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Geological Society of America
Field Guide 6
2005

Birth of the lower Colorado River—Stratigraphic and geomorphic evidence for its inception near the conjunction of Nevada, Arizona, and California

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ABSTRACT

A detailed record of the late Cenozoic history of the lower Colorado River can be inferred from alluvial and (likely) lacustrine stratigraphy exposed in dissected alluvial basins below the mouth of the Grand Canyon. Numerous sites in Mohave, Cottonwood, and Detrital valleys contain stratigraphic records that directly bear on the mode, timing, and consequences of the river's inception and integration in the latest Miocene–early Pliocene and its subsequent evolution through the Pleistocene. This field trip guide describes and illustrates many of these key stratigraphic relationships and, in particular, highlights evidence that supports the hypothesis of cascading lake-overflow as the principal formative mechanism of the river's course downstream from the Grand Canyon.

Keywords: Colorado River, Bouse Formation, Chemehuevi Formation, flood, stratigraphy.

House, P.K., Pearthree, P.A., Howard, K.A., Bell, J.W., Perkins, M.E., Faulds, J.E., and Brock, A.L., 2005, Birth of the lower Colorado River—Stratigraphic and geomorphic evidence for its inception near the conjunction of Nevada, Arizona, and California, *in* Pederson, J., and Dehler, C.M., eds., Interior Western United States: Geological Society of America Field Guide 6, p. 357–387, doi: 10.1130/2005.fld006(17). For permission to copy, contact editing@geosociety.org. © 2005 Geological Society of America

INTRODUCTION

Many details about the mode, timing, and consequences of the inception of the lower Colorado River have eluded geologists for the past 150 years. Much of the research into the problem has focused on the Grand Canyon because of its spectacular setting, but the dominance of erosion there limits the amount and kind of information that can be gleaned about the river's history. Valleys downstream from the Grand Canyon, however, contain extensive exposures of a corresponding record of river and tributary deposition. That record is, in turn, superposed on a preriver stratigraphic framework that documents the environments into which the river first flowed. The composite record supports a robust model of lower Colorado River evolution over the past 5–6 m.y.

The principal geographic focus of this field trip guide is the Cottonwood Valley–Mohave Valley reach of the lower Colorado River (Fig. 1). Here, the river drains an ~169,300 mi^2 (433,000 km^2) watershed that has undergone a series of major changes during the late Cenozoic, including: large-scale drainage integration, excavation of numerous canyons upstream, and multiple climatic changes. Aspects of these events are revealed in extensive exposures of late Cenozoic sedimentary deposits and landforms in Cottonwood and Mohave valleys. Recent detailed mapping of these deposits reveals a richer and more complex record than has been previously known (Faulds et al., 2004; House et al., 2002, 2004a; Faulds and House, 2000; Pearthree and House, 2004).

Basic Geologic Setting of the Lower Colorado River

The lower Colorado River extends from the mouth of the Grand Canyon at the western edge of the Colorado Plateau to the Gulf of California, traversing a series of rugged bedrock canyons separated by relatively broad, elongate alluvial basins typical of the Basin and Range province. The basins are the product of large-scale, regional crustal extension between ca. 25 and 10 Ma (Anderson, 1971; Howard and John, 1987; Spencer and Reynolds, 1989). The river follows a Miocene extensional corridor between Hoover Dam and Parker whose 50–100 km east-west width was doubled by crustal stretching. This extension resulted in tilted fault blocks, many normal faults, and metamorphic core complexes.

The modern course of the Colorado River through this extensional terrain is relatively young. Geologic relations at the western end of Grand Canyon indicate that an integrated Colorado River did not exist prior to 5.6–6 Ma (e.g., Lucchitta, 1979; Spencer et al., 2001; Faulds et al., 2002; Howard et al., 2000); but lava flows intercalated with river gravels within ~110 m of its modern level west of Grand Canyon indicate that it was established by 4.7–4.4 Ma (Howard and Bohannon, 2001). Sedimentologic and paleomagnetic data from the river's early delta in the Salton Trough area indicate its arrival in that area before 4.3 Ma (Johnson et al., 1983). Relations that we have discovered in Cottonwood and Mohave valleys are similar and preclude the presence of a throughgoing major river prior to 5.5 Ma, but require it before 4 Ma.

In the various canyons between Lake Mead and Yuma, deposits of Colorado River gravel occur up to 250 m (800 ft) above the modern river, and discernible bedrock straths and paleochannel features are found at similar and progressively lower levels. Intervening alluvial valleys along the river's modern course contain similarly high fluvial deposits, flights of younger fluvial terraces, and successions of fluvial scarps. As many as seven prominent terrace levels occur along the river, ranging from the modern floodplain 2–10 m above the active channel to the oldest well-preserved terrace that stands ~110 m above the river in Mohave Valley. Higher and older remnant river deposits provide an important component to understanding the early history of the lower Colorado River.

Cottonwood Valley, Pyramid Canyon, and Mohave Valley

A detailed geologic record of the river's late Cenozoic history is preserved along the reach of the lower Colorado River through southern Cottonwood Valley, Pyramid Canyon, and Mohave Valley (Fig. 1). The western edge of this area is bounded by a series of mountain blocks underlain predominantly by Miocene plutonic rocks with a variable cover of Miocene volcanic rocks. The eastern edge is bounded by the Black Mountains, a complex of Proterozoic basement (largely granite and gneiss) with a locally thick cover of Miocene volcanic and minor sedimentary rocks. Mohave and Cottonwood valleys are separated by the "Pyramid hills" (informal name), a relatively low set of rugged bedrock hills that straddle the valley axis between the Black and Newberry mountains. The Pyramid hills are cored by the Davis Dam granite (Faulds et al., 2004), a megacrystic Precambrian granite porphyry. The south end of Mohave Valley abruptly terminates at Topock Gorge, a narrow canyon between the Mohave (east) and Chemehuevi (west) mountains. Mohave Valley is broad and contains extensive exposures of river deposits, late Cenozoic basin fill, and a suite of fluvial landforms. Southern Cottonwood Valley is narrower and is dominated by steeply sloping alluvial fan remnants that flank the shores of Lake Mohave. Post-Miocene tectonic activity in both valleys has been minor. Small faults and some minor tilting have been noted in some late Tertiary basin fill deposits near Laughlin and north of Katherine's Landing. In southern Mohave Valley, structural perturbation of early to middle Pleistocene alluvial fan deposits is clearly evident on the distal end of the Warm Springs fan complex near Golden Shores, Arizona (Purcell and Miller, 1980; Pearthree et al., 1983).

Previous Work on Lower Colorado River Stratigraphy

The late Cenozoic alluvial stratigraphy of Mohave and Cottonwood valleys has been studied and described in various levels of detail beginning with the first geologic observations by Newberry in 1857–1858 (*in* Ives, 1861). Subsequently, a more detailed stratigraphic framework began to evolve from Lee (1908), Blackwelder (1934), Longwell (1936, 1947, 1963), and

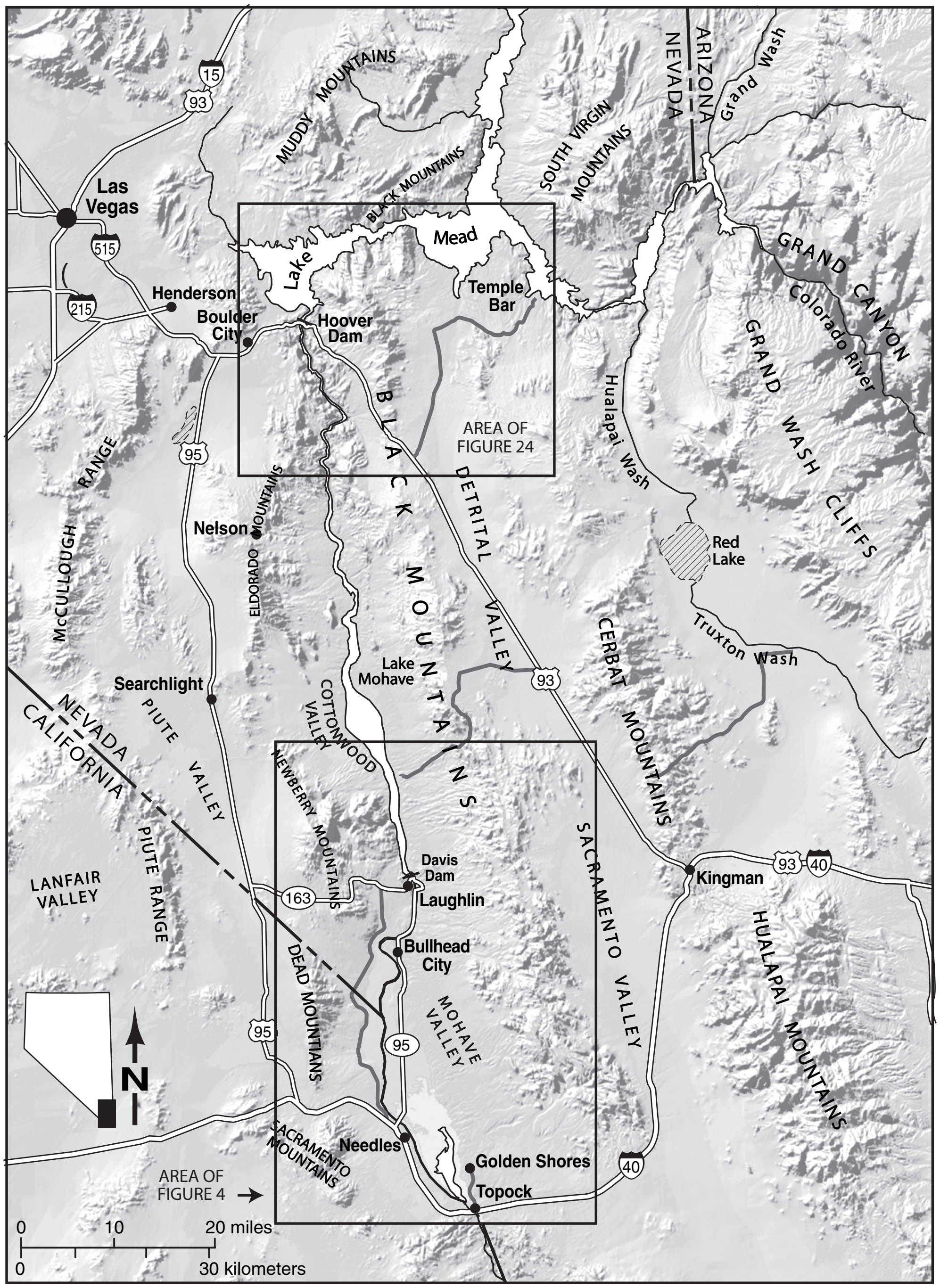

Figure 1. Regional map of the field trip area.

Metzger et al. (1973). The previous work on the river's alluvial stratigraphic record and underlying basin deposits has provided an essential foundation for our detailed studies in the Laughlin area (Fig. 2).

Early reports on the geomorphology of the lower Colorado River (Newberry, 1861, *in* Ives, 1861; Lee, 1908) emphasized fluvial terraces and described 3–5 distinct levels in Mohave Valley. Lee (1908) developed a model of river evolution involving three canyon cutting intervals separated by three major aggradation events. He used the term Chemehuevis gravels for the most conspicuous fill deposits along the river, which were associated with his second major aggradation event. He proposed that the aggradational packages were responses to climatic control. Blackwelder (1933) counted 9–12 distinct terrace levels in the Yuma area and tentatively attributed them to climatic changes or eustatic changes in the Gulf of California. Longwell (1936) investigated

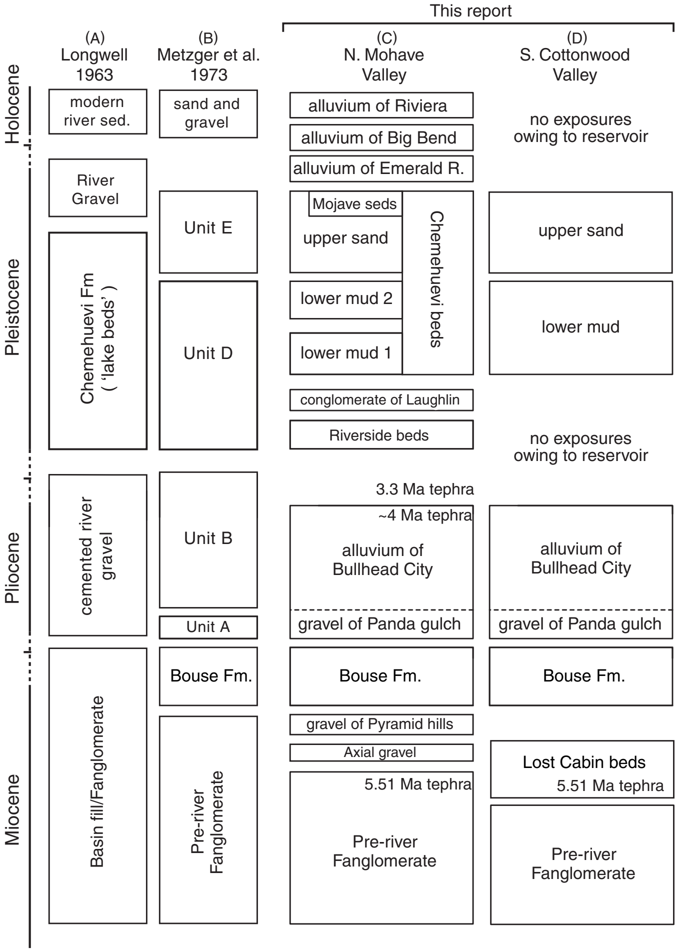

Figure 2. Comparison of various conceptions of the late Cenozoic stratigraphy of the lower Colorado River. Coeval and intervening tributary alluvial fan deposits not shown. Fm—Formation.

the Colorado River deposits in great detail in what is now the Lake Mead area prior to the construction of Hoover Dam. He identified as many as seven levels of alluvial terraces along the river and highlighted the apparent significance of what he renamed the Chemehuevi Formation, which he presumed was a major Pleistocene aggradation package (Fig. 2A). He attributed the river's stratigraphic record to climate variability, but also proposed a lacustrine model for the Chemehuevi Formation associated with some form of downstream blockage (Longwell, 1947, 1963).

In a series of regional hydrogeologic studies, Metzger et al. (1973), Metzger and Loeltz (1973), and Olmstead et al. (1973) evaluated Colorado River deposits from Davis Dam to Yuma and developed the most robust stratigraphic framework for the river's history up to that time (Fig. 2B). It strongly influenced subsequent studies in the 1970s and was augmented by Lee and Bell (1975), Bell et al. (1978), and Ku et al. (1979), who developed some of the first age-controls on key river deposits and related piedmont geomorphic surfaces using U-series, amino acid racemization, and radiometric techniques. Lucchitta (1979) drew upon this framework to link the integration of the lower Colorado River with the development of the Colorado River through Grand Canyon. The resulting paradigm, here called the Metzger model, represents a synthesis of many of the concepts introduced by previous investigators, invoking three major aggradation intervals and three major degradation intervals.

The Metzger model (Fig. 2B), coupled with previously published geochronologic data and interpretations, can be summarized into the following stages:

1. Subsidence of a trough along the course of the lower Colorado River and incursion of an arm of the developing Gulf of California in the late Miocene to early Pliocene resulted in deposition of the Bouse Formation (Metzger, 1968).
2. Integration of the Colorado River sometime after 6.0 Ma (Metzger, 1968; Damon et al., 1978); regional uplift combined with deposition associated with the arrival of the river forced the arm of the sea back to the south (Lucchitta, 1979).
3. Canyon cutting followed by massive backfilling of sand and gravel sometime in the early Pliocene through early to middle Pleistocene time (between ca. 4.4 Ma and 700 ka) (Damon et al., 1978; Kukla, 1975); Unit B, first major aggradation.
4. Deep incision into the previous valley-filling deposits.
5. Backfilling with predominantly fine-grained sediments during the middle or late Pleistocene (the Chemehuevi Formation; ca. 700 ka to 35 ka) (Kukla, 1975; Bell et al., 1978; Blair, 1996; Lundstrom et al., 2000, 2004); Unit D, second major aggradation.
6. Progressive incision into the Chemehuevi fill interrupted by periods of stability and stream-terrace formation at discrete elevations above the river (one prominent level was dated as ca. 80 ka; Ku et al. [1979]).
7. Backfilling with channel and floodplain deposits to form the modern river environment (under way by ca. 8 ka); third major aggradation (Metzger et al., 1973).

AN EVOLVING MODEL OF THE LATE CENOZOIC HISTORY OF THE LOWER COLORADO RIVER

The existing data and concepts regarding the history of the lower Colorado River described above in the context of the Metzger model can be combined with recently identified geologic relations seen on this trip to formulate a more detailed working model of river inception and evolution over the past 5–6 m.y. (Figs. 2C and 2D).

