boulder conglomerate
Trbfl	Fish, pond turtle, rodent, iguanid lizard, clam, ostracode, water reed	R.E. Reynolds, written commun., 2008	Warm Springs SW. quad. at boundary with Topock quad., 5 km NE. of Topock	
af	Mammoth	L. Agenbroad, written commun., 1995	In or beside fill for the railway tracks at Topock.	Tooth. Original stratigraphic origin unknown
Qcr	Pronghorn *Capromerx* sp.	C.A. Repenning, 1968 internal USGS report	North side Sacramento Wash 3 km NE. of Topock	Dentition
Qcr	Gastropods *Bakerilymnaea cubensis* (Pfieffer), *Physa virgata* Gould, (freshwater snails), and *Vertigo ovata* Say, *Succinea?* sp. (land snails)	Taylor (1983)	Same locality data listed as for the *Capromerx*	Paludal(?) environment suggested by assemblage of freshwater and land snails
Qcr	Gastropod *Succinea?* sp.	Charles Powell, written commun., 2009	At or very near same outcrop as the *Capromerx*	In clayey silt overlying resistant sand bed containing root casts at top of Qrr
Qc, Qcm	Casts of reeds and roots	This report	Various sites	
Qcgy	Gastropod *Planorbella* sp.	Charles Powell, written commun., 2009	3 km NE of Topock.	Genus thrives in rich eutrophic environments
Qcs	Rhizoconcretions	This report	Various sites	
Tb	Casts of vegetation fragments	This report	Various sites	

assigned a low potential for mineral resource potential (Miller and others, 1983). Alteration and silicification of Miocene sedimentary and volcanic rocks in association with intrusion by Miocene mafic rocks produced jasper and barite at the Yucca Mine area, Ariz., and in nearby SE¼NW¼ sec. 18, T. 15 N., R. 20 W. in the southeastern part of the quadrangle. The Gold Dome Mine at The Needles, Ariz., in a quartz vein containing gold and copper in Miocene igneous rock, was reported to have produced one carload of high-grade ore of unknown value (Coonrad and Collier, 1960a; fig. 3). The nearby Jackpot Mine adit and other diggings in and near The Needles also expose Miocene fault zones and rocks. Quartz veins of post-Cretaceous age in the east-central part of the quadrangle (NW¼ sec. 30, T. 16 N., R. 20 W.) cut unmapped mafic dikes of likely Miocene age that, in turn, cut the northeastern exposures of the Cretaceous Powell Peak pluton and its Proterozoic wall rocks. A mapped shaft 3 m deep exposes one of these veins, which contains chrysocolla and pyrite, along an unmapped vertical, west-northwest-striking fault (NW¼ sec. 30, T. 16 N., R. 20 W.). The Miocene age of alteration and mineralization at the foregoing prospects and mines likely relates to synextensional faulting and hydrothermal activity. The age of any mineralization exposed by two mapped shafts in Paleoproterozoic rocks 0.8 km southwest of Powell Peak in the east-central part of the quadrangle is unknown.

Three types of nonmetallic deposits have been exploited or explored. Rock has been quarried for riprap from a quarry at the mouth of Bat Cave Wash in the northwestern part of the quadrangle. The quarried rock, mylonitic gneiss in the footwall of the Chemehuevi Detachment Fault, reportedly was brecciated enough that it was not very satisfactory for the intended use as riprap. The Bouse Formation has been prospected for nitrates in the region (Noble, 1931), and the basal limestone of the Bouse Formation contains prospect pits in the northeastern part of the quadrangle (sec. 19, T. 16 N., R. 20 W.). Borrow pits expose gravel from piedmont alluvial deposits in several areas near highway and railway alignments.

Geologic History

Continental crust in the quadrangle dates to Paleoproterozoic time when sediments were deposited, intruded by granitoids, and metamorphosed to high grade between 1,600 and >1,700 Ma (Wooden and Miller, 1990; Bryant and Wooden, 1991). This episode was followed by Mesoproterozoic intrusion: first granitoids around 1,400 Ma (Anderson and Bender, 1989) and then diabase in horizontal intrusive sheets around 1,100 Ma (Howard, 1991).

Strata that elsewhere in the region nonconformably overlie the Proterozoic rocks show that by Cambrian time, deep erosion had exposed the Proterozoic metamorphic-igneous terrane and the unconformity began to drown in a shallow continental shelf. Shallow marine deposition across the craton continued intermittently in the region through Paleozoic and into early Mesozoic time (Stone and others, 1983).

During Mesozoic orogeny, plutonism built a series of granitoid bodies in the region, most conspicuously in the map area as the Late Cretaceous Chemehuevi Mountains batholith and its related cupola-like Powell Peak pluton and Borrow Pit body. Ductile top-to-northeast and left-lateral shearing imposed mylonitic fabric on an early phase of this batholith before the younger phases of this Chemehuevi Mountains Plutonic Suite were emplaced at about 72 Ma (John, 1987a; John and Mukasa, 1990; Nakata and others, 1990). Subsequent undated lamprophyre and other mafic dikes of northeast strike may record Late Cretaceous to early Paleogene dike intrusion during regional northeast-directed orogenic compression. Uplift associated with late Mesozoic orogeny resulted in erosional stripping of Paleozoic and Mesozoic strata across the broad Kingman uplift of western Arizona and adjacent states including the map area (Bohannon, 1984; Faulds and others, 2001; Beard and others, 2010).

Crustal stretching and tectonic denudation of footwall rocks in the region began about 23 Ma according to thermochronologic interpretation of cooling ages (Foster and others, 1990; John and

Foster, 1993). This timing of extension was concurrent with eruption of the oldest dated volcanic units in synextensional Tertiary basins (Brooks and Martin, 1985; Howard and John, 1987; Spencer and Reynolds, 1991; Nielson, 1993; Howard and others, 1993). Synextensional plutons in the Chemehuevi Mountains intruded at 21–19 Ma (Foster and John, 1999; this report). Tertiary continental deposition on the stripped and weathered surface of crystalline Proterozoic rocks typically began with thin red arkosic sandstone, followed by and interspersed within the quadrangle with a series of lower Miocene lahars and volcanic flows of intermediate, mafic, and silicic compositions. Associated dike intrusions, of mostly northwest strike, help to record the northeast-southwest orientation of Neogene extension. The gigantic eruption of the Peach Spring Tuff in the southern Black Mountains 25 km to the north of the quadrangle (Ferguson, 2008) covered much of the quadrangle area in welded tuff at about 18.5 Ma. This ignimbrite accumulated its greatest thickness within the quadrangle in a paleovalley near The Needles.

Large displacements between 18.5 Ma and about 14 Ma on a series of down-to-northeast extensional faults resulted in rapid tectonic denudation and cooling of the footwalls in the region (Foster and John, 1999), most rapidly at 15±1 Ma as recorded by U-Th/He ages in apatite across the Chemehuevi Mountains (Carter and others, 2006). This surge in unroofing and faulting coincided with rock avalanches, landslides, and other debris shed off active northeast-facing fault scarps that accumulated as thick conglomerates and megabreccias in the middle Miocene upper sedimentary and volcanic sequence (Miller and John, 1988, 1999). Sequential clast assemblages in these sediments document progressive unroofing of volcanic, Proterozoic-gneiss, and finally deeper Cretaceous plutonic parts of the crustal section (Miller and John, 1999). Silicic volcanism added tuffs to the section, especially in the southeast. The Chemehuevi Detachment Fault slipped at gentle dips and accumulated ≥18 km of down-to-northeast displacement, while hanging-wall blocks above it and the hanging-wall Devils Elbow Fault tilted (John, 1987a; John and Howard, 1994). It continued slipping after the subparallel, deeper Mohave Wash Fault accumulated its 2–3 km of down-to-northeast slip (John, 1987a). The hanging-wall Tumarion and Jackpot blocks above these slipping faults tilted steeply to the southwest while breaking and separating along the steep, northeast-striking Gold Dome Fault Zone. This fault zone propagated upward, at the base of the Miocene section, as a triangle zone to form a fault-related fold of the layered Miocene rocks. By 15.8±0.4 Ma, the synformal Needles Mountain intrusion was emplaced into the triangle zone at this fault-fold transition and was subsequently deformed by continued slip along the Gold Dome Fault Zone (John and Howard, 1994; Howard and John, 1997). This fault zone strikes obliquely from the direction of detachment slip and likely slipped during tilting, so that separations now along that tilted fault zone are dextral. Gold mineralization accompanied or exploited some Miocene faults.