River Inception—By Lake or by Sea?

The means by which the lower Colorado River developed its modern course remains the subject of debate. There are two contrasting models: (1) subsidence linked with early rifting in the Gulf of California extending up the lower Colorado River valley, driving headward erosion that led to the progressive capture of upstream drainage systems (e.g., Lucchitta, 1972, 1979, 1998; Buising, 1990; Lucchitta et al., 2001); and (2) cascading lake-spillover driven by upstream controls (e.g., Spencer and Patchett, 1997; Meek and Douglass, 2001). General versions of these two contrasting models were initially postulated by Blackwelder (1934) when he compared the dual possibilities that the river carved its valleys in response to regional uplift from near sea level or his preferred interpretation that the river formed via cascading lake-spillover. Geologic relations described in this guide are most consistent with the lacustrine spillover model.

The crux of both models lies in their interpretation of the depositional environment of the Pliocene Bouse Formation (Metzger, 1968)—an enigmatic stratigraphic unit restricted largely to the river corridor and almost certainly linked with the river's early inception (Lucchitta, 1972, 1979; Buising, 1990). The Bouse Formation typically has a thin basal deposit of marl or limestone overlain by varying amounts of mud, sand, and minor gravel, and by tufa lining the valley walls. It has been found in the string of basins along the river from Cottonwood Valley to downstream of Yuma (Metzger, 1968; Irelan et al., 1973). Its highest remnants are at ~330 m (~1082 ft) in the reach from Lake Havasu southward to the Chocolate Mountains of California and are well below sea level south of Yuma. In Mohave and Cottonwood Valleys, Bouse deposits have been documented as high as 550 m (1804 ft) in several locales. Bouse deposits are commonly thin where exposed along valley margins, but have been inferred to be several hundred meters thick in the subsurface in several basins along the lower Colorado River (Metzger et al., 1973; Metzger and Loeltz, 1973). At some locations Bouse deposits are interbedded with locally derived fanglomerates and early Colorado River deposits (Metzger, 1968; Dickey et al., 1980; Buising, 1990).

The age of the Bouse Formation was initially estimated to be early to late Pliocene (Metzger, 1968; Carr, 1991). From results of our recent investigations, we can constrain its maximum age in Cottonwood and Mohave valleys to <5.5 Ma based on geochemical correlation of an underlying tephra to the 5.51 ± 0.13 Ma Connant Creek ash bed from the Heise Volcanic Field (Morgan and McIntosh, 2005).[1]

An exclusively marine-estuarine interpretation of the Bouse Formation, as suggested by paleontologic evidence (Metzger, 1968; Lucchitta et al., 2001), requires that a marine embayment extended from south of Yuma into Cottonwood Valley. Bouse outcrops as high as 550 m elevation near its northernmost known extent in Cottonwood Valley require at least that much regional uplift in the past 5.5 m.y. (Lucchitta, 1979). In this model, regional subsidence that permitted a marine intrusion up the future course of the lower Colorado River also drove headward erosion of a regional drainage system upstream, which resulted in eventual capture of a proto–Colorado River near the western edge of the Colorado Plateau (Lucchitta, 1979; Lucchitta et al., 2001). The deep incision along the lower Colorado River after drainage integration is interpreted as a long-term response to regional uplift.

Some of the difficulties posed to this model will be explored during this field trip. They include the following:

1. Headward erosion by a local or subregional drainage hypothetically proceeded rapidly from the upper end of the proposed marine embayment in Cottonwood Valley into the Colorado Plateau and breached several bedrock divides as it worked its way to the north and east, all without significantly impacting or exploiting tributary and closed basins immediately to the east and west of the lower Colorado River (e.g., Spencer and Pearthree, 2001).
2. The lowest portions of Mohave Valley must have subsided well below sea level by the end of the Miocene to allow the sea to transgress, only to rise in the past 5 m.y. to its current elevation, all in the apparent absence of concurrent major normal faulting.
3. The maximum elevations of the Bouse Formation do not gradually increase to the north, rather they increase abruptly north of Yuma and again at Topock Gorge (Spencer et al., 2005).
4. Strontium isotope ratios in Bouse deposits are more similar to modern Colorado River values than to marine values (Spencer and Patchett, 1997; Poulson and John, 2003).
5. New age controls indicate that the postulated marine incursion, river inception, river aggradation, uplift, and substantial valley carving would have to have transpired in a narrow window of time between 5.5 and ca. 3.3 Ma.
6. Major aggradation along the lower Colorado River postdates Bouse deposition and had to have occurred concurrently with the hypothesized regional uplift. Valleys were sites of major aggradation, not downcutting, immediately after the arrival of the river.

The cascading lake-spillover model invokes headwater processes and requires no regional subsidence or uplift. In this model, some type of drainage rearrangement along the ancestral upper Colorado, possibly overflow from a terminal basin on the Colorado Plateau (e.g., Scarborough, 2001), ultimately resulted in divide-breaching in the eastern Grand Canyon area in the late Miocene. The Colorado River then developed a course through what is now the Grand Canyon and spilled into Grand Wash Trough and the Lake Mead area. Eventually, a divide in the Hoover Dam area was overtopped and the incipient Colorado River spilled through the series of basins along its modern course. The Bouse deposits found along the lower Colorado River thus may record a series of relatively deep, short-lived lakes fed by the earliest arrival of Colorado River water into the region. This model is bolstered by strontium isotope ratios in sediments and shells from the Bouse Formation that are consistent with lacustrine basins fed by the Colorado River and are inconsistent with marine influence (Spencer and Patchett, 1997; Gross et al., 2001).

The basic premise of the lake-spillover model has been criticized by proponents of the marine incursion hypothesis

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[1] Previously, we have linked this bed to the related, but slightly older Wolverine Creek bed (e.g., various abstracts), but the geochemical distinction is difficult to make because the compositions are essentially identical.

largely on the basis of paleontologic evidence from the Parker area southward (e.g., Lucchitta et al., 2001), and the possibility of postdepositional alteration of carbonate Sr isotope ratios (Lucchitta, 1998). Until recently, however, no unequivocal stratigraphic evidence had been found along the lower Colorado River to strongly support either mode of river inception.

This field trip guide describes sites on both sides of the paleodivide between Cottonwood and Mohave valleys that exhibit stratigraphic evidence consistent with the lake-spillover model (Figs. 2C and 2D; Faulds et al., 2004; House et al., 2004b). In the northern Mohave Valley, a coarse fluvial conglomerate derived from a nearby, upstream source (the gravel of Pyramid hills) unconformably overlies a thick-sequence local Miocene fanglomerate and axial channel gravels and, in turn, is conformably overlain by the Bouse Formation (Fig. 2C). The foregoing sequence is, in turn, unconformably overlain and deeply incised by an intricately bedded fluvial deposit of the early Colorado River. Its base (the gravel of Panda gulch), is less than 20 m above modern river level and forms the lowest part of a thick deposit of Colorado River alluvium (alluvium of Bullhead City) that is interbedded with tributary fan gravel ~230 m higher above the river. The composite section reflects a sequence of a local basin conveying a large flood, followed by deep inundation, followed by development of a major through-going drainage.

The stratigraphic sequence in southern Cottonwood Valley closely parallels and complements the Mohave Valley record (Fig. 2D). There, the late Miocene fanglomerate sequence grades upward into a conspicuous sequence of flat-bedded mudstone and sandstone (the Lost Cabin beds) with characteristics of lacustrine and low-energy fluvial deposition. A minor unconformity at the top of the fine-grained Lost Cabin beds is overlain by the Bouse Formation, which is, in turn, overlain along a major unconformity by the deposits of the early Colorado River (alluvium of Bullhead City). This composite record reflects a sequence of two phases of inundation of Cottonwood Valley followed by the development of a major, through-going drainage. We suspect that the first phase of inundation terminated with the flood associated with the gravel of Pyramid hills (lake-spillover) and that the second phase of inundation involved the deposition of the Bouse Formation in both valleys.

Our recent mapping efforts have also contributed to the clarification of the chronology of this sequence of events. Tephra deposits found in fanglomerate in Mohave Valley and in the Lost Cabin beds in Cottonwood Valley constrain the age of Bouse deposition to <5.5 Ma. We discovered a 4.2–3.6 Ma tephra bed in the upper 30 m of the alluvium of Bullhead City on the piedmont of the Black Mountains (Faulds et al., 2002). This tephra indicates a maximum age for the culmination of the primary river aggradation phase. We also found a 3.3 Ma tephra bed in younger alluvial deposits that truncate the upper part of the thick river fill which indicates that the river had begun to incise by this time. These temporal constraints on river inception and early evolution are similar to those developed for the Colorado River at the mouth of Grand Canyon described previously, and the overlap strongly suggests a linkage between canyon incision upstream and thick aggradation in valleys downstream.

Pleistocene History of the Lower Colorado River in the Field Trip Area

The bed of the lower Colorado River through Cottonwood and Mohave valleys was roughly 250 m higher than the modern river by the middle Pliocene. The river subsequently downcut several hundred meters to near the pre-integration valley elevation. A tremendous amount of sediment must have been removed during this period, but the duration of the episode is not well constrained. Suites of progressively lower terrace remnants and coeval alluvial fans that exhibit strong carbonate soils (Stages V+ and VI) suggest that much of deep incision may have transpired in the late Pliocene into the early Pleistocene.

Our recent mapping in the Laughlin area has revealed evidence for at least 3 Pleistocene aggradation events since incision to the pre-integration level. The first deposits laid down by the river following incision into the Bullhead sediments include the Riverside beds and the conglomerate of Laughlin. The Riverside beds comprise an interbedded sequence of mud, sand, and gravel. They are separated from a subsequent series of similar river deposits by the conglomerate of Laughlin, a coarse conglomerate from a postincision flood that further gouged out part of the Pyramid hills. It is composed of a mixture of far-traveled river gravel and large gravel clasts of locally derived granite. A paleochannel formed by the flood has subsequently been backfilled by a thick deposit of Pleistocene river alluvium. This subsequent package (described below) also overlies erosional topography and a moderately developed paleosol (Stage III carbonate) in the underlying deposits.

The Chemehuevi Beds

A series of conspicuous alluvial fills exist along the river between the mouth of the Grand Canyon and Yuma. They are typically characterized by a relatively thick basal unit of flat-bedded mud and fine sand overlain by a comparably thick unit of loose, gravelly sand, often forming conspicuous piles of sediment strewn over a rugged bedrock substrate. Newberry (*in* Ives, 1861) and Lee (1908) concluded that this package was the result of river aggradation. Longwell (1963) concluded that it was a deltaic sequence deposited in a lake(s) associated with valley blockage at unknown downstream locations. Metzger et al. (1973) concluded that the deposits were associated with fluvial aggradation linked to climate variability. The name Chemehuevi Formation has been in common use and now has a general connotation for all fill sequences along the lower Colorado River from Lake Mead to Yuma characterized by flat-bedded mud and fine sand overlain by a looser sequence of gravelly sand beds or of fluvial gravel.

Our studies suggest that this type of sequence is not unique in the history of the river and that the Chemehuevi Formation as envisaged by Longwell (1936) may contain a series of similar, disconformable sequences. Also, the upper sandy package in the archetypical sequence (as envisaged by Longwell, for example) typically overlies the fine-grained package along an erosional unconformity. This is one of the reasons that Metzger et al. (1973) opted to drop the Chemehuevi Formation name altogether in their studies. Instead, they envisioned a lower unit of mud and fine sand, which they called unit D, and an overlying unit of gravelly sand that they called unit E. In this report, we informally refer to the sequence as the Chemehuevi beds for reasons outlined below.

All investigators have agreed that at least one major aggradation event is recorded by the Chemehuevi deposits. Longwell (1936) reported no unconformities in the sequence and concluded that it was the result of a single, thick, and largely uninterrupted aggradation event. In this model, all subsequent fluvial landforms recorded only intermittent hiatuses during net incision into the single fill and the only notable subsequent aggradation is associated with the Holocene fill below the modern floodplain (Metzger et al., 1973). Two recent studies focused on an inferred anomalous sedimentology of the Chemehuevi beds within the context of an uninterrupted episode of aggradation. Blair (1996) interpreted the Chemehuevi Formation as evidence for an abrupt change in the volume and rate of floodplain sedimentation, likely owing to a climatic perturbation. Lundstrom et al. (2000) invoked a single-aggradation model and speculated that the entire fine-grained sequence may have been deposited by a single flood. More recently, Lundstrom et al. (2004) suggested several plausible mechanisms. In a series of geologic maps, Faulds (1996a, 1996b) broadly classified Chemehuevi deposits within an undivided unit of river alluvium spanning the Pliocene and Pleistocene.

We have recently mapped a similarly distinctive deposit of predominantly flat-bedded, fine-grained fluvial mud and sand overlain unconformably by a sequence of loose medium sand to gravelly sand in the Laughlin area (Faulds et al., 2004). We have also identified a prominent unconformity within the lower, fine-grained part of this package that juxtaposes two very similar deposits of fluvial mud and fine sand. The overlying gravelly sand caps fluvial terraces that are roughly 100 m above the modern channel of the lower Colorado River. This entire package (upper sand and two lower mud deposits) overlies a paleosol and erosional topography in a similar set of fine-grained Colorado River deposits (the Riverside beds) and a conspicuous, coarse fluvial conglomerate (conglomerate of Laughlin). Thus, the Chemehuevi Formation of Longwell (1936, 1963) is locally, at least, an assemblage of a series of disconformable packages of river laid alluvium that have a generally homogeneous appearance. For this reason, we use the broader designation of the Chemehuevi beds to distinguish the composite package as a single map unit. Division of the Chemehuevi beds into a series of upper and lower components as well as a fluvial gravel component provides for a more detailed characterization of the deposit where warranted.

The Mohave Sediments

The Mohave sediments comprise a package of fluvial sand, mud, and gravel that underlies the terrace below the Mohave Generating Station in Laughlin (the Mohave terrace). The terrace surface is ~60 m above the modern lower Colorado River channel. Deposits below the terrace surface share compositional similarities with the Chemehuevi beds exposed elsewhere, but their stratigraphic context suggests that they may be a younger sequence. Compared to the exposures of Chemehuevi beds a mile to the north, this package contains a more variable assemblage of fluvial mud and sand overlying a conspicuous coarse-grained channel gravel and interbedded with tributary fan gravels. The core of the fluvial package interfingers toward the west with alluvial fan deposits derived from the Newberry Mountains and to the east with alluvial fan deposits from the Black Mountains; thus, tributary deposits constrain a paleochannel position beneath the Mohave Generating Station (the Mohave paleochannel). The bounding fan deposits grade upward into a widespread piedmont map unit—Qai2. That relation suggests this sequence is younger than deposits exposed in the Davis Dam bluffs, where the upper Chemehuevi beds are coeval with an older piedmont alluvial unit (Qai1). We have designated the Mohave paleochannel deposits the Mohave sediments and consider them the youngest deposits in the Chemehuevi beds. Without the bounding tributary deposits it is difficult to confidently identify Mohave sediments as a discrete package.

Age of the Chemehuevi Beds and Similar Packages

The ages of the Quaternary alluvium have been harder to pin down than the ages of the Miocene to Pliocene deposits. To date, the existing data are contradictory and compromised by incomplete or ambiguous exposures of stratigraphy. However, there are several interesting lines of evidence.

Fossils. Newberry (*in* Ives, 1861) reported the first Pleistocene fossil discovery along the river in upper Cottonwood Valley when he extracted a mammoth tooth from lower Chemehuevi muds. The species and age of the specimen are uncertain. Metzger et al. (1973) discovered a Pleistocene mammoth tusk in the Chemehuevi beds. Bell et al. (1978) performed U-series analysis on the specimen and reported an age of ca. 102 ka. In contrast, an amino acid racemization analysis on a mammoth skull from lower Chemehuevi-like beds near Parker, Arizona, yielded an age of 900 ka, and nine small vertebrate fossils from near Blythe, California, yielded amino acid ages of ca. 100 ka (Lee and Bell, 1975). According to L.D. Agenbroad (1995, personal commun.), there is evidence for 3 *Mammuthus meridionalis* fossils along the river between Laughlin to just south of Parker, and their most likely age range is 1.5–1.7 Ma.

Isotopic and Luminescence ages. Samples of intact and unaltered wood are rare in the Chemehuevi beds. However, in one instance, Blair (1996) collected a wood specimen from mud in the lower Chemehuevi beds near the north end of Cottonwood Valley, which yielded a radiocarbon age of 35 ka. Lundstrom et al. (2004) reported that a series of luminescence ages from lower Chemehuevi deposits from various sites along the river range from ca. 40 ka to 70 ka. They also obtained U-series ages on carbonate-coated gravels from inset younger terrace surfaces that ranged in age from 32 to 60 ka.