By late Miocene time after the climax of extensional tectonism, alluvial fans built a fanglomerate within ancestral Mohave Valley, apparently a closed basin lacking a drainage exit. At about 5 Ma, rapid submergence in a lake or estuary resulted in deposition of the Bouse Formation in the valley, where a few meters of the basal limestone accumulated along the valley bottom and sides, followed by tens to hundreds of meters of layered mud and sand. The mud and sand represent deltaic deposits heralding the arrival of Colorado River water into this region (Buising, 1990; Spencer and Patchett, 1997).

A newly formed, throughgoing ancestral Colorado River incised deeply into the Bouse Formation, draining southward through an apparently new steep-walled bedrock gorge (ancestral Topock Gorge) en route to the Gulf of California. Subsequent Pliocene aggradation of river-laid sediments deposited a thick accumulation at about 4 Ma (House and others, 2008). Younger renewed incisional lowering of the valley floor resulted in progradation of thick piedmont alluvial fans and an accumulation along an ancestral Sacramento Wash. The flood-carried boulder conglomerate of Bat Cave Wash was deposited in a paleovalley not far above the level of the historical river. In the Late

Pleistocene, the river aggraded again with more than 70 m of fluvial sand and mud of the Chemehuevi Formation, including gypsiferous mud, paleosols, marsh deposits, and tributary gravel that accumulated at the valley margin.

Younger Late Pleistocene re-incision of at least 100 m stranded a series of fluvial and piedmont-alluvial terrace steps, culminating in a valley thalweg tens of meters lower in elevation than the present one. Holocene re-aggradation, likely related in part to rising eustatic sea level, then deposited more fluvial sand, mud, and gravel on the valley floor. Further fluvial and deltaic aggradation and valley flooding occurred in response to the 20th century impoundment of Lake Havasu by Parker Dam.

DESCRIPTION OF MAP UNITS

[This map uses the informal term Anthropocene for Holocene units deposited during the 20th century]

SEDIMENTARY AND VOLCANIC ROCKS AND DEPOSITS

af **Artificial fill (Holocene, Anthropocene)—**Fill materials in highway and railway grades, and levee in Topock Marsh. Thickness to 10 m

d **Disturbed ground (Holocene, Anthropocene)—**Mapped where pre-construction geology is obscured

ds **Dredged sand (Holocene, Anthropocene)**—In northwestern part of quadrangle. Medium sand dumped on Colorado River banks from dredging of river channel. In part, reworked by wind. Maximum thickness several meters

Piedmont alluvium

Qa4 **Youngest piedmont alluvium (Holocene, Anthropocene)**—In Sacramento Wash, other active modern washes, and alluvial aprons. Angular to subangular, poorly to moderately sorted, unconsolidated sand and gravel of local derivation. Clasts derived locally dominantly from Proterozoic and Cretaceous rocks and Tertiary volcanic rocks; locally include rounded quartzite, chert, and limestone pebbles and sand reworked from Colorado River deposits. Deposits mostly not dissected. Typically exhibits bar-and-swale topography with <1 m of local relief. Commonly supports riparian vegetation. Fan that borders Topock Marsh at the mouth of Sacramento Wash postdates a 1902 U.S. Geological Survey topographic survey. Corresponds to unit described as Q4 in the adjacent Mohave Mountains area on the east (Wilshire and Reneau, 1992; map unit Qs4 of Howard and others, 1999). Correlative to deposits mapped as Qay in Needles 7.5-minute quadrangle on the northwest (Malmon and others, 2009)

Qa3 **Younger piedmont alluvium (Holocene)**—Forms little-dissected surfaces, typically standing ~1 m above active modern washes. Surface relief commonly expressed as bar-and-swale landforms with <1 m of local relief. Angular to subangular, poorly to moderately sorted, unconsolidated sandy gravel. Clasts derived locally dominantly from Proterozoic and Cretaceous rocks and Tertiary volcanic rocks; locally include rounded quartzite, chert, and limestone pebbles and sand reworked from Colorado River deposits. Inset into intermediate-age piedmont alluvium (Qa2) and overlies the Chemehuevi Formation (Qc and subunits). Corresponds to unit described as Q3 in the adjacent Mohave Mountains area on the east (Wilshire and Reneau, 1992; map unit Qs3 of Howard and others, 1999). Correlated generally to deposits mapped as Qayi in Needles 7.5-minute quadrangle on the northwest (Malmon and others, 2009)

Qa2 **Intermediate-age piedmont alluvium (Pleistocene)**—Fan remnants scattered throughout the quadrangle. Dissected and isolated into patches by modern drainages. Typically surfaced by varnished pebbly desert pavement. Near Colorado River and Sacramento Wash, forms series of terraces 10 to 40 m above modern stream grade. Deposits on highest terrace include basalt boulders near the north edge of quadrangle. Soil development greatest on highest terraces (stage II carbonate) and less on lower terraces (for example, stage I carbonate or no carbonate). Commonly veneers terraces on Chemehuevi Formation (Qc), on older piedmont alluvium (QTa1), or on terrace gravel and sand (Qtg). Unit veneers noticeable terrace flights within 3 km on either side of Topock Marsh. Thickness 1–10 m. Correlative with at least the younger part of Q2 unit(s) in the adjacent Mohave Mountains area on the east described by Wilshire and Reneau (1992; map unit Qs2 of Howard and others, 1999). Correlative to deposits mapped as Qai in Needles 7.5-minute quadrangle to the northwest (Malmon and others, 2009)

Qf **Floodplain and deltaic deposits (Holocene, Anthropocene)**—In northwestern part of the map area and in Topock Gorge. Unconsolidated sand, silt, and mud in the floodplain of the Colorado River and Topock Marsh and along the river banks. Upper 5–8 m mostly deposited into backwater resulting from the 1938 closure of Parker Dam, which led to 5–8 m rise in the average river stage near Topock (Metzger and Loeltz, 1973). Area near Topock Marsh includes sand deposited by a historical crevasse-splay across dredged sand into Topock Marsh. Includes shoreline sand bars along Topock Gorge that dam tributary valleys and isolate backwater ponds. (Unmapped wider expanses of silty marsh and floodplain deposits and sandy bars along the margins of the river channel have been deposited and exposed since the 1970 base map was drawn)

Qs **Windblown sand (Holocene)**—In northern third of quadrangle. Loose, medium to coarse sand. Locally contains pebbles from lag of alluvial deposits

Ql **Landslide block (Holocene)**—In northeastern part of quadrangle, on south side of Sacramento Wash (sec. 13, T. 16 N., R. 20½ E.)

Colorado River-related deposits

Qtg **Terrace gravel and sand (Upper Pleistocene)—**Well-rounded gravel and quartz-rich silty sand. Forms terraces and veneers bedrock straths on the northwest flank of upper Topock Gorge at and below 600 ft (183 m) elevation, 45 m above modern river. Lower terraces are as low as 5 m above modern river. Deposits in highest and lowest terraces on northwest flank of upper Topock Gorge include boulders, some as large as 0.9 m; boulders include vesicular basalt, quartzite (to 0.3 m across), coarsely porphyritic (Mesoproterozoic) granite, and cemented roundstone conglomerate derived from the sandstone and conglomerate unit of the ancestral Colorado River deposits (Trbs). Overlooking the mouth of Mohave Wash, forms a roundstone-gravel veneer 0.1–5 m thick on bedrock from elevations ~630 to 560 ft, including a strath terrace at ~600–560 ft., all overlain by intermediate-age piedmont alluvium (Qa2) having an eastward-sloping preserved depositional surface near 630 ft, graded toward the valley axis. As mapped, includes gravel lag capping the sand subunit of the Chemehuevi Formation (Qcs) at about 680 ft elevation 1 km east of River Island, and gravel occupying paleovalleys to this elevation in Calif. near Devils Elbow and near the south edge of the quadrangle in Ariz.. Highest terrace deposits may be equivalent to sand unit (Qcs) of the Chemehuevi Formation. Likely correlative deposits upstream near Lake Mohave yielded U-Th dates mostly