Paleomagnetic data. Paleomagnetic analyses of Chemehuevi deposits from near Parker, Arizona, showed that they are normally magnetized, and thus less than 780 ka (Bell et al., 1978).

Lundstrom et al. (2000, 2004) also report normal magnetization in the Chemehuevi beds from various sites.

Tephra beds. Longwell (1936) reported on and sampled a 3 m thick tephra bed at the base of his Chemehuevis Formation near the town of Callville, Nevada (now submerged by Lake Mead). Neither the source nor the age of this ash is known. The Lava Creek B ash (0.62 Ma) and either the Bishop (0.74 Ma) or the older Glass Mountain ashes are Pleistocene ashes previously reported from the general area of the lower Colorado River (Whitney, 1996; Merriam and Bischoff, 1975); A. Sarna-Wojcicki, 1998, personal commun.), but have not been collected from Colorado River deposits. Recently we (Brock, House, and Pearthree) discovered and sampled a tephra bed from the lower Chemehuevi–type muds north of Katherine's landing. The stratigraphic context of the bed indicates to us that it is of Pleistocene age. Analysis and identification of this tephra by the U.S. Geological Survey is pending.

The Pleistocene stratigraphy in the Laughlin area indicates a complex history of processes along the river during that time. There is evidence for at least three likely Pleistocene-age sequences of predominantly fine-grained Colorado River alluvium separated by unconformities. This record is difficult to resolve from the basis of a series of similar but scattered outcrops of alluvium, and is inferred from detailed study in a relatively small area. We believe that the Chemehuevi beds may represent a series of responses of the fully integrated Colorado River to a cyclic, external control—presumably, but not certainly, climate.

FINALLY—OUR WORKING MODEL

The working model that we have developed for the late Tertiary and Quaternary record of the lower Colorado River based on relations in the Laughlin area is outlined below and shown schematically in Figure 3. Age estimates for events in the Quaternary are not closely constrained at this time. Parenthetical terms (below) are informal names that we have developed for representative stratigraphic units in the Laughlin area that record the sequential events, including a variety of late Pleistocene terraces and strath veneers that are not described in the previous sections. The chronological assignments are based on new data and our interpretation of the likely context of previously reported data and are, in some cases, conjectural placeholders.

1. Local basins filling with extensive alluvial fans (Miocene fanglomerate).
2. Transition from local fan and axial channel deposition to intermittent lacustrine conditions in Cottonwood Valley prior to 5.5 Ma (Lost Cabin beds); roughly concomitant development of axial drainages in northern Mohave Valley (axial gravel complex).
3. Spillover/divide-failure through the Pyramid hills and major flooding from Cottonwood Valley into Mohave Valley sometime after 5.5 Ma (gravel of Pyramid hills).
4. Deep lake formation in Mohave Valley and Cottonwood valleys soon after 5.5 Ma owing to damming at Topock divide (Bouse Formation).
5. Incision through the Bouse Formation and underlying deposits due to lake spillover and drainage through Topock Gorge; arrival of bedload associated with the Colorado River (gravel of Panda Gulch).
6. At least 250 m of river aggradation culminates between 3.6 and 4 Ma (alluvium of Bullhead City).
7. Deep incision begins by 3.3 Ma and eventually reaches near modern river level (series of fans and river terraces with strong carbonate soils).
8. Minor aggradation ca. 1.5–1.7 Ma. (Riverside beds).
9. Locally catastrophic flood (conglomerate of Laughlin).
10. Multiple aggradation/degradation cycles up to 35 ka (lower Chemehuevi beds, upper Chemehuevi beds, Mohave sediments).
11. Progressive incision, strath formation, minor aggradation (alluvium of Emerald River, alluvium of Big Bend, various strath veneers).
12. Incision followed by Holocene aggradation to form the modern floodplain (Metzger et al., 1973; alluvium of Riviera).

FIELD TRIP

Day 1: Las Vegas to Laughlin: The Debut of the Colorado River

Total driving distance: ~100–120 mi (Figs. 1 and 4).

Directions and Highlights en Route to Stop 1.1

The field trip begins at the intersection of Hwy 93 and Hwy 95 between Henderson and Boulder City, Nevada (0.0 mi) (Fig. 1). From here, drive south on Hwy 95 toward Laughlin, Nevada. At about the 10 mi point, the route passes the turnoff to Nelson's Landing, Nevada, the site of a catastrophic and fatal flash flood down Eldorado Canyon on 14 September 1974 (Glancy and Harmsen, 1975). Enter Searchlight, Nevada, at 35.7 mi atop the 3500-ft divide between Eldorado Valley (closed basin) and Piute Valley (lower Colorado River tributary). About 20 mi south of Searchlight, exit left (east) on Hwy 163 to Laughlin, Nevada (reset odometer). This route traverses a pediment on the west flank and in the interior of the rugged Newberry Mountains, underlain mainly by Miocene granite. Note the changing regional topography as you continue toward Laughlin. The floor of Piute Valley is at ~2516 ft (767 m), and the highway quickly climbs to 2960 ft (901 m) before it begins a steep descent to the Colorado River at 500 ft (152 m).

The highway eventually debouches onto the steeply sloping head of the Dripping Springs Wash alluvial fan at the foot of the Newberry Mountains. At ~2.5 mi below the mountain front, the highway flattens slightly as it skirts the southwestern edge of the Davis Dam terrace, the higher of two major Pleistocene river terraces in the Laughlin area. To the southeast, the Mohave Generating Station sits atop the other, lower terrace which we call the Mohave terrace. Exit right on Civic Drive near the base

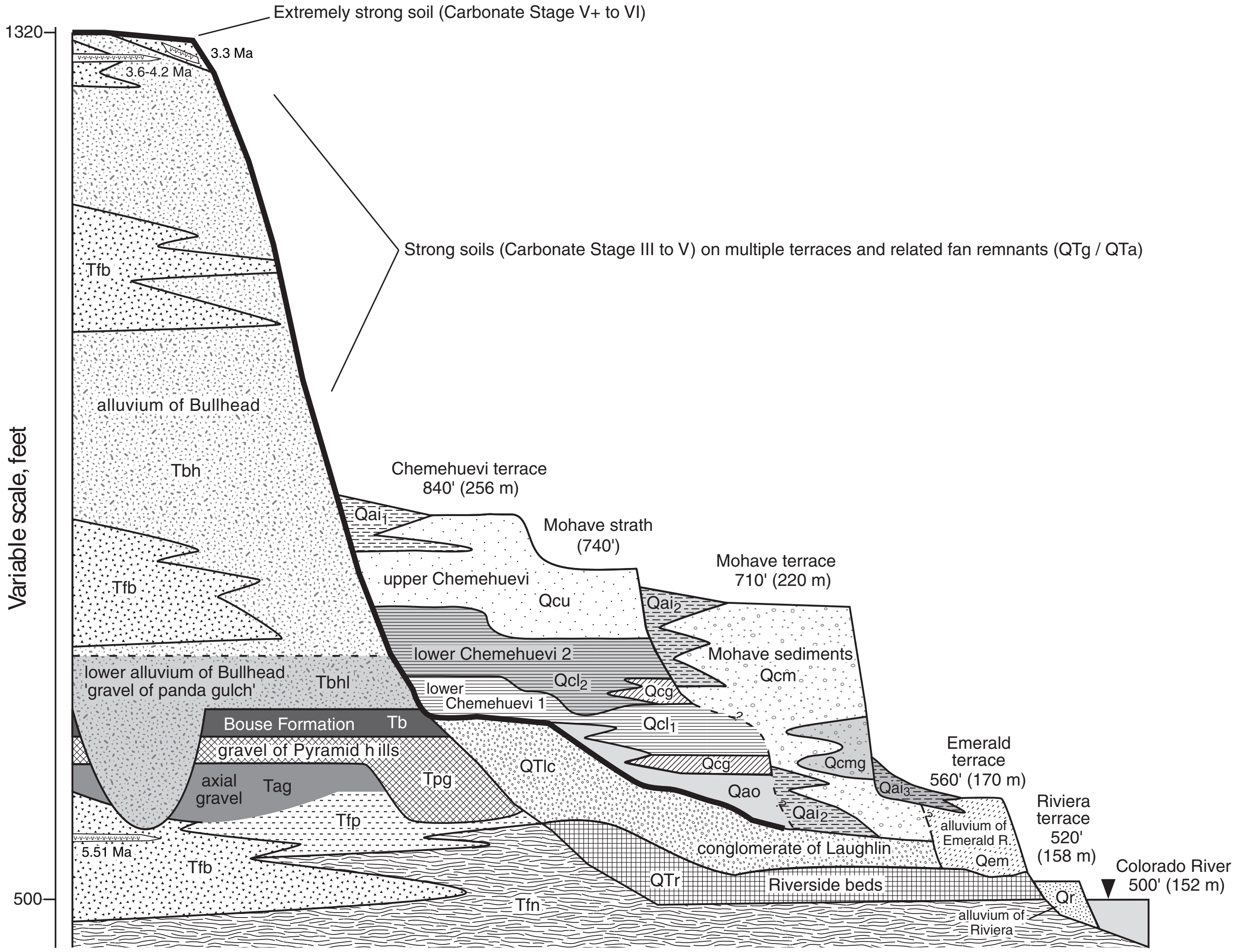

Figure 3. Schematic representation of late Cenozoic stratigraphy of the Colorado River and its piedmont tributaries in northern Mohave Valley. Nomenclature described in text.

of the piedmont slope and then turn right (south) onto Edison Drive (Fig. 5). Large boulders exposed here are part of the Laughlin conglomerate. The coarse conglomerate is unconformably overlain by the Chemehuevi beds that are visible along the north side of Edison Blvd. Follow Edison Blvd. to the top of the Mohave terrace across an array of late Cenozoic river and alluvial fan deposits. Crest the terrace and take a right turn at the traffic signal (1.95 mi) onto Casino Drive (southbound). Pass the Harrah's Casino and continue until you reach a deeply incised wash visible along the east side of the road (~0.5 mi from traffic light). Park on the east side of the road just above the wash (see Fig. 5 for specific locations).

Stop 1.1: The Laughlin Bluffs

A series of steep gulches carved in the east face of the Laughlin bluffs expose the key stratigraphic evidence that documents a change from local, possibly enclosed drainage, to deep inundation with standing water, and then finally to a major throughgoing river. We refer to the deposits recording these events as the transitional sequence. The sequence here is linked to a related sequence of concurrent and complementary changes in depositional conditions in Cottonwood Valley (see Day 3). The deposits of the transitional sequence form a spine of relatively indurated late Miocene to early Pliocene sediments surrounded and overlain by various Quaternary alluvial fan and Colorado River deposits resulting in a complex assemblage of deposits (Fig. 6).

Stop 1.1a: Panda gulch. The first stop will focus on exposures of the transitional sequence in Panda gulch. Each member of the sequence is clearly visible on the northwest facing slope above the gulch (Fig. 7A). Late Miocene, untilted fanglomerates from the Newberry Mountains form the base of the section and are overlain by a cross-stratified channel gravel deposit contain-

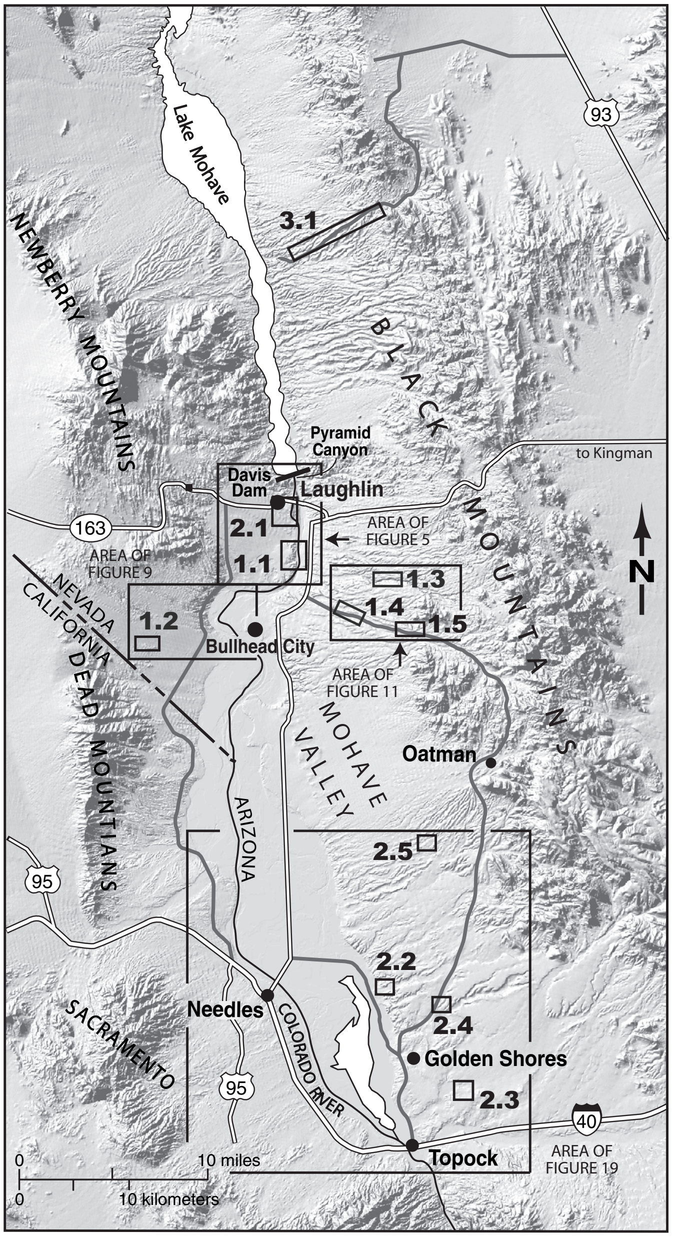

Figure 4. Map showing physiographic setting and location of field trip sites in Southern Cottonwood Valley and Mohave Valley.

ing clasts of local rock types—the "axial gravel" (Tag; Fig. 7B). We interpret these gravels as marking the position of an axial channel near the head of Mohave Valley at a time when it was not directly connected with drainage through Cottonwood Valley.

The axial gravel and underlying fanglomerate are unconformably overlain by the gravel of Pyramid hills (Tpg; informally named Pyramid gravel; Fig. 7C), a conspicuous, immature boulder conglomerate. Deposition of the Pyramid gravel was accompanied by erosive enlargement of the axial channels and locally deep scour into the underlying fanglomerate. The

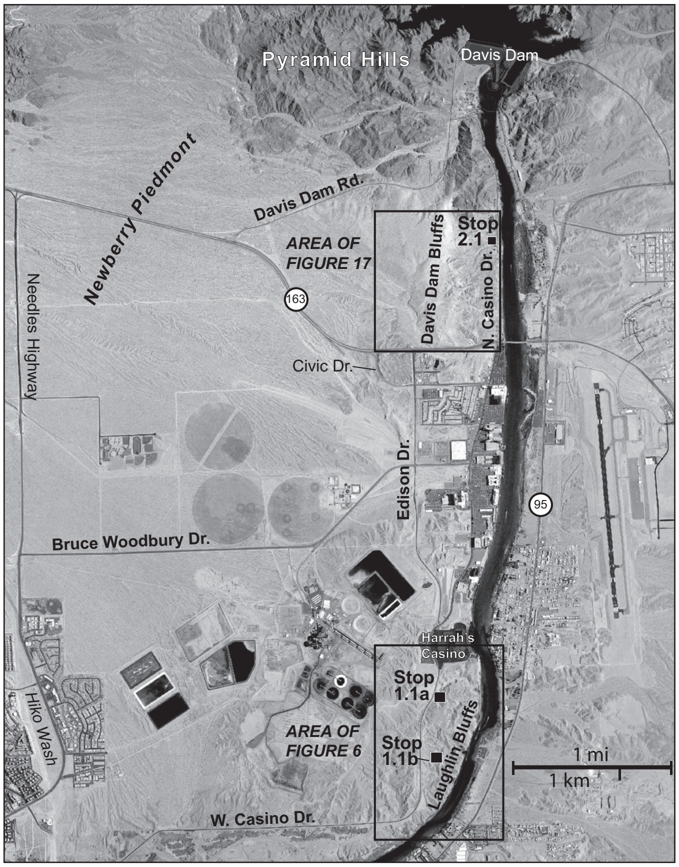

Figure 5. Air-photo map showing locations of field trip stops in the immediate Laughlin area.

Pyramid gravel is predominantly a cobble-boulder conglomerate with a maximum thickness of ~20 m. Many clasts are subrounded to rounded. Some exposures contain sparse, locally derived sediments (reworked fanglomerate), and others are dominated by thick, stratified sequences of monomictic grussy sand and subrounded pebble-gravel possibly derived from regolith stripped from slopes of the Pyramid hills. Cross-stratification is evident in some intervals of the Tpg (e.g., trough cross-bedding; Fig. 7C). Many exposures show a clast-supported structure, whereas some are matrix-supported and slurry-like.