32–60 ka (Lundstrom and others, 2008). Locally, subdivided into the following:

Qtp **Pink silty sand**—In northwestern part of quadrangle. Massive to bedded, pale-orange-gray, quartz-rich clayey silty fine sand. Locally includes iron-stained basal gravel as thick as 1 m of rounded non-local pebbles. Occurs as layers and lenses interfingered with and underlying intermediate-age alluvium (Qa2) that has stage-0 carbonate soil and, north of I-40, is graded to terraces 70 ft (20 m) or lower above Colorado River. Under railway trestle west of Topock in California, veneers steep paleoerosional surfaces cut on fanglomerate (Tf). Lithologically resembles the Chemehuevi Formation; some outcrops possibly could be designated instead as that older unit

Qc **Chemehuevi Formation (Upper Pleistocene)**—Weakly to moderately consolidated sand, silt, and clay. Well bedded (see fig. 14C of Malmon and others, 2011). Sand unconsolidated, commonly reworked by the wind. Feldspar content increases with distance from the Colorado River. Contains interbeds of well-sorted, rounded-pebble gravel. Locally capped by a surface lag of rounded and angular gravel and soil containing pedogenic calcareous nodules. Locally contains concretions, calcareous rhizoconcretions, gypsum crystals, one or more internal paleosols, and iron-stained root casts. Root casts extend downward from the base of the formation as much as 0.6 m vertically into a paleosol developed on a substrate of the older alluvium (QTa1) 2 km east of Topock (0.4 km south of BM 609). Maximum exposed thickness 70 m. Formation reaches maximum elevations about 690 ft 1 km east of River Island and also 3–4 km southeast of Topock. The Chemehuevi Formation was defined by Malmon and others (2011) and is largely equivalent to units D and E of Metzger and Loeltz (1973) and Chemehuevi beds of House and others (2005). Locally, subdivided into the following:

Qcs **Sand**—Unconsolidated medium to fine, rounded, quartz-rich sand. Very light gray. Typically erodes to rounded slopes of loose sand. North and northeast of the mouth of Sacramento Wash, distinction from mud facies (Qcm) is poorly defined; there, much of the sand subunit is pale pinkish, partly silty or micaceous and laminated, contains gypsiferous clayey silt and cemented sandstone laminae, and is cemented in lower part. Contains subrounded fine-pebble gravel and angular, locally derived gravel bed at base, over erosional surfaces on underlying mud (Qcm) and gypsiferous mud (Qcgy*).* Capped locally by lag of rounded and angular pebbles (in places mapped as terrace gravel and sand, Qtg) and by stage II carbonate soil. Maximum exposed thickness 60–65 m, excluding 5–10 m angular gravel (Qca) in two interbeds at Sand Dunes hill in paleovalley east of River Island (fig. 3). Typically overlies mud and gypsiferous mud subunits (Qcm and Qcgy). Equivalent to unit E of older alluviums of Metzger and Loeltz (1973). Interpreted as Colorado River channel and crevasse-splay deposits

Qcm **Mud**—Bedded to massive silt, fine sand, and poorly consolidated mudstone. Grayish orange pink to pale orange pink (7.5YR8/3). Locally includes minor rounded or angular pebble gravel. Locally contains concretions. Typically erodes as bluffs. Grades into and interfingers with gypsiferous mud (Qcgy). Typically underlies sand subunit (Qcs). Maximum thickness 35 m. Equivalent to unit D of Metzger and Loeltz (1973). Interpreted as deposited in floodplain during aggradation of Colorado River. Tentatively dated elsewhere approximately between about 40 and 70 ka using luminescence (Malmon and others, 2007; Lundstrom and others, 2008). Interpreted as Colorado River floodplain deposits

Qcgy **Gypsiferous mud**—Occurs along the valley margin. Bedded silt, clay, and sand. Pale yellow (10YR8/2) to very pale orange, pale grayish yellow (5Y8/2), and pale grayish yellow green (5GY8/2). Secondary selenite crystals common on outcrop regolith. Includes a few laminae and thin beds of carbonate-cemented fine sandstone. Pinker parts occur at top and bottom of subunit where gypsiferous mudstone forms lens or lenses gradational with and interfingered with pinkish mud more typical of mud subunit (Qcm). Contains interbeds of locally derived angular pebble gravel and one or more white, calcareous interbeds (paleosols?). Rare gastropods. Lowest beds drape over underlying erosional unconformity. Maximum thickness 30 m. Interfingers with pink siltstone (Qcm) and locally with upper part of deposits of old railway grade (Qcr); underlies upper sand (Qcs) and overlies old piedmont alluvium (QTa1) and older units

Qca **Angular gravel**—Interbeds of locally derived gneiss and volcanic clasts representing alluvial-fan and debris-flow deposits. Five hundred meters east of River Island includes angular pebbles of chloritic granitoids similar to faulted bedrock in Chemehuevi Mountains, Calif. Maximum thickness 5–10 m

Qcr **Deposits of old railway grade**—Variegated, interbedded sandstone, mudstone, gravel, and calcareous paleosol deposits north of Sacramento Wash near abandoned historic Old Railway grade of Atlantic and Pacific Railway (figs. 3, 18). Typical exposures are shown in a photo in figure 5 of Howard and Malmon (2007). Heterogeneous assemblage of sandstone, thin gray calcareous sandstone, thick buff-toned sandstone, clay, silt, locally derived angular gravel, and white mudstone marked by calcareous nodules. Uppermost part includes gastropod-bearing silt containing thin, cemented sandstone laminae over paleosol on 1- to 2-m-thick resistant sand and silt containing abundant vertical iron-stained root casts 1–4 mm in diameter and as long as 0.5 m (fig. 6 of Howard and Malmon, 2007). Upper part of unit (8 m) interfingers with silt (Qc) and gypsiferous mud subunit (Qcgy) of the Chemehuevi Formation; thins eastward to 2 m. Lower parts of unit include light-toned, calcareous paleosol; pale orange mud resembles or correlates to mud subunit of Chemehuevi Formation (Qcm). A representative section consists, in ascending order, of 3–7 m pebbly sandstone, 15 m of sand and clay, and 3.5 m of cliff-forming, pebbly sandstone. Includes freshwater and land snails (Taylor, 1983; table 2). Subunit, 16–25 m thick, overlies sandstone and conglomerate subunit of ancestral Colorado River deposits (Trbs) and upper part of facies of Santa Fe Railway (Trbfu) on angular unconformity. Tentatively considered to be a heterogeneous facies of the Chemehuevi Formation. Interpreted as fluvial, paludal, debris-flow, and paleosol materials representing intermittent periods of Colorado River, wetland, and tributary deposition and exposure at Colorado River valley margin during the aggradation that deposited Chemehuevi Formation in the river's floodplain

Old piedmont alluvial deposits—Mostly alluvial-fan aprons consisting of angular to subangular debris of local derivation. Divided into the following:

QTa1 **Older piedmont alluvium (Pleistocene and Pliocene)**—Angular to subrounded, poorly sorted, sandy cobble and boulder gravel and pebbly sandstone. Angular to subangular debris of local derivation. Clasts mostly resemble volcanic, granitoid, and gneiss bedrock in the area but, near Sacramento Wash, include vesicular basalt resembling rocks in southern Black Mountains and round chert and quartzite pebbles derived from ancestral Colorado River deposits (Trbs, Trbfu). Deeply dissected or buried alluvial fan deposits as much as tens of meters thick. Includes coarse basal bed of 1- to 2-m blocks 3–5 km southeast of Topock. Locally preserves surface desert pavement and stage III to stage IV carbonate soil. Maximum thickness >18 m. Underlies Chemehuevi Formation; unconformably overlies the cemented old piedmont alluvium (Tao), the facies of Santa Fe Railway, and older units. In central part of area 2 km north of Jackpot Mine, rests on calcareous paleosol developed on cemented old piedmont alluvium (Tao). In adjacent quadrangles unit comprises fan material of several ages having different soil development and different fan heights above modern drainage (Metzger and Loeltz, 1973). Correlated to unit C of older alluviums of Metzger and Loeltz (1973). Correlated to unit QT1 of Wilshire and Reneau (1992; map unit QTs1 of Howard and others, 1999) in the adjacent Mohave Mountains area to the east. Parts possibly correlate to units Q2a and Q2b of Bull (1991). Correlated to units mapped in Needles 7.5-minute quadrangle to the northwest as older intermediate-age piedmont gravels (Qoa) and old piedmont gravels units (Malmon and others, 2009). Locally, includes the following:

QTa1s **Deposits of ancestral Sacramento Wash**—Near Sacramento Wash. Moderately well sorted, bedded, pale-brownish-gray, subrounded, fluvial gravel and feldspathic sand and poorly consolidated sandstone (photo in fig. 4 of Howard and Malmon, 2007). Contains clasts of basalt, gneiss, two-mica granite gneiss resembling rocks in Hualapai Mountains, rare clasts of rounded quartzite and sandstone derived from the (Pliocene) sandstone and conglomerate unit (Trbs), and clay balls 2 m across. Crossbed foresets as high as 2 m. Clast imbrication subparallel to the modern Sacramento Wash drainage

Tao **Cemented old piedmont alluvium, undivided (Pliocene and Miocene(?))**—In northeastern part of area within 2–3 km of I-40. Includes 8 m of calcareous-cemented basal pebbly arkosic sandstone and conglomerate. Clasts in exposures near Sacramento Wash include biotite granodiorite typical of Chemehuevi Mountains Plutonic Suite, gneiss, and basalt. Northeasternmost exposure (NE¼ sec. 18, T. 16 N., R. 20 W.) contains clasts of yellowish claystone typical of nearby Bouse Formation. Clasts in outcrops 3–4 km east-southeast of Topock dominated by angular pebbles derived from the diorite of Topock (Kt) and other rocks exposed to the south, including gneiss, volcanic rocks, dacitic dike rocks, and rocks of Chemehuevi Mountains Plutonic Suite. Includes 15 m of crossbedded sand (planar crossbeds 0.3 m high) in SW¼ sec. 11, T. 16 N., R. 20½ W. Commonly forms or capped by ledge-forming calcareous paleosol (stage IV) 1 m thick.

Underlies older piedmont alluvium unit (QTa1, less cemented) and locally underlies sandstone and conglomerate unit of ancestral Colorado River deposits (Trbs). Mostly overlies Bouse Formation (Tb) and is correlated to units C(?) of older alluviums of Metzger and others (1973); where the mapped Bouse Formation is absent from sections 3–4 km east-southeast of Topock, mapped cemented unit may also include deposits correlative with the fanglomerate unit (Tf)

Ancestral Colorado River deposits—Equivalent to unit B of older alluviums of Metzger and Loeltz (1973)

QTcg **Colorado River gravel, undivided (Pleistocene and (or) Pliocene)—**Several localities, in and near Topock Gorge (for example at Devils Elbow), at elevations 600–800 ft (in part higher than the Chemehuevi Formation). Sand and gravel containing well rounded clasts of quartzite, limestone, chert, and less-rounded gneissic and volcanic rocks. Similar deposits at elevations no higher than the Chemehuevi Formation are mapped as terrace gravel and sand (Qtg). Where shown under the river on cross section B–B′, likely includes sand and mud

Trbb **Boulder conglomerate of Bat Cave Wash (upper Pliocene(?))—**In northwestern part of quadrangle west and southeast of Topock and near center of quadrangle at River Island. Cemented boulder and cobble conglomerate, lacking internal beds (fig. 16). Contains rounded quartzite pebbles. Contains subrounded boulders as coarse as 0.9 m of rounded quartzite and gneiss at River Island and of volcanic and gneissic rocks west of Topock (fig. 11 of Metzger and Loeltz, 1973). Unit fines upward (upslope) to small boulder and large cobble size at higher elevations (fig. 3 of Howard and Malmon, 2007). Locally, clasts include sandstone blocks derived from the underlying sandstone and conglomerate unit (NW¼NW¼SE¼ sec. 1, T. 15 N., R. 21 W.) or (400 m to NW.) abundant angular clasts of epidote-bearing granite and granodiorite typical of rocks exposed across the Colorado River in the Chemehuevi Mountains. Rests unconformably on channelized to sloping contact on varied substrates, including sandstone and conglomerate unit (Trbs). Geomorphic and stratigraphic position inset into subjacent sandstone and conglomerate unit (Trbs) suggests the boulder conglomerate of Bat Cave Wash also likely postdates deposition and incision of the facies of Santa Fe Railway, but no direct stratigraphic relation observed. Relation to older piedmont alluvium (QTa1) not observed. Lowest elevations of unit 480–500 ft, about 15 m above the pre-dam Colorado River. Occurrences elsewhere as high as 30 m higher in elevation suggest a projected original thickness ≥30 m. Exposures of the unit west of Topock were illustrated by Metzger and Loeltz (1973) as part of their unit B of older alluviums. Possibly correlative with boulder deposits downstream in Chemehuevi Valley (Howard and Malmon, 2011; D.V. Malmon, unpub. mapping, 2010) and upstream (the Laughlin conglomerate of House and others, 2005)

Facies of Santa Fe Railway (Pliocene)—North of Sacramento Wash in the northern part of the quadrangle (fig. 15). Divided into the following:

Trbfu **Upper conglomerate—**Clast-supported rounded-pebble conglomerate and underlying matrix-supported roundstone pebble diamictite. Unit is barely deformed and overlies older members on angular unconformity; 5 m thick. Capped by stage II–III carbonate soil overlain by roundstone conglomerate assigned to older piedmont alluvium (QTa1)

Trbfm **Middle part**—Varied assemblage of lenticular beds consisting of well-sorted roundstone pebble conglomerate (pebbles dominantly quartzite, chert, limestone, and gneiss); pebbly mudstone diamictite; poorly sorted calcareous sandstone; poorly sorted, pale-orange, mud-rich, pebbly sandstone; white mudstone; white paleosols containing calcareous nodules; green sandstone; and angular conglomerate containing clasts of local derivation. Calcite nodules over fine sandstone in lower part. Maximum exposed thickness 45 m or more. Exhibits fanning dips as steep as 18°; some beds in this fanning sequence pinch out northward. Overlies other facies of ancestral Colorado River deposits concordantly. Dipping beds were photographed by Lee (1908) and Metzger and Loeltz (1973, their fig. 16), who also portrayed them in an interpretive sketch (their fig. 12)

Trbfl **Lower claystone and sandstone**—Pale-greenish-gray claystone and underlying sandstone. Claystone contains bivalves, reed impressions, and a vertebrate fauna including fish, pond turtle, rodent, and lizard (R.E. Reynolds, written commun., 2008). Thickness about 10 m. Tilted. Rests on conglomerate that is part of the sandstone and conglomerate unit (Trbs)

Trbs **Sandstone and conglomerate (lower Pliocene)**—Medium to coarse, moderately cemented, crossbedded, pale-gray quartz-rich sandstone, containing rounded pebbles of chert, quartzite, and other rocks, and layers of cemented roundstone and sharpstone pebble conglomerate that locally contains 0.2-m-wide clay balls. Thick bedded. Along the north-central margin of the quadrangle, contains beds as thick as 4 m of bedded mud. Exposures along I-40 include conglomerate containing both angular and rounded pebbles, interbedded with lesser mud and crossbedded sandstone; dated by cosmogenic burial technique as ~4 Ma (Matmon and others, 2012). In eastern exposures, sandstone is feldspathic with rounded quartz grains, contains rounded pebbles of gneiss and volcanic rocks, and exhibits west-directed current imbrication; conglomerate interbeds are dominated by angular pebbles, features suggesting derivation largely from an ancestral Sacramento Wash; overlain in places by resistant calcareous pebbly sandstone assigned to oldest piedmont alluvium unit (QTa1). Thickness >120 m, based on exposures ranging in elevation from 480 ft (base not exposed) to 860 ft. Elevation range 3 km north of quadrangle is 460 ft (base not exposed) to 1,020 ft, suggesting thickness ≥170 m. Correlated to unit mapped by Malmon and others (2009) in the Needles 7.5-minute quadrangle as the alluvium of Bullhead City of House and others (2005)