Most outcrops of the Pyramid gravel are composed almost entirely of cobbles and boulders of megacrystic granite from the Pyramid hills and reworked local fanglomerate from the Newberry Mountains. We interpret the Pyramid unit as a catastrophic flood deposit from a clear-water breach through a paleodivide in the Pyramid hills. Deposits in Cottonwood Valley (Stop 3.1) indicate a roughly concurrent lacustrine environment some 12 mi upstream of the Pyramid Hills.

The Pyramid gravel is conformably overlain by the Bouse Formation, indicating inundation of this area by standing water following the deposition of the gravel (Fig. 7A and 7D). Outcrops

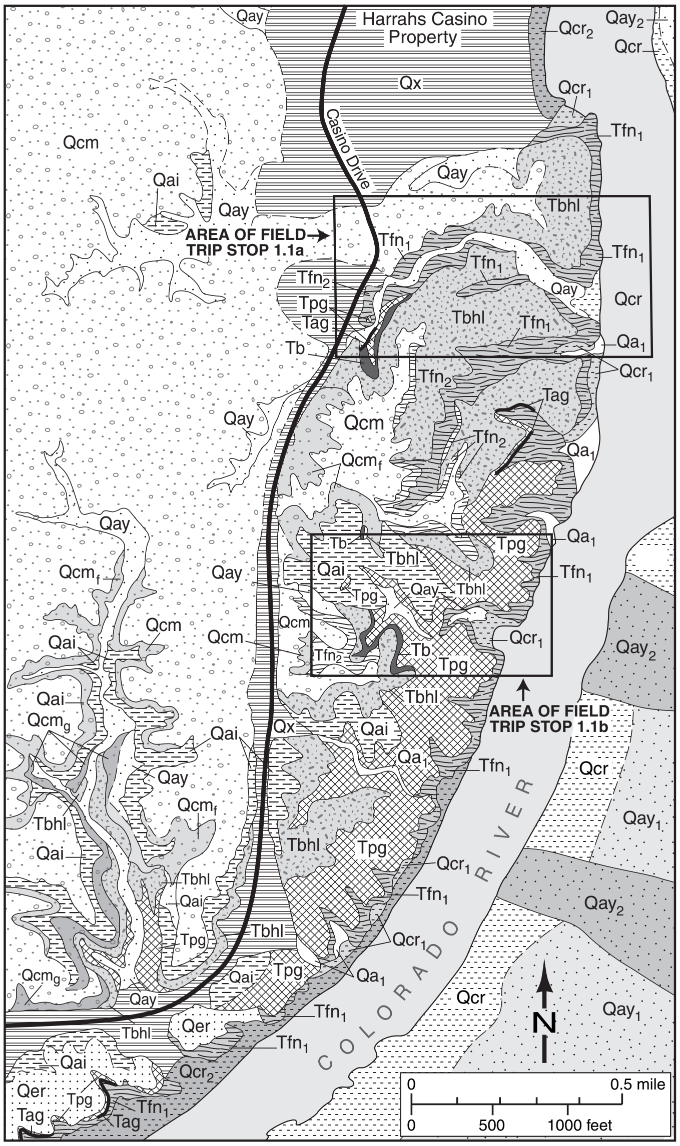

Figure 6. Detailed geologic map of the Laughlin bluffs area (modified from Faulds et al., 2004). See text for discussion of various units. Tfn—Miocene fanglomerate from Newberry Mountains (Tfn$_1$—pre-Bouse; Tfn$_2$—syn/post-Bouse); Tag—axial gravel; Tpg—Pyramid gravel; Tb—Bouse Formation; Tbhl—lower Bullhead alluvium (Panda gravel); Qcm—Mohave sediments (Qcm$_f$—fine facies; Qcm$_g$—gravelly facies); Qai—intermediate age alluvial fans (late Pleistocene?); Qer—alluvium of Emerald River; Qay—young alluvial fans (Holocene); Qcr—alluvium of Riviera; Qx—extensively disturbed areas.

of Bouse in the Laughlin bluffs range from 0.5 to ~3 m thick and include beds of marl, mud, and minor sand. The outcrops in the Laughlin bluffs occur only 140 ft above the surface of the modern Colorado River. The sequence of Bouse over Pyramid gravel suggests that a catastrophic flood from an upstream source, possibly a lake, was immediately followed by quiescent deposition in a large body of standing water.

The preceding sequence is unconformably overlain and deeply incised by gravels and sands of the early Colorado River—the alluvium of Bullhead City (Tbh; informally called the Bullhead alluvium). The Bullhead alluvium is generally equivalent to units A and B of Metzger et al. (1973). The gravel at the base of the Bullhead unit is largely comprised of locally derived sand and gravel reworked from Newberry Mountain–sourced fanglomerates, but is also peppered with well-rounded pebbles of chert and well-rounded cobbles of diverse lithologies from far upstream. The mix of light colored local sand and gravel with the exotic, mostly dark-colored pebble component imparts a distinctive black and white speckled appearance to the unit, hence our informal name Panda gravel (Tbhl; Fig. 7E).

The Panda gravel has a cobble-rich basal conglomerate containing mainly clasts of reworked fanglomerate and Pyramid gravel. Look on the slopes for examples of fluted (stream-worn) boulders. The base of the Panda unit dives down-section into the late Miocene fanglomerate down the wash (Fig. 8) and then climbs up toward the east and the modern course of the Colorado River. The base of the Panda gravel here thus defines a large paleochannel. Evidently, the arrival of the river in northern Mohave Valley immediately preceded or was accompanied by an interval of erosion following the recession of the Bouse water body. The step-like geometry in the Panda gravel channel here (Fig. 8), the occurrence of stacks of laterally continuous layers of coarse gravel, and the abundance of locally derived clasts in the body of the deposit suggests lateral erosion and reworking of the Miocene substrate by a rapidly aggrading, greatly over-fit river. The Bullhead unit is discontinuously exposed from this point (~20 m above the river) up to gravel lags and river sands interfingered with Black Mountain alluvial fan gravels at levels as high as 250 m (~820 ft) above the river.

Stop 1.1b: Lavender gulch. A thicker section of the Pyramid gravel (similar to that shown in Fig. 7C) can be evaluated in Lavender gulch ~0.5 mi to the south of Panda gulch. In general, the deposits continue to thicken toward the south from here until the Big Bend of the Colorado, beyond which the transitional section is not preserved. To reach this site, drive south on Casino Drive from the Panda gulch pullout for ~0.45 mi. Once you reach the surface of the Mohave terrace, there is an expansive flat area along the east side of the road. Park there. Look for a narrow terrace ridge with a clear vehicle track that extends quite far toward the east. Head down the steep north side of the ridge. About halfway down this traverse, a 3–5 m thick interval of the Bouse Formation is exposed. The gulch terminates in a precipitous pour-over at the contact between the Pyramid gravel and the axial gravel. An excellent perspective on the obtrusive nature of the Pyramid gravel, its channel forms, and its erosive contact is also available from Arizona Hwy 95 in Bullhead City. The Pyramid unit forms a prominent dark swath in the middle of the Laughlin bluffs and many paleochannel forms are easily discerned.

Directions and Highlights en Route to Stop 1.2

Return to Casino Drive and continue south. The road turns westward along the Big Bend of the Colorado River (Fig. 5). Deep

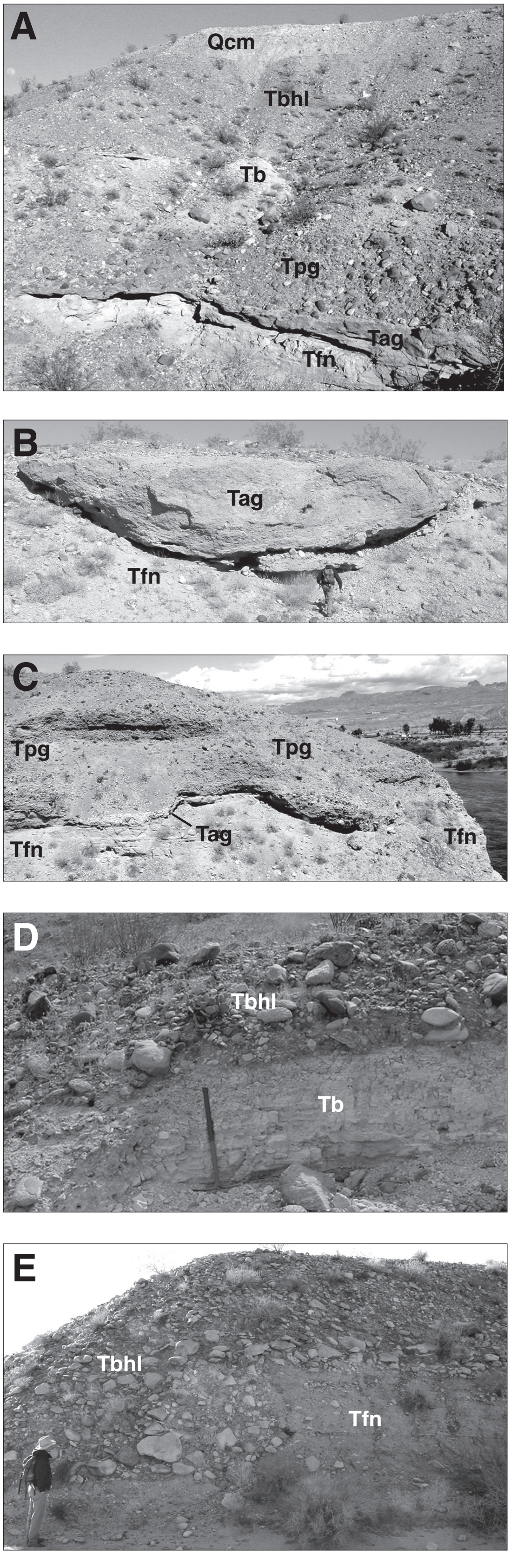

Figure 7. Annotated photographs of the late Miocene–early Pliocene transitional sequence and bracketing deposits exposed in upper Panda Gulch and key locations in the Laughlin Bluffs. (A) Complete, compressed section. Tfn—Newberry Mountains–derived fanglomerate; Tag—axial gravel; Tpg—gravel of Pyramid hills; Tb—Bouse Formation; Tbhl—lower alluvium of Bullhead City (gravel of Panda gulch); Qcm—Quaternary Colorado River deposits (Mohave sediments). (B) Paleochannel in axial gravel unit (Tag). (C) Gravel of Pyramid hills in channel carved in fanglomerate. Tpg is ~20 m thick here. (D) Bouse Formation limestone overlain by the gravel of Panda Gulch. (E) Base of paleochannel incised in fanglomerate and filled with the gravel of Panda Gulch.

washes incised in the Mohave terrace to the north expose some of the transitional sequence and parts of the Mohave paleochannel, a much younger package of Colorado River sediments, and interbedded alluvial fan gravels are exposed in Arizona gulch, the largest drainage on the Mohave terrace (Fig. 6). Fan gravels exposed in roadcuts between Panda gulch and the major bend in the highway at ~0.5 mi are derived from the Black Mountains and bound the eastern margin of the paleochannel. Heading due west, outcrops to the north show late Pleistocene alluvial fans derived from the Newberry Mountains and interbedded Colorado River sediments that define the western margin of the paleochannel. The road then drops onto the toe of the Hiko Springs alluvial fan, the terminus of one of the largest drainages on the Newberry Piedmont and site of the tallest flood control structure in Clark County (2.5 mi up the wash). At the stoplight, turn south (left) on the Needles Hwy (4.8 mi from the Edison Drive–Casino Drive intersection; Fig. 9). The road crosses an unnamed wash and drops onto the historical (predam) floodplain of the Colorado River. On the west side of the road is an exposure of the Newberry detachment fault. The reddish rock clinging to the base of the Newberry Mountains is an upper-plate remnant of Proterozoic granite. Beyond the fault exposure, the road continues to follow the historical floodplain and then climbs through a sequence of late Miocene, pre-Bouse fanglomerate. At just ~2 mi from the last stoplight, look for an unmarked exit on your right to reach a frontage road paralleling the west side of the highway. Continue south on the frontage road. After 2.3 mi, turn right (W) on the pipeline road and proceed up the piedmont between the Newberry and Dead mountains. Much of the piedmont is a pediment formed on late Miocene fanglomerate and granite. The fanglomerates extend to near modern river level and are likely coeval with fanglomerates in the Laughlin bluffs.

Outcrops of the Bouse Formation overlying the fanglomerate are exposed 0.5 mi due west from this intersection. Follow the pipeline road for 2.3 mi. Turn left (S) at the intersection with a powerline road. Follow this road for ~1 mi and turn left (E) down a narrower track. Follow this track for 0.4 mi to the bedrock outcrops.

Stop 1.2: Manchester Beach

This stop highlights a variety of deposits of the Bouse Formation that illustrate the extent of the body of standing water

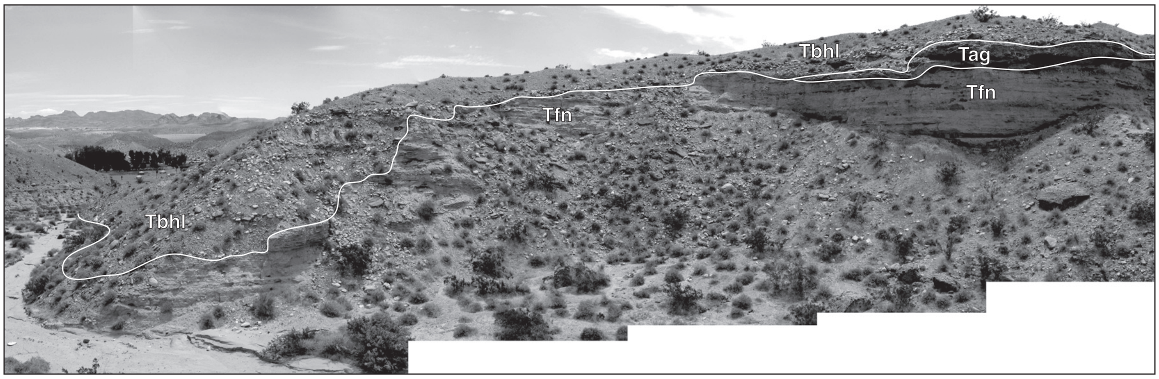

Figure 8. Annotated photo mosaic of exposure in Panda gulch showing the disconformable basal contact of the Panda gravel (Tbhl) over axial gravels (Tag) and fanglomerate (Tfn).

that formed in Mohave Valley following the large flood through the Pyramid hills divide.

An extensively pedimented bedrock outcrop on the northeast edge of the main block of the Dead Mountains is underlain by Miocene granite and quartz diorite (House et al., 2004a). Along the northern margin of the pediment at this stop lie a series of enigmatic deposits of locally derived, rounded gravels. We interpret these as beach gravels deposited along the margin of the Bouse basin. The gravels are locally interbedded with sandstone and calcareous mud that onlap the bedrock. They occur as relatively flat benches hemmed in by bedrock protrusions along the northern margin of the pediment. They have a distinctive yellowish-orange oxidized patina. The lag of rounded, local gravels can be traced north across the piedmont to a sparse lag of rounded gravels on deeply weathered, craggy fanglomerate remnants and to stratigraphic exposures at ~548–560 m (1800–1840 ft) in washes draining the Newberry Mountains. Some of the gravel beds have unidirectional cross-stratification and are locally interfingered with thin beds of flat-lying sandstone.