Tb **Bouse Formation (lower Pliocene)**—Bedded, pale-green clay; tan or yellowish siliceous claystone; and tan to pinkish sandstone (fig. 14). Locally contains green nodules and yellowish-brown and white concretions. Contains small dark casts of vegetation fragments in siltstone and claystone, and rounded quartz grains in calcareous sand beds. Drilled thickness of clay assigned to the Bouse Formation between overlying gravels and underlying fanglomerate in two wells in north-central part of map area is 77 m (sec. 11, T. 16 N., R. 20½ W.) and 57 m (sec. 14, T. 16 N., R. 20½ W.) (Metzger and

Loeltz, 1973, p. 10 and table 11), indicating that the unit in subsurface extends as low as 362 ft elevation; 1 km west of quadrangle, drilled unit extends to 290 ft elevation (Metzger and Loeltz, 1973, table 11). Possible thickness 215 m in quadrangle, based on elevation difference between lowest drilled and highest exposed occurrences. Includes the following:

Tbl **Basal limestone**—North of Powell Peak 3 km in sec. 19, T. 16 N., R. 20 W. Resistant, white, silty limestone 3–4 m thick at elevations 920–1,120 ft. Overlies pre-Tertiary rocks or fanglomerate, and locally dips 15° north

Tf **Fanglomerate (upper Miocene)**—In northwestern part of quadrangle. Poorly sorted sandy conglomerate of locally derived angular to subangular clasts. Well indurated; may form vertical to overhanging arroyo walls as high as 30 m. West of Colorado River, contains gneiss clasts resembling rocks exposed in adjacent Chemehuevi Mountains. East and northeast of Topock, consists of poorly sorted, lenticular, cemented, angular pebble conglomerate that is pale pinkish to gray, or exhibits yellowish stain, exhibits northeastward-directed clast imbrication, and contains greenish pebbles of chlorite- and epidote-bearing granitoid rocks typical of footwall of detachment faults in or adjacent to the Chemehuevi Mountains; fewer pebbles are of volcanic rocks and gneiss. This clast assemblage and northward-directed clast imbrication indicates alluvial fans sloping northeast and north into a depositional basin that bottomed east of the modern axis of southern Mohave Valley. Locally dips as much as 8–10° but more commonly is undeformed. Where immediately underlying the Bouse Formation limestone 7 km ESE. of Topock, upper 1–2 m of fanglomerate unit locally consists of well-sorted, planar crossbedded conglomerate; this occurrence is interpreted as fanglomerate reworked by waves in a water body in transition to deposition of the Bouse Formation. Rests with angular unconformity on conglomerate of the upper sedimentary and volcanic sequence and on mylonitic gneiss and migmatite. Maximum exposed thickness 30 m

ROCKS DEPOSITED DURING EXTENSIONAL DEFORMATION

Upper sedimentary and volcanic sequence (middle Miocene)—Interbedded tuff and basalt within a few kilometers outside the quadrangle dated 15.5 to 13.3 Ma ($^{40}Ar/^{39}Ar$; Miller and John, 1999). Thickness 400–2,000 m. Consists of the following:

Tc **Conglomerate**—Angular and subangular, locally subrounded. Commonly red. Typically contains abundant mud matrix (more than the fanglomerate unit, Tf), is moderately well cemented, and is deformed. Paleocurrent directions dominantly to southeast, northeast, and north (Miller and John, 1999). Locally, subdivided on the basis of dominant clast type into the following:

Tcgn **Gneiss-clast conglomerate**—Red to red-brown weathering, poorly sorted alluvial fan deposits. Clasts subangular to subrounded, derived from source rocks that are characteristically above the Chemehuevi Detachment Fault: Proterozoic gneisses (Xg), granite (Yg), amphibolite (Xga), quartz porphyry (TKq), diorite of Topock (Kt), and some volcanic rocks (Tv). Locally between The Needles and Topock, includes chloritic clasts and granodiorite clasts typical of rocks below that detachment fault

Tcv **Volcanic-clast conglomerate**—Reddish-brown, poorly sorted alluvial-fan deposits. Clasts are angular volcanic rocks, as large as 1 m. Moderately well sorted. Locally crossbedded in sandy parts

Tsb **Sedimentary breccia—**Includes matrix-supported, polymict**,** debris-flow deposits; local laminated (varve-like) sandstone and siltstone; and (1.8 km north of Devils Elbow) megablocks derived from diorite of Topock (Kt) and augen gneiss (Xag)

Tm **Megabreccia**—Monolithologic breccia and partly intact blocks. Structures include irregular wispy layering. Exhibits range of textures including mosaic textures typical of landslide and rock-avalanche deposits. Locally, divided on the basis of clast lithology into the following:

Tmg **Granite-clast megabreccia**—Clasts are granodiorite and other rocks derived from the Chemehuevi Mountains Plutonic Suite and similar rocks

Tmgn **Gneiss-clast megabreccia—**Consists of brecciated rocks derived from gneiss (Xg). Breccia includes partly intact slide blocks hundreds of meters across. Rocks north of Devils Elbow include rock types derived from gneiss (Xg), augen gneiss (Xag), diabase dikes (mapped as Yd within the megabreccia where little disrupted), quartz porphyry (TKq), and diorite of Topock (Kt)

Tmt **Tuff-clast megabreccia**—On north side of River Island. Derived from Peach Spring Tuff

Tst **Sedimentary rock and tuff**—In southeastern part of quadrangle. Well-bedded sandstone, poorly sorted sandy conglomerate, and interbeds of tuff. Conglomerate pebbles and rarer cobbles include angular to subangular volcanic rocks of mafic and intermediate composition and, locally, rounded boulders derived from Peach Spring Tuff. About 1.5 km northwest of Yucca Mine (SW corner sec. 8, T. 15 N., R. 20 W.), unit is coarsely bedded to massive sandstone, pebbly sandstone, conglomeratic sandstone, and cobble to boulder conglomerate, probably deposited as mud flows and debris flows on irregular erosional surface. In lower part of unit, subangular to subrounded clasts are predominantly derived from basalt, pumice, and Peach Spring Tuff; upper part contains a greater proportion of gneiss and granite clasts. Sandy matrix is at least 50% pumice and also contains quartz grains and feldspar crystals. Layers in lower part vary from coarse sandstone to matrix-supported conglomerate, with clast sizes coarsening upward; many large blocks are oriented with long axes vertical. Some clast-supported pebble conglomerate is entirely volcaniclastic, composed largely of fragments of oxidized and fresh basalt mixed with light-colored pumice, probably reworked from lapilli tuff deposits. Northeast of Yucca Mine, a thick lens of massive matrix-supported conglomerate, possibly a lahar deposit, consists of subrounded boulders of Peach Spring Tuff more than 1 m across and large cobbles and boulders of basalt and other volcanic rock types. This lens is overlain by well-bedded coarse sandstone and conglomeratic sandstone, mostly volcaniclastic. In upper part of unit, matrix contains abundant rounded quartz sand, in addition to dominant volcanic grains; gneiss and granite clasts may be as abundant as volcanic rock types and the content of basement clasts larger than 10 cm is greater than in lower part of the unit. Thin beds of ashfall tuff are interbedded in the upper part. Thickness 60–80 m

Tfb **Higher basalt flows**—Flows stratigraphically close above Peach Spring Tuff. Dyktitaxitic olivine basalt**.** Lithologically resembles basalt flows (Tvb) stratigraphically close below Peach Spring Tuff

Tp **Peach Spring Tuff (early Miocene)**—Resistant single flow and cooling unit of welded rhyolite ashflow tuff. Tan to pinkish. Phenocrysts dominantly sanidine (commonly adularescent blue) and lesser quartz, plagioclase, biotite, hornblende, and sphene. Dark lithic lapilli also present. Basal parts include brecciated tuff, vitrophyre. Forms resistant ridges, cliffs, and rock slopes of pinkish rock. As mapped, includes massive, white, nonwelded tuff as thick as 4 m below the welded tuff. Nonwelded where thin, near gaging station on Colorado River. Fiamme reach dimensions of 55 x 15 cm 1ocally at the south end of River Island and west across Colorado River. Thickness of tuff varies from 2–3 m near the Topock Gaging Station to 150 m where the tuff occupies and partly defines a paleovalley fill near Jackpot Mine. Upper part of tuff near Jackpot Mine contains travertine veins as thick as 40 cm and upper surface locally has 2–3 m of sharp relief or is capped by calcite-cemented conglomerate; these features suggest hot-springs activity, weathering, and erosion prior to deposition of overlying Miocene sedimentary rocks. Locally, the top of the tuff below overlying conglomerate defines mushroom-like forms at River Island, suggesting eroded paleohoodoos. Fiamme in tuff dip 0–15° more steeply than overlying rocks of the upper sedimentary and volcanic sequence in Gold Dome Mine area, and rocks of the upper sedimentary and volcanic sequence locally buttress depositionally against the tuff. Thickness varies from few meters to >100 m. Dated elsewhere as 18.5 Ma (Nielson and others, 1990)