The distribution of various deposits of the Bouse Formation in this part of Mohave Valley are suggestive of a "mega-drape" of sediment that covered a preexisting, deep valley similar to the present one (Fig. 10). Bouse sediments on the north flank of the Dead Mountains pediment occur from 1320 to 1740 ft elevation. A marl outcrop along the powerline road overlies fanglomerate

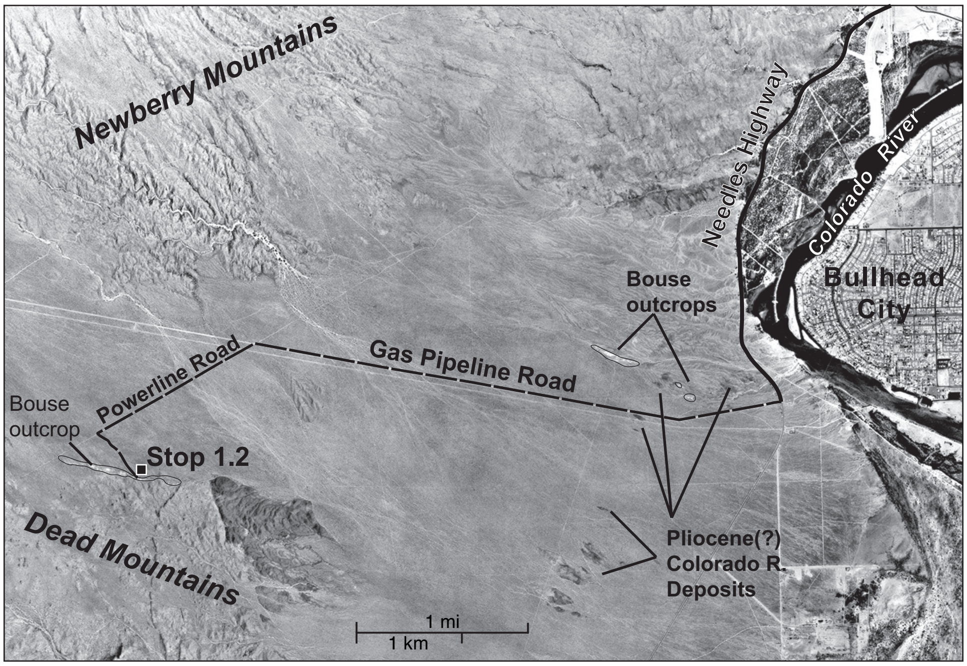

Figure 9. Air-photo map of route to and location of Stop 1.2.

along a span from 760 ft to 1000 ft elevation. Five mi (8 km) south of the Manchester beach site, Bouse roundstone gravels are found in association with tufa encrustations on the bedrock face of the Dead Mountains and tufa-cemented colluvium between 350–440 m (1160 and 1440 ft) above sea level (asl). We have also found large tufa clasts on late Miocene fanglomerate ~1.5 mi (~2.4 km) southeast of here at 365 m (~1200 ft). The tufa rinds and beach gravels at successively lower elevations probably indicate periods of stasis in a fluctuating (possibly slowly draining) deep body of water. Additional Bouse outcrops along the Dead Mountain piedmont include beds of marl that steeply onlap bedrock at ~305 m (~1000 ft), and project below thick deposits of mud and sand that are exposed between 170 and 305 m (560 and 1000 ft). In summary, the distribution of Bouse exposures in this part of Mohave Valley ranges from 170 m (560 ft) to at least 548 m (1840 ft). In most cases, Bouse sediments overlie late Miocene fanglomerate or sit directly on bedrock.

The highest clastic deposits that we have identified in this area may approximate the peak elevation of the Bouse water body in Mohave and Cottonwood valleys. They occur at the same elevation as the highest previously documented Mohave Valley Bouse outcrops in Silver Creek Canyon (Stop 1.3) (Metzger et al., 1973; Spencer and Patchett, 1997), and they also occur at the same general elevation of the highest outcrops of likely Bouse basin margin deposits that we have found in Cottonwood Valley (Stop 3.1), 18 mi (30 km) to the north.

The Black Mountains piedmont. The next several field trip stops are on the Black Mountains piedmont (Figs. 4 and 11) and focus on evidence for the timing and nature of maximum valley inundation during the Bouse interval and the subsequent major aggradation and incision of the early Colorado River. The character and distribution of deposits preserved on the Black Mountains piedmont provide insights into the timing, nature, and duration of the Bouse interval, excellent evidence for the maximum aggradation of the Colorado River to 250 m (820 ft) above the modern river, and evidence for the timing of initial incision of the river after maximum aggradation. Tephra beds discovered on this piedmont provide timing constraints for each of these important intervals, restricting all of this activity to the period between the Miocene–Pliocene boundary and the middle Pliocene (between ca. 5.5 and 3.3 Ma; Fig. 12).

The southern Black Mountains consist of early to middle Miocene volcanic rocks and are lithologically distinct from the predominantly granitic rocks exposed on the west side of Mohave Valley. These rocks are much less tilted and extended than coeval rocks across the river. Reconstructing eastward slip on the east-dipping Newberry detachment fault across the river to the west (Spencer, 1985), the extrusive rocks in the Black Mountains would rest approximately above middle Tertiary granitic rocks in the Newberry and Dead Mountains 20–30 km to the west. The Black Mountains are capped by mesa-forming olivine basalt dated at 15.8 Ma, which unconformably overlies the early Miocene sequence (Gray et al., 1990) and is a major source of fan gravels on the piedmont.

Directions and Highlights en Route to Stop 1.3

Retrace your route back through Laughlin to Hwy. 163. Turn right (E) and cross the Colorado River on the Laughlin bridge (reset odometer). Continue straight through the stoplight immediately east of the river onto Bullhead Parkway. The road ascends the lower piedmont of the Black Mountains and bends to the south, passing Bullhead City Airport. At ~0.9 mi, there is a small exposure of the basal limestone of the Bouse Formation in a low roadcut on the east side of the road. Just farther to the east and below the Bouse outcrops there are several small outcrops of the Pyramid gravel. At ~2.2 mi, the route approaches higher ridges that extend down the deeply dissected piedmont. Many rounded ridges are 10–40 m higher than adjacent valley bottoms. The ridges are almost uniformly capped by several meters of tributary gravel with moderately to strongly developed petrocalcic soil horizons. The oldest remnants may date to the middle Pliocene (site 1.5). Many of the ridges beneath the capping gravel are composed of Colorado River deposits of the Bullhead alluvium (Fig. 13). Continuing to the south, there are several excellent exposures of weakly to moderately indurated, cross-bedded sand and rounded river gravel of the Bullhead unit. The elevation here is ~280 m (920 ft) asl, roughly in the middle of the major Pliocene river aggradation sequence.

At 3.3 mi, turn left (E) across the northbound lane onto a dirt track in the valley of Secret Pass Wash, a large drainage that heads in the Black Mountains. Along the route in the active channel you will see as many as three prominent Pleistocene terraces in the valley. A few good exposures along the valley sides reveal predominantly river deposits with some tributary fan gravel. Between 1.2 and 1.4 mi up the wash there are better exposures of the Bullhead unit interfingered with tributary fan deposits on the north side of the valley, up to ~360 m (1180 ft) asl. This is near the upper limit of voluminous Colorado River deposits, although limited river sand and gravel deposits and lags can be found at numerous localities up to 400 m (1320 ft) asl in this area. The road forks at ~2.2 mi; stay in the valley bottom by bearing left. As the valley narrows and you will see several rotated blocks and pillars of indurated fanglomerate on the north side of the valley. These blocks have slid down over fine-grained deposits of the Bouse Formation, which is exposed at ~2.5 mi. Proceed to 3 mi and stop along the road.

Stop 1.3: Secrets of Secret Pass

At this stop the character of the Bouse Formation can be examined, including new maximum age constraints on its deposition. Here is an ~20 m thick exposure of the Bouse that has most of the components described by Metzger (1968) and Metzger and Loeltz (1973). The basal unit is a thin, poorly exposed limestone overlying fanglomerate at the north edge of the wash. This relationship is better exposed and higher above the wash upstream, and not exposed downstream, implying that the fan surface on which the Bouse Formation was deposited sloped more steeply to the west than the modern channel (~2° versus 1.5°). The basal limestone is overlain by pale green mudstone

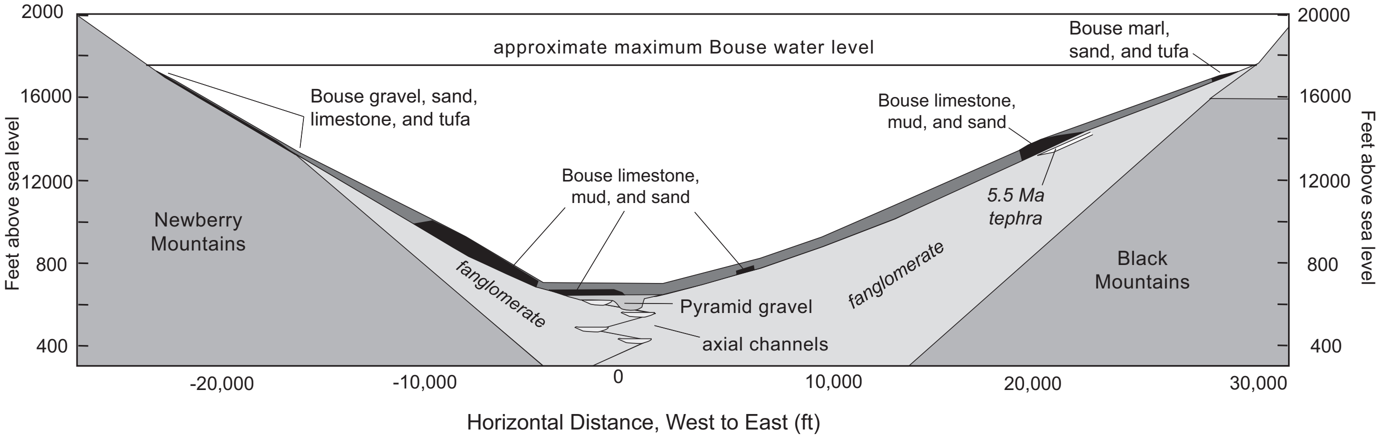

Figure 10. Schematic cross-profile of Mohave Valley showing distribution of key late Neogene stratigraphic units. Positions of mapped outcrops of the Bouse Formation are shown in black. Inferred extent of Bouse shown in dark gray. Inferred sequence of axial channels also shown. Depiction of uppermost axial channel overlain by the gravel of Pyramid hills represents relations in Laughlin bluffs.

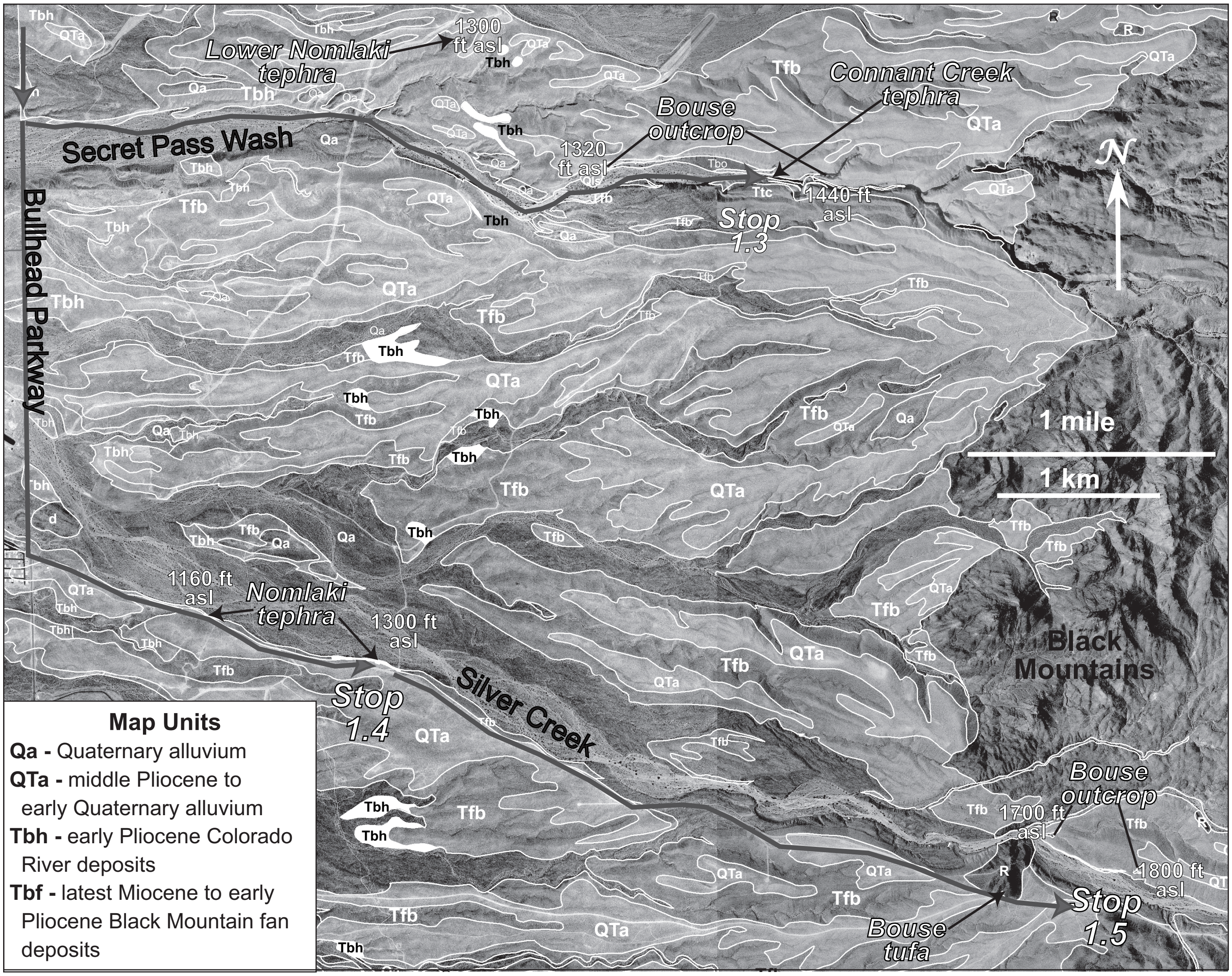

Figure 11. Surficial geologic map of part of the Black Mountains piedmont. The field trip route is shown by a heavy gray line and field trip stops are identified.

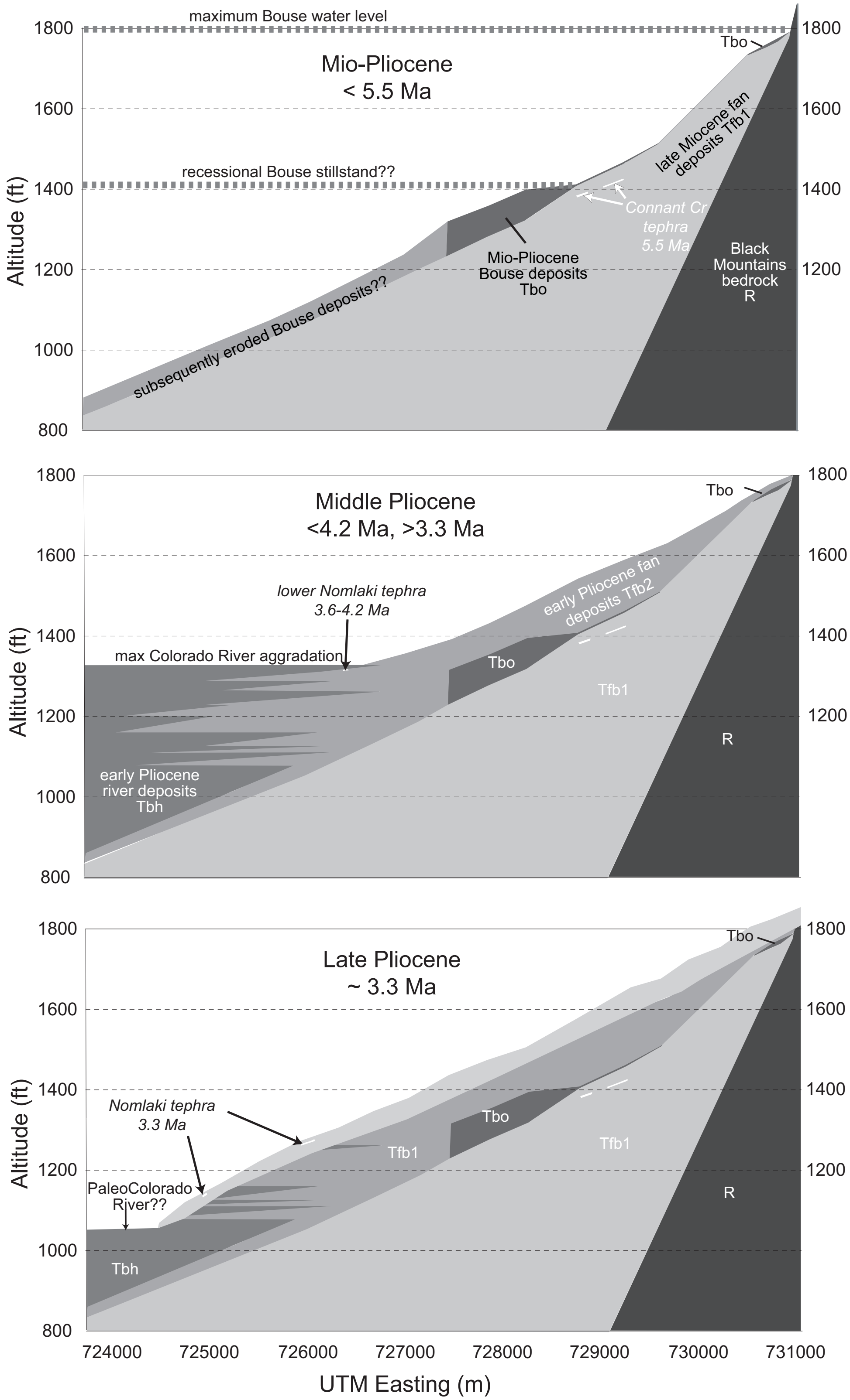

Figure 12. Schematic cross sections of upper Black Mountains piedmont showing relationships at the time of the Bouse lake filling, maximum Colorado River aggradation, and the beginning of Colorado River incision after maximum aggradation.

that grades up into brown mudstone on the lowermost slopes north of the wash. The mudstone is overlain by more indurated tan sandstone and siltstone beds; many of the beds are massive, but locally the sandstones have cross-bedding. The uppermost sandstone and siltstone beds are interfingered with beds of fine, locally derived gravel.