Ts **Sedimentary rocks (lower Miocene)**—Poorly bedded volcanic-clast conglomerate and sandstone. Yellowish to locally reddish. Near Jackpot Mine, matrix-supported, angular to subrounded, fines upward from coarse (to 2 m) boulders to cobbles and pebbles, includes white sandstone. Clasts are mafic to silicic volcanic rocks and minor porphyritic granite (resembles Yg). Includes thin flows of hornblende-plagioclase andesite and of jackstraw-textured plagioclase-phyric latite. Thickness 0–215 m. Forms paleovalley fill, along with intercalated basalt flows (Tvb), underlying thickest Peach Spring Tuff in The Needles area. Near Split Rock, includes section ~10 m thick that underlies some of the lower volcanic sequence (Tv)

Tv **Lower volcanic sequence (early Miocene)**—Includes subvolcanic intrusions. Lower part in the southern part of the quadrangle, dominated by mafic to intermediate flows; in central part of the quadrangle, includes thick green to reddish, andesitic, matrix-supported, mixed-volcanic-clast lahar agglomerate. Rest of unit is flows of basalt, basaltic andesite, and lesser porphyritic latite, andesite, dacite, and rhyolite; tuff; and volcanic-clast conglomerate. Tuffs and sedimentary rocks are dominant in the southeast; flows and agglomerate dominate in the north and west. A date of 20.5±0.7 Ma using $^{39}Ar/^{40}Ar$ was obtained on biotite from an agglomerate clast sampled 1.5 km southwest of Tumarion Peak; the clast is dacite in which the feldspar and groundmass experienced potassium metasomatism (J. Nakata, written commun., 1994, sample H89MH-12). Thickness 500–1,000 m. Overlies and contains interbeds of arkose and conglomerate unit (Tac) or is nonconformable on pre-Tertiary rocks. Overlain conformably by sedimentary rocks unit (Ts), by tuff and sedimentary rocks subunit (Tvts), or locally, by Peach Spring Tuff. Broadly correlates with volcanic rocks in nearby Mohave Mountains dated 19.8±0.6 Ma (whole-rock K-Ar; Nakata and others, 1990). Locally, divided into the following:

Tvb **Basalt flows**—In central and southeastern parts of quadrangle. Massive basalt. Flows as thick as several tens of meters. Includes aphyric basalt, olivine-phyric basalt, and mafic flows containing plagioclase microphenocrysts. Lithologically similar to higher basalt flows (Tfb) stratigraphically above Peach Spring Tuff. Thickness 0–80 m. Intercalated with sedimentary rocks unit (Ts) or directly underlies Peach Spring Tuff (Tp) and overlies tuff and sedimentary rocks (Tvts)

Tvbt **Basalt, tuff, and conglomerate**—In southeastern part of quadrangle. Basalt flows and light-colored silicic tuff. The basalt is extrusive equivalent of mafic intrusive rocks in unit Tvi, and the tuff is equivalent to tuff mapped separately as Tvt. Basaltic flows have intersertal to holocrystalline groundmass rich in plagioclase; some glassy samples show seriate size distribution of groundmass plagioclase. All flows contain plagioclase phenocrysts, and most flows also have sparse, large glomerocrysts of intergrown pyroxene grains. Olivine present as rare small grains, most of them altered to red clay. Red clay also forms veinlike masses within groundmass. Thickness ~80 m. Underlies Peach Spring Tuff

Tvt **Tuff**—In southeastern part of quadrangle. Light-colored silicic ashfall tuff and tuff breccia. Massive to thinly bedded, locally coarse-grained. Silicified zones ubiquitous. Thickness as much as 85 m. Underlies Peach Spring Tuff

Tvi **Volcanic and intrusive rocks**—In southeastern part of quadrangle. Tuff, sedimentary rocks, and lava flows (equivalent to Tvt, Tvts, Tvf, and Tvbt) intruded by abundant mafic sills and dikes (intrusive equivalent of Tvb). Tuff is replaced by jasper near abundant intrusions at the Yucca Mine and 1 km to the northwest

Tvts **Tuff and sedimentary rocks**—In southeastern part of quadrangle. Buff-colored ash-fall and ashflow tuff, conglomerate, and sandstone. Conglomerate clasts are crystalline and volcanic rocks. Thin basal red conglomerate and siltstone conformably overlie lava flows (Tv). Bulk of unit consists of tuffaceous conglomerate that intertongues with pumice-rich silicic welded tuff. Clast imbrication in tuff locally suggests ash-flow transport to the southwest. Replacement jasper is abundant in SE¼NW¼ sec. 18, T. 15 N., R. 20 W. Thickness ~150 m

Tvf **Lava flows**—Mapped in southeastern part of quadrangle. Mafic and intermediate flows and flow breccia. Largely basalt and basaltic andesite, and lesser andesite, dacite, and latite; predominantly porphyritic. Some light-colored intermediate flows have felted feldspar-rich groundmass and abundant magnetite grains, sparse plagioclase phenocrysts, and rare black pyroxene phenocrysts. Locally, these flows have trachytic texture. Other flows and flow breccias have very fine grained, plagioclase-rich groundmass that also contains apatite and magnetite and phenocrysts of plagioclase, hornblende (locally oxyhornblende), and biotite. Plagioclase phenocrysts may be as large as 6.5 mm; mafic minerals are smaller (hornblende 2 mm or less, biotite in smaller dispersed flakes). Hornblende grains may contain abundant needles of apatite. Massive flows are characterized by euhedral phenocrysts, but phenocrysts in flow breccia show incipient fragmentation. Darker flows consist of andesite or latite with plagioclase-rich groundmass, locally abundant, large (1 to 3 mm length) plagioclase phenocrysts, and smaller phenocrysts of dark-green pyroxene. Pyroxene phenocrysts are sparse or absent. Tabular plagioclase phenocrysts locally are aligned so that weathered outcrops display jackstraw texture. Mafic minerals are partly altered to red clay and hematite. Thickness 100–300 m. Rests nonconformably on pre-Tertiary rocks. Overlain conformably by the tuff and sedimentary rocks (Tvts) unit

Tac **Arkose and conglomerate (lower Miocene)**—In southern part of quadrangle. Red arkosic sandstone, which underlies the lower volcanic sequence or is underlain by a single basal volcanic flow of that sequence. Also includes coarse (to 4.5-m diameter) polymict gneiss-boulder conglomerate (derived from gneiss, unit Xg) interbedded with and overlying thick basal volcanic agglomerate in the lower volcanic sequence, for example, 3 km south-southwest of Tumarion Peak. Thickness 5–10 m

INTRUSIVE AND METAMORPHIC ROCKS

Ti **Hypabyssal intrusions (Miocene)**—Near center of quadrangle. Intermediate composition. Most prominent body is the Needle Mountain intrusion, including satellite dikes and sills, consisting of altered dacitic rock containing phenocrysts of biotite, feldspar, and minor quartz and apatite; contacts chilled against host Proterozoic gneiss; SiO_2 content 58% by weight (one sample). Needle Mountain intrusion defines a southwest-plunging synform and occupies a position near synclinal corner at base of Tertiary section where faulted against, and partly detached by, Gold Dome Fault Zone (John and Howard, 1994). Needle Mountain intrusion is faulted and brecciated less than adjacent Proterozoic rocks. Needle Mountain intrusion dated 15.8±0.4 Ma by K-Ar on fresh biotite (J.K. Nakata, written commun. 1994); potassium-metasomatism of groundmass and some phases in the dated rock is indicated by whole-rock K_2O content 15 times greater than Na_2O content