These Bouse sediments likely were deposited in a near-shore environment with abundant clastic sediment input of material from tributary drainages off of the Black Mountains. This site is more than 100 m below the maximum level of inundation, but it is not clear whether the clastic sediments here were deposited at maximum inundation or at some recessional level. The Bouse deposits are overlain by tributary fanglomerate. At some locations the Bouse grades upward into the tributary gravel, but in other places they are separated by an erosional unconformity. At this location it appears that only a modest amount of erosion of the Bouse Formation occurred upon recession of the large body of standing water, prior to onlapping by tributary alluvial fans. On the south side of Secret Pass Wash we see almost entirely indurated tributary fan deposits, however, with only a small outcrop of Bouse deposits preserved near the base of the cliffs several hundred meters downslope. We infer that the Bouse deposits were substantially eroded there prior to deposition of the thick tributary fan package, but it is not clear whether this fan package correlates with the fan deposits immediately above the Bouse on the north side or is younger.

Walk slightly less than 0.3 mi up the wash to where a sizable tributary enters from the north. Here the Bouse Formation and an underlying tephra bed are exposed in a thick package of tributary fanglomerate (Fig. 14). The Bouse Formation consists only of a thin bed of limestone ~10–15 m above the wash. The limestone bed can be traced intermittently from our previous stop to this location and continues on in the narrow canyon to the east. In some exposures upstream, the Bouse Formation consists primarily of massive or cross-bedded sand deposits over a very thin limestone layer, but in contrast to a few hundred meters to the west, the total deposit thickness is 3 m or less. The Bouse deposits here seem to represent a brief incursion of quiet water into an alluvial fan environment, but it is possible that more of the Bouse was removed by erosion prior to renewed tributary fan deposition. Just above the active channel, there is a fairly continuous layer of tephra up to 0.5 m thick and several other large pods of tephra at the same level; these have been identified as the 5.5 Ma Connant Creek tephra via geochemical analysis and correlation. The tephra and Bouse beds are separated by ~10 m of fanglomerate. This site is high up on the margin of the valley, so the 5.5 Ma date provides a maximum constraint for the age of the filling of Mohave Valley with deep water.

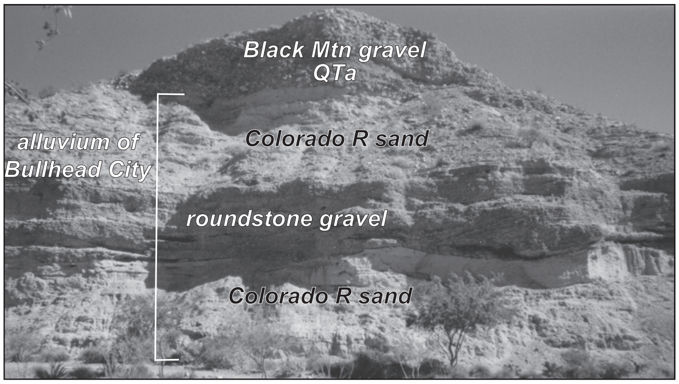

Figure 13. An example of alternating sand and gravel beds in the alluvium of Bullhead City. The Bullhead beds are unconformably overlain by coarse tributary fan gravel.

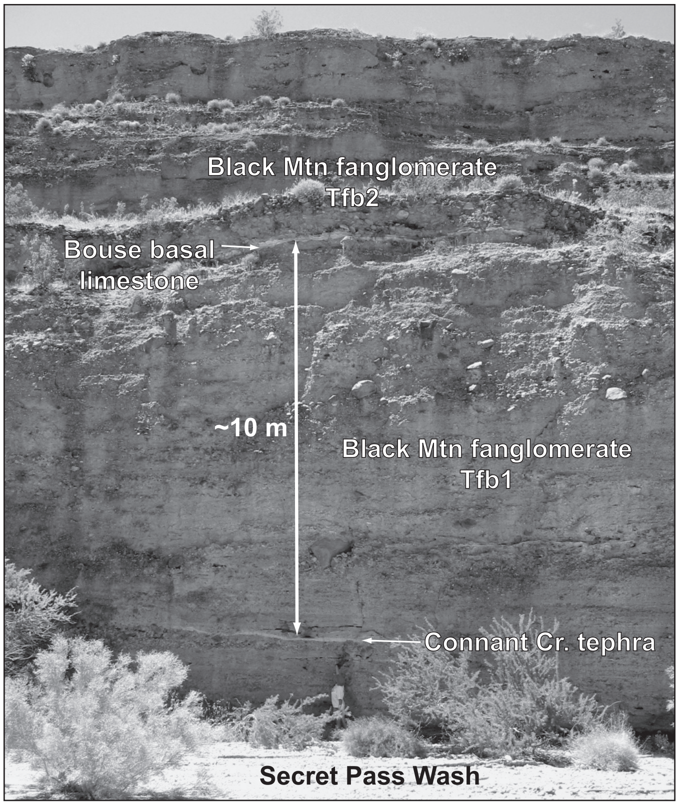

Figure 14. Photograph of the north wall of Secret Pass Canyon showing a thin, fairly extensive bed of the 5.5 Ma Connant Creek tephra and the thin, continuous basal limestone bed of the Bouse Formation separated by ~5 m of local fanglomerate. The altitude of the wash bottom at this site is ~415 m (1360 ft) above sea level.

Directions and Highlights en Route to Stop 1.4

Return west down Secret Pass Wash to Bullhead Parkway. Turn left (S) onto Bullhead Parkway and reset odometer. At ~0.5 mi there are more exposures of the Bullhead unit in roadcuts on both sides of the road. Enter the valley of Silver Creek at ~1.2 mi. At 1.7 mi, turn east (left) on Silver Creek Rd and proceed up the piedmont on dissected Plio-Pleistocene fan remnants for 1.7 mi. Pull off on the left side of the road. Hike to the bottom of Silver Creek (the broad, deep wash north of the road) and proceed ~100 m (328 ft) down the wash along the south side of the valley.

Stop 1.4: "Plush Toy" Nomlaki Tephra Site

At this site (named for some of the interesting trash that litters the slope) there is a middle Pliocene tephra deposit preserved in tributary fan gravels. It provides a minimum constraint on the inception of Colorado River downcutting following maximum aggradation (Figs. 12 and 15). As was discussed in the introduction, two separate middle Pliocene tephra deposits have been discovered in Mohave Valley. The older Lower Nomlaki tephra (3.6–4.2 Ma) has been found in distal tributary fan deposits that underlie the highest levels of the Bullhead unit and, thus, provides a maximum constraint for the culmination of river aggradation. The older Nomlaki tephra is described at Stop 2.5. Along Silver Creek, the younger Nomlaki tephra (3.3 Ma) is incorporated into tributary gravels that rest on an unconformity on top of Bullhead deposits and, thus, provides a minimum constraint for the timing of incision of the river after peak river aggradation.

The lower 10 m or so of section exposed here is primarily sand and gravel deposits of the Bullhead unit, with some interfingered tributary gravel deposits. These deposits are truncated by a slight angular unconformity that is overlain by 5–8 m of tributary fan gravel dominated by local lithologies, with minor reworked Colorado River gravel. There are several "pods" of tephra approximately in the middle of the capping tributary gravels, 125–300 m downslope from the dirt track. The highest outcrop of the tephra bed is 395 m (1300 ft) asl, slightly below the highest level of Colorado River aggradation (400 m asl). Farther down Silver Creek, the same bed is found at 350 m (1160 ft) asl, indicating that the river had incised at least 50 m below its maximum level of aggradation by 3.3 Ma. Thus, the Colorado River reached its maximum level of aggradation sometime after 4.2 Ma and possibly as late as 3.6 Ma, and by 3.3 Ma was substantially incised.

Directions and Highlights en Route to Stop 1.5

Proceed for ~2.7 mi up Silver Creek Road, passing a low bedrock hill on your left. An outcrop of tufa associated with the Bouse Formation is preserved on the side of this hill at an altitude of 260 m (1785 ft) asl. This is the highest tufa outcrop associated with the Bouse that has been found (Metzger and Loeltz, 1973), and its altitude is consistent with the Bouse deposits at Stop 1.6. Continue 0.2 mi farther east and pull off on the left side of the road. Follow the dirt road to the bottom of Silver Creek and cross the valley to view outcrops of the Bouse limestone intercalated between alluvial fan deposits.

Stop 1.5: Silver Creek Bouse Site

The purpose of this stop is to view the highest extensive Bouse deposits found along the lower Colorado River. This is also a classic, enigmatic exposure of a limestone a few meters thick sandwiched between relatively coarse alluvial fan deposits. The limestone is draped over cobbles and boulders that mantled an alluvial fan surface (Fig. 16). In the westernmost part of the outcrop, the Bouse is fairly pure, fine-bedded white limestone. There is a clastic component interbedded with limestone farther to the east and higher up in the section, and at the easternmost exposure there is abundant fine gravel. The altitude of the base of the Bouse ranges from ~530 m (1740 ft) asl in the west to 550 m (1810 ft) asl in the east. The contact between the limestone and the overlying fanglomerate is clearly erosional in some places; for example, notice where the fan gravels fill small channels cut into the Bouse deposits. In other places fine gravel beds and limestone are intercalated and the transition appears to have been more gradual. Substantial fan aggradation continued after the interval of Bouse deposition, as evidenced by the ridge capped by alluvial fan deposits that rises to 585 m (1920 ft) asl northeast of this site.

The tranquil water into which the Bouse Formation was deposited here surely represented a dramatic and (likely) brief departure from the subaerial alluvial fan conditions that had previously dominated the upper piedmont. It is interesting to note here how little-disturbed the underlying alluvial fan surface appears to have been when it was inundated. If the Bouse Formation represented a marine incursion into this area, one might

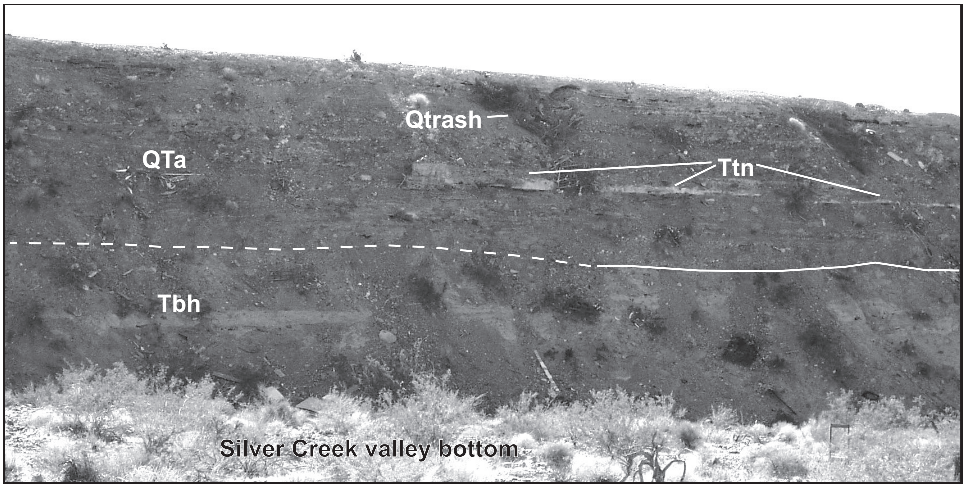

Figure 15. Photograph of a bed of the 3.3 Ma Nomlaki tephra (Ttn) in tributary gravel deposits at the "Plush toy" site. The tributary deposits rest above a slight angular unconformity on the sand and roundstone gravel of the alluvium of Bullhead City. Tbh—alluvium of Bullhead City (Colorado River deposits); QTa—locally derived alluvial fan deposits derived from the Black Mountains.

expect to see a more elaborate transgressional sequence including beach deposits overlain by quiet water deposits as water depth gradually increased. Even wave action along the shore of a gradually rising lake would probably disturb the underlying fan surface, although this location might have been sheltered by the bedrock hill to the west. It is possible that the maximum level of inundation in the valley was short-lived and possibly modulated by short-term variations in regional climate.

Day 2: Start and End in Laughlin

Directions and Highlights en Route to Stop 2.1

Travel north on S. Casino Drive through Laughlin and turn left (W) onto NV 163. Prepare to take an abrupt right turn onto N. Casino Drive, follow its sharp curve back to the east and then continue north toward Davis Dam. At ~0.6 mi park along the side of the road (see Fig. 5). Hike due west through the abandoned gravel pit. This pit served as an aggregate source during construction of the dam and its facilities. A large construction camp with many structures once occupied the flat area immediately north of here. Presently, the area serves as home to a small population of transient residents. Please be respectful of their home and their privacy, but also lock your vehicle.

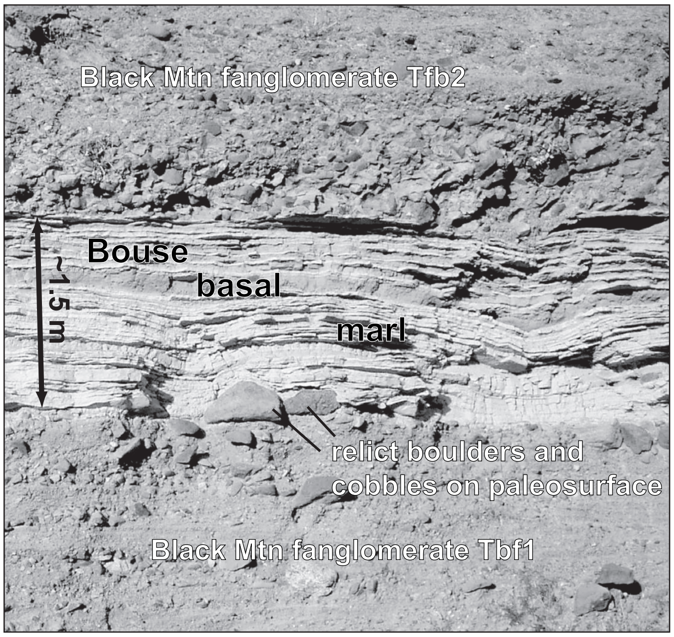

Figure 16. Photograph of the basal Bouse limestone intercalated between indurated tributary fanglomerates on the north bank of Silver Creek. The lower Bouse beds are draped over cobbles and small boulders on a relict alluvial fan surface. At this location, there are many thin sandstone and siltstone beds in the upper part of the Bouse exposure. The upper contact of the Bouse Formation here is mildly erosional, but in other parts of this exposure the upper fanglomerate fills small channels cut into the Bouse beds. Tbf1—pre-Bouse fanglomerate of Black Mountains; Tbf2—post-Bouse fanglomerate of Black Mountain.

Introduction

There are extensive exposures of Pleistocene alluvium of the Colorado River near Davis Dam, just north of Laughlin. Our mapping in this area has revealed a series of flood deposits, unconformities, and stratigraphic ambiguities that make unraveling the record and characterizing the Chemehuevi beds a challenge (Fig. 17).

Stop 2.1: The Davis Dam Bluffs—Best Dam Stratigraphy Ever

This stop highlights various aspects of the Quaternary record of the Lower Colorado River including evidence for a post-integration catastrophic flood through the Pyramid hill area and important discontinuities in distinctive packages of Pleistocene Colorado River deposits.

Davis Dam was constructed between 1942 and 1945 and 1947–1950 (the brief hiatus owing to material shortages during World War II). It is an earth-fill dam. Its base sits on river alluvium at a depth of 45 ft below the streambed. Exploratory borings made during dam planning and construction indicate that the depth to bedrock at the dam site is 200 ft (Bahmoier, 1950;

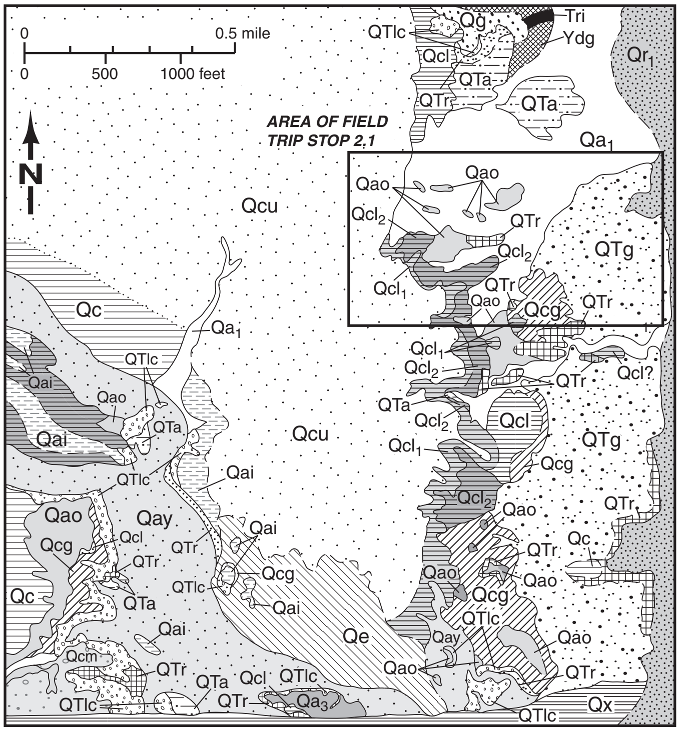

Figure 17. Detailed geologic map of the Davis Dam bluff vicinity (modified from Faulds et al., 2004); Ydg—Davis Dam granite; Tri—Rhyolite intrusion; QTg—undifferentiated Plio-Pleistocene river gravel; QTa—Plio-Pleistocene alluvial fan gravel; QTr—Riverside beds; QTlc—Laughlin conglomerate; Qao—early Quaternary alluvial fan gravel; Qc—Chemehuevi beds (Qcg—river gravel; Qcl—lower Chemehuevi beds; Qcl_1—mud unit 1; Qcl_2—mud unit two; Qcu—upper Chemehuevi beds; Qcm—Mohave sediments); Qai—intermediate age alluvial fans (middle to late Pleistocene); Qr1—alluvium of Riviera (Holocene).

U.S. Bureau of Reclamation, 1955). The dam is named in honor of Arthur Powell Davis, director of the Bureau of Reclamation from 1914 to 1932, and an important figure in the development of the Colorado River's water resources.

Hike west from N. Casino Drive for a few hundred yards and climb onto one of several terrace remnants for a good, panoramic view of the deposits that form the core of the bluffs. (Fig. 18). The base of the section includes sparsely exposed, indurated remnants of Pliocene or early Pleistocene fanglomerate. Late Miocene Newberry Mountains–derived fanglomerates are exposed immediately east of the river. The basal fanglomerate unit is overlain by the Riverside beds, a Colorado River deposit of mud, sand, and gravel. Thinly bedded, flat-lying fine-grained components of the Riverside beds are exposed along N. Casino Drive and are similar in composition and appearance to overlying river deposits. Beds of fluvial gravel and gravelly sand in the Riverside unit are exposed locally.

The Riverside beds are unconformably overlain by the conglomerate of Laughlin (informally called the Laughlin conglomerate), a coarse conglomerate comprised of cobbles and boulders of locally derived Proterozoic granite mixed with well-rounded, far-traveled pebbles and cobbles. The Laughlin unit is texturally similar to the transitional Pyramid gravel, but with the important distinction that the Pyramid unit does not contain exotic clasts. The Laughlin conglomerate was deposited well after the river had incised through the Bullhead fill to near the pre-integration valley axis. Otherwise, its age is not well constrained. Erosional topography and a paleosol in the Laughlin conglomerate indicate prolonged subaerial exposure of the unit prior to burial by a series of disconformable fluvial units.

We interpret the Laughlin unit as the result of a large flood that eroded a weak bedrock outcrop in the Pyramid hills area adjacent to the main channel. Exposures of the deposit define a lobe that widens downstream from a paleochannel in the large outcrop of Proterozoic granite southwest of Davis Dam. The Laughlin conglomerate has a total thickness of ~20 m (70 ft), and we have found no evidence to suggest that it is comprised of more than one deposit.

Erosional topography on the Laughlin unit and underlying deposits is overlain by the base of the Chemehuevi beds, which form the core of the two major fluvial terraces at this site. The thickest part of the sequence backfills the lower end of the paleochannel that was the conduit and likely source of the Laughlin conglomerate. The higher terrace has a maximum elevation of 252 m (830 ft), but the maximum traceable extent of the underlying deposits reaches to 256 m (840 ft) on the Newberry piedmont. The lower terrace surface evident here is predominantly a strath. It has a maximum elevation of 225 m (740 ft). The riser separating the two terraces is mantled with colluvium, and both terrace surfaces have locally extensive mantles of eolian sand.

Proceed from the overview spot toward the steep bluffs. The central part of the bluffs is covered with loose, sandy veneer. Just beyond the covered section to the south are a series of alluvial fan remnants protruding from the base of the bluffs. Hike up the

Figure 18. Annotated photo mosaic of the Davis Dam bluffs, north of Laughlin, Nevada. Qao—older (early Pleistocene?) alluvial fan deposits; Qao/Qcl—interfingered fan gravel and Colorado River sediment; Qcls—immature fine sand of lower Chemehuevi beds; Qcl_1—mud unit 1 of the lower Chemehuevi beds; Qcl_2—mud unit 2 of the lower Chemehuevi beds; Qcu—medium sand and gravelly medium sand of the upper Chemehuevi beds; Qe—veneer of eolian sediment.

spine of the northernmost remnant and peer into the precipitous gully (just left of center in Fig. 18).

The base of this section is a fining-upward sequence of alluvial fan gravel from the Newberry Mountains (Qao) and interfingered sand of possible Colorado River origin. This package grades upwards into a massive bed of flat-lying, immature fine sand that comprises the base of the lower Chemehuevi beds. The composition of these sands suggests a largely local derivation, but their texture and sorting suggest reworking by the Colorado River. The immature sand is overlain by flat-lying, slightly red fluvial mud which is, in turn, unconformably overlain by a very similar looking deposit of mud. This unconformity within the lower Chemehuevi beds is obvious here, but it becomes cryptic toward the south where it is flat and unremarkable in many places. Here, the mud-on-mud contact is marked by a sandy, homogeneous slab-like feature, likely a soil formed in fine-grained hillslope colluvium. The irregular trend of the "slab" suggests a furrowed, badland-type erosional setting. The mud-on-mud unconformity represents a hiatus in river aggradation followed by subaerial exposure and erosion which was followed by a second episode of aggradation of fluvial mud.

The two mud units are unconformably overlain by a thick sequence of clean, medium fluvial sand and minor gravel (the upper Chemehuevi beds). This contact can be traced from the north for several hundred meters to this point. Just beyond this point, it abruptly drops ~10 m, and then continues as a flat contact for several hundred meters to the south. The steep drop in the sand-on-mud contact suggests a channel margin. The continuity of stratigraphy in the upper unit indicates a thick net aggradation event. We have identified a paleosol in the lower part of the upper sand unit that indicates some complexity in the deposit's history.

The alluvial fan unit that is graded to the top of the Davis Dam terrace (Qai_1) is only clearly coeval with the gravelly sand component of the upper Chemehuevi beds. Relatively weak soils in the fan surface (distinct Bw and stage II to ~stage III Bk horizons) suggest that the upper Chemehuevi beds are late Pleistocene. Similar soils were dated at ca. 60 ka in the Parker area (Ku et al., 1979). The ages of the underlying mud beds are, however, not fully resolved, and we suspect that the lower Chemehuevi mud unit here is much older than the upper sand unit, while the younger mud unit may be closer in age and may form the base of a floodplain package that flanks the lateral margin of the thick sandy unit. Luminescence ages from a similar sequence of muds near Cottonwood Landing (34 km north) range between 40 and 70 ka (Lundstrom et al., 2000, 2004).

Directions and Highlights en Route to Stop 2.2

Upon leaving Laughlin, proceed west about a mile to Needles Hwy, and turn left (S) ~22 mi along the east flank of Mohave Valley to Needles, California, where you will enter I-40 eastbound (toward Kingman,. Arizona). Proceed southeast on I-40 seven mi through and past Needles (Figs. 4 and 19).

On the right is the domal Sacramento Mountains metamorphic core complex, and ahead is the Chemehuevi Mountains core complex, two elements of the Colorado River extensional corridor. In between, at ~two o'clock, a lone peak exposes the Miocene Sacram plutonic suite of Campbell and John (1996) which was intruded during the extension. Mafic plutonic rocks of Miocene age in this suite are part of an elongate zone over 200 km long of high residual isostatic gravity highs that track the axis of the Colorado River extensional corridor (Simpson et al., 1990). Carr (1991) speculated that isostatic subsidence of the dense rocks that cause the gravity high may have influenced the Colorado River's southward course.

Beyond the agricultural inspection station, part of I-40 is built on swelling clays of the Bouse Formation. Swelling of the clay after heavy rains in the early 1990s made the highway unsafe and required expensive repairs. A thin bed of white Bouse marl is present in this area, and extensive exposures can be seen ahead of horizontal-bedded mud and sand of the Bouse.

When you have been on I-40 for ~6 mi, the route passes near the Park Moabi exit and the river is visible. Recent drilling efforts here related to groundwater remediation efforts have provided new information on the subsurface stratigraphy, including identification of tens of meters of river laid sand recovered from below the west bank of the Colorado River. The upper part of this sand section is believed to be historical, as the river here aggraded ~8 m in the mid–twentieth century in the backwaters of Lake Havasu (Metzger and Loeltz, 1973). A wood fragment collected from fluvial sand at a total depth of 18 m (60 ft) recently yielded a mid-Holocene ^{14}C age. This supports the conclusions of Metzger and Loeltz (1973) and Metzger et al. (1973) that the predam river aggraded ~20–30 m in the Holocene. They based that conclusion on Holocene-age wood fragments recovered from drilling in fine-grained fluvial sediments beneath the floodplain 100 km downstream, and from a similar section drilled 15 km north of this spot.

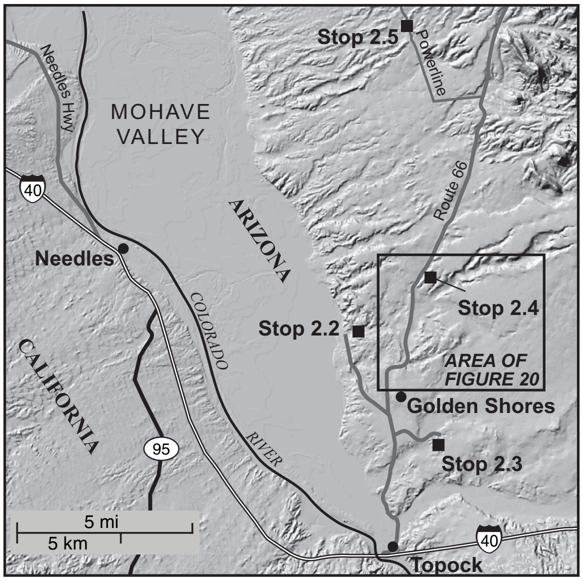

Figure 19. Map of field trip stops in southern Mohave Valley.

After 6.5 mi, cross the Colorado River on I-40 into Arizona. You will see the Needles on the right, pinnacles of synextensional, steeply west-tilted lower Miocene volcanic and sedimentary rocks (Howard and John, 1997). To the left (NE) of the Needles, the basement substrate of this section is exposed to paleodepths of 8 km below the Miocene rocks. All of these rocks were tilted and structurally superposed by eastward fault slip on the Chemehuevi Mountains metamorphic core complex in Miocene time (John, 1987; Miller and John, 1999). Gently east-sloping rock surfaces on the California side of the river indicate the position of the exhumed bounding Chemehuevi detachment fault, which projects eastward under the allochthonous rocks of the Needles. The river's path follows near this structural boundary as it courses southward through Topock Gorge. Continue 0.8 mi past the river to Exit 1, exit right and turn left over the freeway toward Topock. Proceed 4.4 mi. Much of the floodplain of the Colorado River in this area is now occupied by Topock Marsh, which flooded as a consequence of the river aggradation in response to Parker Dam downstream. From the fork at Golden Shores, keep left and proceed 2.7 mi. Turn right on an obscure jeep path, and proceed up the wash 0.2 mi to an area traversed by buried pipelines.

Stop 2.2: Piedmont Fans Interrupt the Colorado River's Fun

From here, take a walking traverse ~3 km round trip up the main wash to the east and a tributary to the northeast. Along the transect, one can examine well-exposed stratigraphy, compare older and younger Colorado River deposits and intervening fanglomerate, and consider depositional environments and geomorphic response to at least two successive episodes of river incision and aggradation. The stratigraphy here matches that described by Metzger et al. (1973) and Metzger and Loeltz (1973).

The high banks of the main wash expose >20 m of cross-bedded fluvial sandstone and interbeds of fluvial roundstone conglomerate. These deposits can be traced to exposures a mile and a half to the north-northeast that were identified by Metzger and Loeltz (1973, their Figure 14) as their unit B, which we consider equivalent to the Pliocene-age alluvium of Bullhead City of this report. Look for well-rounded pebbles of chert, quartzite, and Paleozoic limestone derived from far upstream. Locally derived angular or subangular clasts of volcanic rocks and gneiss make up at least half of the larger clasts. Well rounded quartz sand grains in the sandstone may be reworked from Permian and Jurassic sandstones on the Colorado Plateau. Rusty zones in the deposits here are commonly associated with clay balls, wood casts, or vertebrate remains. The clay balls may derive from bank erosion of rare clay beds in the sequence, or from the Bouse Formation. Note the planar crossbeds in both sandstone and conglomerate. Do the thickness of crossbeds indicate flow depth and large discharge of a braided stream?

One km to the southwest, the fluvial sand overlies basalt-clast fanglomerate that may either predate or postdate the Bouse Formation. It may correlate with a fanglomerate 100 km to the south that Metzger et al. (1973) recognized (their unit A) as over the Bouse Formation and unconformably overlain by unit B alluvium (our Bullhead City unit).

Note that the cross-bedded fluvial sandstone is exposed in the bed of the modern wash. This indicates that the modern flat-floored drainage is graded to Topock Marsh on a pedimented surface, and by inference this particular wash postdates the 20–30 m of Holocene aggradation known for the nearby Colorado River floodplain downstream.

Capping the alluvium of Bullhead City is a paleosol overlain by dark, coarse-grained alluvial-fan deposits (fanglomerates) dominated by basalt derived from the Black Mountains. Metzger and Loeltz (1973) described a series of such fanglomerates (their unit C, piedmont gravels) as alluvial fans that prograded into the valley as the thick underlying fluvial aggradation package (unit B, our alluvium of Bullhead City) underwent incision. Several ages and terrace levels of such fans are preserved in the landscape east of us. The Bullhead City unit into which these fans are inset can be traced intermittently to the east from here to valley-flank elevations as high as 200 m above the river, indicating the thick valley fill the unit represents.

Walk up a narrow tributary to the NW and see that the Bullhead City unit here, slightly more distal from the valley axis, lacks the two conspicuous conglomerate layers that are nearer to the parking area, and instead exposes mainly sandstone and 3–4 clay lenses as thick as 0.3 m. Do these clays record standing ponds in distal parts of a braidplain? Sandstone regionally dominates the Bullhead City unit. Resistant roundstone pebbles derived from less thick interbedded conglomerate layers form conspicuous lags and are commonly reworked into alluvial fans and soils.

At the head of the gully, pale orange layered mud and very fine sand (unit D of Metzger and Loeltz, 1973) of the Chemehuevi beds overlies the sandstone, locally with a thin intervening alluvial-fan deposit of basalt boulders (unit C) or a pebbly paleosol. One km to the NW, 2 m of calcite-cemented paleosol lies at the top of the fanglomerate, indicating long exposure before the Chemehuevi Formation was deposited. The overlying Chemehuevi layered mud unit is many meters thick at this position, but thins to 0.5 m within 1.5 km to the north. Does the mud represent overbank deposits on a floodplain?

Here, as elsewhere, the mud is overlain by well sorted, unconsolidated, light-toned sand, which forms gentle slopes. The sand, unit E of Metzger et al. (1973) and Metzger and Loeltz (1973), is ~20 m thick and locally exhibits two internal red pebbly paleosols. A lag of roundstone and angular pebbles caps the sand. Nearby (1 km from here) a thin (0.5 m) basalt-clast fanglomerate intervenes between the loose sand and thin underlying mud of unit D. This stratigraphy suggests that an alluvial fan prograded into the valley as the mud deposition ceased.

Climb to the top of the sand for an overview of the stratigraphy and of the preserved fan morphology upslope of the fanglomerate deposits that interfinger in the section. A succession of unit C fans, graded to increasingly lower topographic levels, may correspond to intermittent incisional lowering of the valley floor after unit B aggraded, or to smaller episodes of intermittent river aggradation during or following the major lowering. Muds and sands of the Chemehuevi beds (units D and E) represent one or more cycles of aggradation and subsequent degradation of the river valley. The best existing dates for these beds are late Pleistocene, between 35 and ca. 100 ka (Bell et al., 1978; Blair, 1996; Lundstrom et al., 2004).