Tmi **Mafic intrusive rocks (Miocene)**—In southeastern part of quadrangle. Groups of sills and dikes hosted by units of lower volcanic sequence. Unmapped similar intrusions also occur in other Miocene volcanic units, especially Tvi

Tdl **Light-colored dikes (Miocene)**—Leucocratic dacitic dikes mostly 2.5 to 15 m thick. Plagioclase and rare rounded quartz phenocrysts, about 1 mm in diameter. Cuts lamprophyre dikes (TKl), biotite granodiorite (Kcb), and older units. East-striking dike in central part of quadrangle cuts a Miocene(?) fault parallel to Gold Dome Fault Zone

Tdm **Mafic dikes (Miocene)**—Dikes of mafic rocks, including lamprophyre, that intrude pre-Tertiary host rocks. Locally vesicular. Locally has trachytic texture. Some unmapped dikes intrude Miocene faults in the Gold Dome and other fault zones. Thickness of mapped and unmapped dikes ranges from 0.4 to 3 m, averages 1 m

Dike swarm of Chemehuevi Mountains—Intrudes Chemehuevi Mountains Plutonic Suite and other rocks below the Chemehuevi Detachment Fault. May represent beheaded equivalents of some dikes exposed east of and above that fault. Dike thickness varies from centimeters to ~10 m. Mapped in part from aerial photographs. Subdivided by orientation into two units, based on field observation that most northeast-striking dikes are cut by northwest-striking dikes and most northeast-striking dikes are diabase or lamprophyre, whereas northwest-striking dikes include a wider lithologic variety. Subdivided into the following:

Tcd **Northwest-striking dikes (Miocene)**—Andesite, biotite dacite porphyry, diabase, appinite, coarse-grained hornblende diorite, and rare fine-grained basalt. Commonly weathers gray to tan

TKcd **Northeast-striking dikes (Tertiary or Late Cretaceous)**—Primarily fine- to medium-grained, subophitic diabase and lamprophyre containing two generations of mafic minerals. Includes rare biotite and hornblende-biotite dacite dikes in the central Chemehuevi Mountains. May correlate in part with similarly oriented lamprophyre dikes (TKl) and some other dark dikes (TYd) above the Chemehuevi Detachment Fault. Suspected to be mostly Cretaceous on the basis of lithology and orientation, but could be Tertiary or include both ages

TKl **Lamprophyre dikes (Tertiary or Late Cretaceous)**—In east-central part of map area. Steeply northwest-dipping biotite lamprophyre dikes, typically 1 to 1.5 m thick and occurring as families of closely spaced parallel dikes of dark rock containing 1- to 4-mm hornblende and bronze-colored (locally poikilitic) biotite phenocrysts in fine-grained (0.2 mm) matrix. Locally spherulitic, exhibits elongate amygdules, and has finer grained chilled margins. Cuts Powell Peak pluton (Kcb). (Unmapped subhorizontal lamprophyre dikes also cut the northeastern part of the Powell Peak pluton.) Cut by light-colored dike (Tdl). Suspected to be Cretaceous on the basis of lithology and orientation, but could be Tertiary or include both ages

TKq **Quartz porphyry (Tertiary or Late Cretaceous)**—Light-colored micrograniitic rock. Very fine grained (0.05–0.01 mm) groundmass. Euhedral phenocrysts (as much as 35%) of quartz and commonly biotite (as large as 3 mm), sphene, plagioclase, and orthoclase (as large as 8 mm). Forms small stocks or irregular bodies that are elongate east-west, and a northeast-striking dike. Cuts biotite granodiorite (Kcb) and Proterozoic rocks

TKf **Fine-grained granite (Tertiary or Late Cretaceous)**—Forms two small stocks in central part of map area. Fine-grained, very light gray, equigranular biotite granite. Cuts Proterozoic gneiss (Xg)

TYd **Dark dikes, undivided (Tertiary to Proterozoic)**—Mapped largely from aerial photographs. Includes lamprophyre and dacite dikes. Some cut biotite granodiorite (Kcb)

Whale Mountain sequence of John (1987b)

TKwq **Quartz monzonite (Miocene and Cretaceous(?))**—Hornblende-biotite quartz monzonite, granodiorite, and granite in the northwestern part of quadrangle.

Typically exhibits mylonitic fabric. Much of unit characterized by unzoned microcline megacrysts as large as 3 cm and mafic enclaves that make up as much as 10 percent of the rock volume. Small included sheets of mylonitic two-mica±garnet granite occur in Bat Cave Wash, 1 km southwest of Topock. Ion-probe U-Pb age on zircon (table 1) is 19.4±0.4 Ma for strongly foliated, chloritic, hornblende-biotite granodiorite at the mouth of Bat Cave Wash (sample H12WM-10) and is 19.0±0.3 Ma for mylonitic and chloritic, hornblende-biotite feldspar-phyric granite 1.7 km west of quadrangle (sample H12WM-9), mapped as part of the same unit by John (1987b)

Chemehuevi Mountains Plutonic Suite (Late Cretaceous)—Named and analyzed petrologically by John and Wooden (1990). Forms Chemehuevi Mountains batholith in western part of quadrangle and adjoining areas and detached small plutons in eastern part of quadrangle. Late Cretaceous age indicated by U-Pb study of zircon on four samples west of the quadrangle (John and Mukasa, 1990) and a sample in the east half of the quadrangle (this report)

Kcc **Chemehuevi Peak Granodiorite—**Medium- to coarse-grained, subporphyritic to porphyritic biotite granodiorite and monzogranite. Zoned, elongate microcline megacrysts, as long as 6 cm, make up as much as 40 percent of the rock. Contains 5–12 percent biotite, accessory coarse sphene and allanite-cored epidote euhedra (to 2 mm), and rare primary muscovite. Along the eastern margin or floor of the Chemehuevi Mountains batholith, the unit is characterized by discontinuous bands 10–20 cm wide of plagioclase+K-feldspar+quartz and biotite-rich bands 2–5 cm thick. John and Mukasa (1990) interpreted the crystallization age from U-Pb study of zircon as 68±6 Ma

Kcb **Biotite granodiorite**—In western part of map, forms part of Chemehuevi Mountains batholith. Light-gray to tan, subequigranular biotite granodiorite; lacks mylonitic fabric. Biotite most abundant mafic phase (to 12%), typically euhedral (to 5 mm diameter) and associated with rare blue-green hornblende. Sphene (to 2%) occurs as euhedral crystals as large as 2 mm and as overgrowths on magnetite.

In eastern part of map, forms Powell Peak pluton, a small outlier 1 km west of Powell Peak, and the small Borrow Pit body 3.5 km northwest of Powell Peak. Light-gray, medium-grained (2–3 mm), equigranular granodiorite to, locally, monzogranite. Rarely contains K-feldspar phenocrysts 5 mm across. Feldspars white. Plagioclase shows oscillatory zoning. Biotite content 5–9%, mostly 6–7%. Contains small amount of hornblende in some northwestern exposures of Powell Peak Pluton and western exposures of Borrow Pit body. Contains abundant accessory sphene and sparse allanite. Hypidiomorphic granular. Small outlier 1 km west of Powell Peak is fine-grained porphyrytic rock, with interstitial quartz and rare quartz phenocrysts 2 mm across. SiO_2 68% for a sample from the Powell Peak pluton (John and Wooden, 1990, sample H80Mh-287) and 67% for a sample from the Borrow Pit body. Locally interleaved with adjacent gneisses or extends many apophyses into gneisses. Veins, alteration, and intrusive breccia originating from the Borrow Pit body affect the diorite of Topock (Kt), indicating that the diorite of Topock is older. Powell Peak Pluton shows chilled fine-grained porphyritic textures against the hornblende-biotite granodiorite (Kch) and intrudes the diorite (Kd) and adjacent quartz monzonite (KYq), which locally exhibits hornfels recrystallization. Southeast of Powell Peak, has thin, gently east-southeast-dipping mylonitic gneiss zone exhibiting northeast-trending lineation. Ion-probe U-Pb age on zircon 74.6±1.1 Ma from the Borrow Pit body (sample H89MH-47 in table 1). Small body 1.3 km west of Powell Peak (quartz monzodiorite porphyry) yielded a 72.0±1.8 Ma K-Ar date on biotite (sample H81MH-154 of Nakata and others, 1990)

Kcg **Porphyritic hornblende-biotite granodiorite**—Forms border unit of the Chemehuevi Mountains batholith in western part of quadrangle. Gray, medium-grained, quartz-poor, variably porphyritic. Equant microcline megacrysts to 1 cm diameter; 4–20% stubby blue-green hornblende; 2–5% euhedral biotite; 1–3% coarse sphene; accessory magnetite, allanite, epidote, and zircon. Epidote considered late magmatic based on textural relations. The granodiorite bears mylonitic foliation and subhorizontal lineation

Kch **Hornblende-biotite granodiorite**—Forms a small body bordering the Powell Peak pluton 1 km south of Powell Peak. Gray, medium-grained, equigranular hornblende-biotite granodiorite; contains accessory sphene. Mafic minerals (~25% of rock) clotted in anhedral masses. Aligned mafic minerals define vague igneous foliation. Intruded by biotite granodiorite (Kcb) in Powell Peak pluton and considered to be a border phase of that pluton

Kd **Diorite (Late Cretaceous)**—In the northeastern part of quadrangle. Medium-grained (2–5 mm), equigranular biotite-hornblende diorite to quartz diorite. Mafic minerals 15–35%. Subhedral to euhedral, bronze-colored biotite and black hornblende. SiO_2 content (one sample) 58 percent. Contains abundant inclusions and screens of gneiss and amphibolite. Primary foliation parallels steep southern intrusive contact against the older KYg unit. Also cuts diabase unit (Yd). Intruded by biotite granodiorite (Kcb) unit, although Kcb yielded a slightly older U-Pb age (table 1). U-Pb age on zircon 72.7±0.9 Ma (Kd sample H12TO-1, table 1). Resembles part of the Whale Mountain sequence of John (1987b) and John and Wooden (1990) west of the quadrangle

Kt **Diorite of Topock (Cretaceous(?))**—Forms small (1-km) pluton and satellite bodies in north-central part of the area. Dark-gray, fine-grained (0.2–0.3 mm) biotite-hornblende microdiorite to micro-quartz diorite and micro-granodiorite. Color index 10–30%. Biotite is conspicuous in outcrop, locally poikilitic. In thin section, plagioclase laths show trachytic texture. Silica content (one analyzed sample*)* 57%; percentages of other major elements dissimilar from diorite (Kd) and from Whale Mountain sequence of John (1987b) as analyzed by John and Wooden (1990). Intrudes Proterozoic gneiss and granite and is intruded by biotite granodiorite (Kcb) unit (Borrow Pit body) and abundant (mostly unmapped) Tertiary dikes

KYg **Granite (Cretaceous or Mesoproterozoic)**—North of Powell Peak in northeastern part of quadrangle. Biotite to hornblende-biotite monzogranite. Equigranular; grain size 2–4 mm. Mafic crystals appear ragged. Color index about 5%. Intruded by diorite (Kd) and biotite granodiorite (Kcb); intrudes or is gradational with quartz monzodiorite (KYq)

KYq **Quartz monzodiorite (Cretaceous or Mesoproterozoic)**—North of Powell Peak in northeastern part of map area. Equigranular hornblende-biotite quartz monzodiorite to tonalite. Grain size dominantly 2–3 mm with subequant hornblende as long as 4 mm. Feldspar gray to pale purplish. Color index 15–20%. Mafic minerals appear ragged or clotted in hand specimen. Hornblende is rimmed by biotite. Hypidiomorphic granular in thin section. Intruded by diorite (Kd) and biotite granodiorite (Kcb)

Yd **Diabase (Mesoproterozoic)**—Intrusive sheets averaging 3 m thick. Margins commonly sheared. Very dark gray rock. Ophitic texture; white plagioclase laths 2–5 mm long set in a black groundmass mostly of uralitic amphibole secondary after pyroxene. Most sheets are steep, strike northwest, and restore to subhorizontal orientation before Miocene tilting (John and Howard, 1994; fig. 8). In thickest (45 m) sheet, the plagioclase grains are locally concentrated in patches near the southwest side inferred to be the original top and are as long as 10 mm (NW¼ sec. 25, T. 16 N., R. 20½ W.). Also shown where mappable diabase dike relics are identified within Miocene deposits of megabreccia. Correlated with diabase widely distributed across Arizona and southeastern California dated about 1.1 Ga (Howard, 1991; Hammond, 1991)

Yg **Granite (Mesoproterozoic)**—In north-central part of map area. Coarse-grained gray to red biotite-hornblende syenogranite and monzogranite containing aligned tabular K-feldspar phenocrysts and lesser medium-grained gray granite and quartz monzodiorite. Sphene bearing. Mafic minerals recrystallized (hornfelsed?). Locally foliated. Contains xenoliths including leucocratic gneiss and black quartzite. Cut by diabase (Yd), diorite of Topock (Kt), and younger dikes

Xgm **Mylonitic gneiss and migmatite (Paleoproterozoic protolith)**—In Chemehuevi Mountains below Chemehuevi Detachment Fault. Mylonitic, heterogeneous crystalline rocks including migmatite, granite, and amphibolite-facies orthogneiss and paragneiss. Commonly intruded by light-tone granitic dikes and sheets, including (unmapped) satellites to the Chemehuevi Mountains Plutonic Suite. Mylonitic foliation mostly dips gently southwest; west-southwest-striking mylonitic lineation locally present. Mylonitic texture is Cretaceous (John, 1987a) and, locally, Miocene in age

Xag **Augen gneiss (Paleoproterozoic)**—Forms large elongate dike-like pluton in east-central part of quadrangle and small bodies in other southern parts of quadrangle. Medium-gray to brownish; locally dark gray. Coarse-grained; K-feldspar megacrysts. Hornblende-biotite granodiorite to quartz monzodiorite in composition. Mafic mineral content 14–25%, greater where margin of main pluton is locally dioritic and fine grained (chilled) against older gneissic pegmatite. Contains inclusions of biotite gneiss, amphibolite, and leucocratic gneiss. Cut by mapped and unmapped pegmatite dikes. Apophyses and dikes of augen gneiss from the large pluton cut across the foliation of adjacent leucocratic gneiss in the gneiss (Xg) unit. Biotite K-Ar age of 863±22 Ma and zircon fission-track age of 73.8±7.5 Ma considered to be cooling dates younger than age of crystallization (Nakata and others, 1990, sample H81MH-155). Resembles rocks dated as 1.64 Ga by U-Pb in the Bill Williams Mountains by Wooden and Miller (1990)

Xg **Gneiss (Paleoproterozoic)**—Heterogeneous. Includes layered to massive, fine-grained, gray biotite granite gneiss, amphibolite, mafic gneiss, biotite schist, and black impure quartzite, all cut by younger leucocratic granite gneiss, gray biotite granite gneiss, and pegmatite. Unit locally subdivided according to dominant rock type; subunit boundaries gradational, approximately located, and cannot be used to calculate fault separations. Locally, subdivided into the following:

Xgp **Pegmatite and granite gneiss**—In southeastern part of map. Medium-grained, medium-gray, poorly foliated, massive biotite (±garnet) monzogranite to granodiorite gneiss (metamorphic texture; color index 6%) and crosscutting garnet-bearing white pegmatite. Cut by diabase (Yd) unit and much of unit probably cut by augen gneiss (Xag), but unit as mapped includes pegmatite dikes that cut the augen gneiss

Xgl **Leucocratic gneiss**—Very light gray, medium-grained leucocratic granite gneiss and crosscutting pegmatite. Both lithotypes commonly spotted with coarse (as wide as 1.5 cm) garnets or chlorite pseudomorphs after garnet

Xga **Amphibolite**—Two mapped patches in east-central part of quadrangle. Foliated hornblende-plagioclase rock. Smaller amphibolite bodies are common within the other mapped gneiss units

Xgs **Mixed granite gneiss and metasedimentary rocks**—Two patches, in east-central and southeastern parts of quadrangle. Granite gneiss and lesser seams or layers of supracrustal biotite schist, garnet-biotite gneiss, and black feldspathic biotite quartzite

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