Directions en Route to Stop 2.3

Return to vehicles and to Hwy 95. Turn left and backtrack 2.7 mi, passing back through Golden Shores and the fork for the Oatman Hwy. Turn left on to Polaris Road, and proceed east for 1.5 mi (Fig. 19). Park at the crest of a small hill.

Stop 2.3: Mammoth Retires at Golden Shores

At this stop, the stratigraphic setting and implications of an early Pleistocene mammoth site can be examined and considered.

Mammoth remains were first reported from the Colorado River valley by Newberry (*in* Ives, 1861). He found a tooth at what the expedition called Elephant Hill, now in Lake Mohave. Other sites up and down the river valley have been discovered over the years, and the total now exceeds 12 sites from the Lake Mead area to Mexico (Agenbroad et al., 1992). Many of the specimens have been designated as *Mammuthus columbi,* whereas others have been designated as the older *Mammuthus meridionalis*.

A nearly complete skeleton was recovered at this site. The mammoth evidently settled on its back in shallow water and was encased in fine clays; abundant imprints of reeds and sedges in the clay suggest a marshy environment (Agenbroad et al., 1992). Unfortunately, teeth were removed from the remains and not available for examination. Agenbroad (L.D. Agenbroad, 1995, 2005, personal commun.) evaluated a photograph of the teeth and concluded that it was probably a *M. meridionalis*, and dates to ca. 1.5–1.7 Ma.

The Golden Shores mammoth site occurs at an elevation of 207 m (680 ft) asl within a section of interbedded and interfingering Colorado River gravel, sandstone, mudstone, and locally derived angular gravel containing some reworked roundstone pebbles. Nearby within the deposits, root casts below a minor paleosol indicate that deposition of the fluvial section was discontinuous.

The mammoth site lies south of the road across a gully, and is marked by a post and a sign that warns against disturbance. Inasmuch as North American mammoths are not known before the Pleistocene (L.D. Agenbroad, 1995, personal commun.), the mammoth age and the facies assemblage suggest deposition during an early Pleistocene aggradational episode of the river. If so, this postdates the alluvium of Bullhead City and predates or may overlap in age with some of the Chemehuevi beds or the older, post-Bullhead riverside beds.

Alluvial-fan deposits that lie below the mammoth horizon contain roundstone pebbles that suggest derivation from older (Bullhead City) river deposits. From the mammoth site to 5 km to the east are discontinuous exposures of fluvial sand and gravel, which we regard as mostly B, the alluvium of Bullhead City. There are many such exposures of unit B in this part of the valley. The exposures east of the mammoth site extend to a hilltop 5 km east where reworked (unit B) roundstones in a soil reach an elevation of 311 m (1020 ft) asl, over 100 m higher than the mammoth site. Assuming these are older Bullhead deposits, they provide a potential source for later reworking of roundstones into alluvial-fan deposits that interfinger with or underlie the fluvial section at lower elevation that hosts the mammoth. Do the deposits that hold the mammoth represent a local fluvial aggradation inset into the older, thick Bullhead City sequence following a major late Pliocene or earliest Pleistocene incision? If so, this hints that, in addition to the aggradation recorded by the Chemehuevi beds, the river experienced at least one gravel-rich early Pleistocene aggradational episode.

Directions and Highlights en Route to Stop 2.4

Turn around, return south 1.5 mi, and turn right on Route 66. In 0.7 mi, fork right (straight) on the Oatman Hwy (Fig. 19). This road is part of historic Route 66, famed in song and immortalized in John Steinbeck's *The Grapes of Wrath*. As you pass through the community of Golden Shores, ponder the desperate people fleeing the 1930s dust bowl en route to California. Two and a half miles farther, the road crosses extensive deposits of red mud of the lower Chemehuevi beds. Then, 1.7 mi farther, just past a major gully, park on the right side of the road at a bend to the left.

Stop 2.4: The Crinkled Quaternary Alphabet

The object of this stop is to discuss evidence for deformation in Mohave Valley since the inception of the Colorado River.

Compared to southwestern California, deformation features younger than Miocene are uncommon along the lower Colorado River valley. This relative tectonic quiescence made the region attractive in the 1970s for site-proposals for nuclear power plants downstream near Vidal and Blythe. The plants were never built, but related geologic investigations added much to the knowledge of late Cenozoic geology in the region. The Golden Shores area of Mohave Valley is one of the rare areas where several faults and folds deform post-Bouse deposits. Tilting and faulting were recognized by Metzger and Loeltz (1973) 9 km south of this stop in their unit B (Bullhead alluvium of this report), at a locality earlier photographed by Lee (1908). Based on the presence of faults and tilted beds, and of gravels logged from a well 95 m (310 ft) below the floodplain of central Mohave Valley, Metzger and Loeltz (1973) suggested that their unit B (our Bullhead City unit) may be structurally sagged beneath Mohave Valley. Pleistocene alluvial fan deposits are clearly faulted in the Needles graben a few miles southeast of this site (Fig. 20; Purcell and Miller, 1980; Pearthree et al., 1983).

Looking east across the gully from Stop 2.4, view an exposure of sandy-gravel alluvial-fan deposits that dip southwest 20° and are cut by a pair of conjugate WNW-striking normal faults. The deformed deposits are capped unconformably by a basalt-clast fanglomerate, which exhibits >2 m thick calcic soil horizon that is not obviously deformed. This suggests that the deformation age was earlier than middle Pleistocene.

The undeformed capping fanglomerate forms a partly preserved fan terrace (C2 on Fig. 20) that is one of a downward

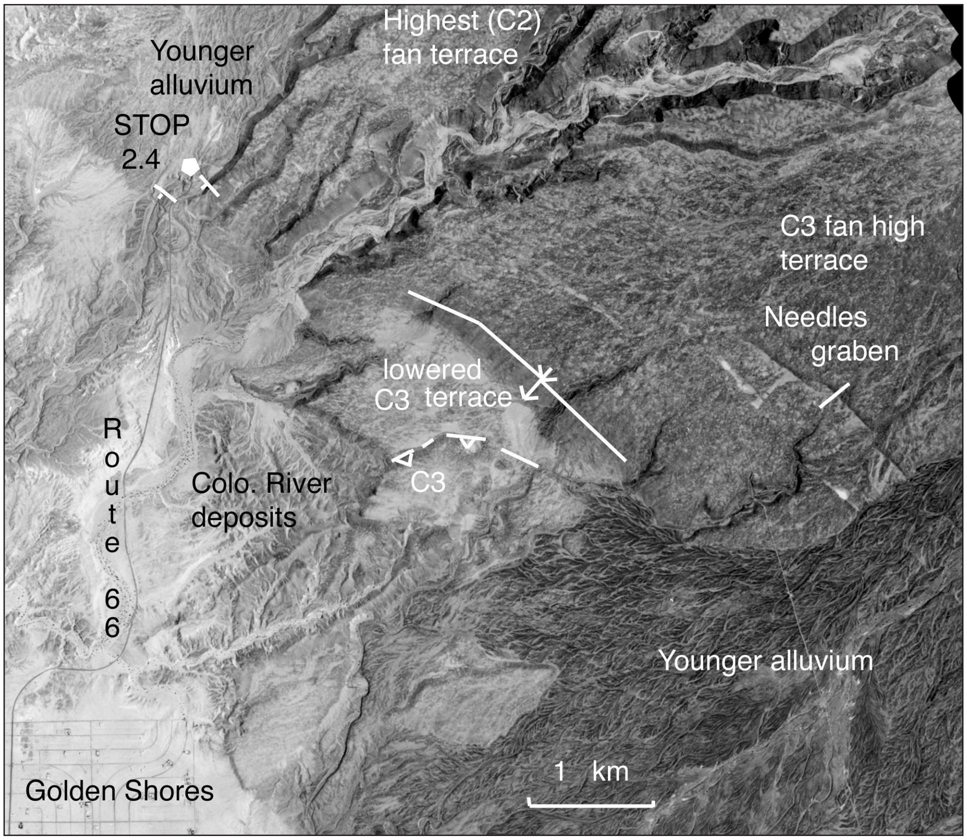

Figure 20. Deformation features near Golden Shores, Arizona. Air photo of (1) Needles graben, (2) monocline (double arrow symbol), and (3) small thrust fault (with teeth) northeast of Golden Shores, Arizona. These features deform an old fan (C3) that is one of several that postdates the alluvium of Bullhead City. The C3 fan is inset into the topographically higher and older C2 fan, which unconformably overlies dipping beds (dip symbols) indicating older (Pliocene?) deformation. Small offsets along the Needles graben trace southeastward into younger alluvium (upper Quaternary), indicating that deformation on the graben faults continued into late Pleistocene or Holocene time.

succession of post-Bullhead fans from the Black Mountains graded toward the central part of the valley. Metzger and Loeltz (1973) also reported this observation in relation to their stratigraphy.

A mile ESE of this location, the Needles graben and two other structures deform at least 2 younger Pleistocene alluvial surfaces (Fig. 20). The most prominent faulted surface is also capped by thick calcic soil and exhibits several deformation features: (1) the NW-striking Needles graben (Purcell and Miller, 1980; Pearthree et al., 1983), (2) a NW-striking ramp interpreted here as a monocline, and (3) a thrust fault that strikes perpendicular to those features. There is evidence for recurrent fault movement during the middle and late Quaternary along the graben (Pearthree et al., 1983), and the large scarp associated with the monocline (~25 m) is consistent with recurrent deformation. Within a few kilometers of here are also several other faults and a syncline that deform the alluvium of Bullhead City or younger deposits.

Quaternary graben structures have also been reported in alluvial fans near the river 100 km south of here near Blythe and 30 km south in Chemehuevi Valley (Purcell and Miller, 1980). The cause of the local extension recorded by these grabens is uncertain. The Needles graben and related monocline and small thrust directly overlie a gravity low indicative of thick low-density sedimentary fill (Gray et al., 1990). Sedimentary compaction of this fill may explain the graben and monocline. The shape of the gravity low, however, does not offer an obvious explanation for the bulk downthrow to southwest, or for possible sagging of sediments under the river valley as suggested by Metzger and Loeltz (1973).

Highlights and Directions en Route to Stop 2.5

Continue 6 mi NE on Hwy 66. Turn west (left) onto dirt track and head nearly due west down the piedmont (Fig. 19). The fine-grained sediment that is extensively exposed on the north side of this valley may be the Bouse Formation, although no basal limestone is evident here. The altitude of these deposits is between 378 and 390 m (1240–1280 ft) asl, so they could be related to the Bullhead unit, but no cross-bedded sand or roundstone was observed in this outcrop. Continue west for 1.4 mi and turn north (right) onto the dirt track that follows the powerline. The road traverses a moderately to darkly varnished late (?) Pleistocene alluvial fan deposits, with limited Holocene deposits along active washes. Much higher ridges east of the powerline are probably capped with Plio-Pleistocene fan remnants. The first limited exposure of the Lower Nomlaki tephra is visible about 1.8 mi along the powerline on the eastern nose of a ridge remnant west of the dirt track. Continue north ~2.5 mi and stop on this low ridge beneath the powerline.

Stop 2.5: Fantastic Tephra Outcrop

Several years ago, we made a fortuitous discovery of a thin tephra bed interbedded with fan and river deposits near the 13th green of a planned golf course near Bullhead City. This discovery helped us reframe our conception of the river's early history. We subsequently found (or in one case, rediscovered) the same tephra in two additional locations, along the powerline road north of Topock and northwest of Cottonwood Landing, Nevada, in Cottonwood Valley.

All of the tephra outcrops are within 30 m of the highest extant gravels of the Bullhead alluvium. Geochemical fingerprinting of tephra samples from each site indicates that they are the Lower Nomlaki tephra, which is dated between 3.6 and 4.2 Ma (A. Sarna-Wojcicki, 2002, personal commun.). The Nomlaki series tephra beds are members of the Tehama and Tuscan Formations of the Sonoma Volcanic Field in north central California (sources cited in Sarna-Wojcicki et al., 1991). Because of its presence high in the Bullhead aggradation sequence, this tephra provides an important constraint on the timing of maximum Colorado River aggradation in this valley.

The area immediately around us contains extensive exposures of the Lower Nomlaki bed. A tephra exposure in this area was first noted by Metzger, who described it to J. Bell in the early 1970s. At that time its chronologic and stratigraphic importance was not fully appreciated. Tephra is intermittently exposed on the sides of at least 3 parallel ridges for ~1.5 km in a north-south direction. Altitudes of the exposures range from ~365 m (1200 ft) to 370 m (1215 ft) asl. Everywhere we have observed the tephra bed in this area it rests on sand, silt, or fine gravel and it is overlain by similar deposits; no definitive Colorado River deposits have been identified immediately above or below the tephra outcrops here, but limited exposures of Colorado River gravel and sand deposits are on this ridge that lie stratigraphically above the tephra and there are outcrops of clean sand and river gravel that appear to underlie the tephra bed ~0.5 km west of the powerline road.

Because the tephra bed is so extensive here, we can reconstruct the shape of the surface on which it was deposited. This paleosurface dipped gently (~0.5°) to the west or southwest. Based on the character of the deposits surrounding the tephra and the surface slope, we infer that the tephra was deposited on a gently-dipping, relatively fine-grained distal alluvial fan not far from the Colorado River floodplain. Subsequent to tephra deposition, the Colorado River continued to aggrade and eventually onlapped the distal alluvial fans, depositing limited river sand and gravel at least as high as 385 m (1260 ft) asl in this area.

The geologic and geomorphic settings of the other two exposures of Lower Nomlaki tephra were also apparently marginal to the Colorado River floodplain. In each case, the tephra is found ~400 m (1320 ft) asl. In the 13th green exposure, the tephra bed rests on fan gravel but is overlain by gravel that includes roundstone gravels. At the Cottonwood Landing site, the tephra bed is at the base of a tabular bed of Colorado River sand interfingered with fan deposits.

The tephrochronologic constraints on the fluvial transition in Mohave and Cottonwood valleys (as defined by the pre–Bouse Connant Creek tephra and the Bullhead peak aggradation Lower Nomlaki tephra) nearly perfectly mirrors what is currently known about the integration and incision of the Colorado River through the Grand Canyon. The same Connant Creek bed is beneath river-precluding lacustrine deposits in the western Lake Mead area (Faulds et al., 2002). At Sandy Point, Arizona, near the mouth of the Grand Canyon, a recently redated 4.4 Ma basalt flow is intercalated with river gravels 100 m above present river grade, so the Colorado River was obviously well-established and probably aggrading west of Grand Canyon at 4.4 Ma (Howard et al., 2000). These new geochronologic constraints support the process-linkage between canyon incision upstream and massive valley aggradation downstream.

Casting the mechanism for the deposition of the alluvium of Bullhead City in this new light is an important step in reframing the problem of the evolution of the river. It appears that the process of drainage integration forced a huge pulse of fluvial aggradation, and Cottonwood and Mohave valleys were buried, not carved by the Pliocene Colorado River. The deposition of the Bullhead unit was a unique event in the history of the river that was driven by an internal adjustment to a particularly voluminous, relatively coarse sediment load. Thus, the character and volume of sediment deposited by the river in the early Pliocene is quite different from any depositional interval during the Quaternary, when aggradation was presumably driven by external controls such as climate change.

Day 3: Laughlin to Las Vegas Via Detrital Valley and Hoover Dam

Introduction

Driving distance ~180 mi. Stops during the first half of Day 3 are in Cottonwood Valley and contain evidence for the body of standing water that formed above and eventually breached the Pyramid hills divide, which filled both Mohave and Cottonwood valleys with a deeper and larger body of standing water. Stops during the second half of the day involve looking at distant outcrops of the late Miocene Hualapai Limestone and high-level Pliocene Colorado River deposits in Detrital Valley, and a spectacular set of high-standing potholes carved in bedrock near Hoover Dam.

Directions and Highlights en Route to Stop 3.1

Depart Laughlin by heading north on Casino Drive and turning east at the intersection with Hwy 163. Bear left (N) at the intersection of the Bullhead Parkway and AZ 68 (0 mi) (Figs. 1 and 4). At 11.4 mi the route crosses Union Pass into Sacramento Valley. Continue 25.5 mi to the Junction with U.S. 93 and take the exit for Boulder City/Las Vegas, Nevada. At ~39 mi, the route crosses the low divide between Sacramento and Detrital valleys near the turnoff to Chloride, Arizona. Exit left at the junction with Cottonwood Road at 46 mi. Follow Cottonwood Road for 8 mi through a sparse residential area to the Lost Cabin Spring turnoff to the left (not marked). Follow this dirt track (high-clearance best but not absolutely necessary) for 3.2 mi to Lost Cabin Spring and continue south for 5.8 mi until the road forks at upper Lost Cabin Wash. Take the right fork down the wash (W). The first stop is the base of a prominent west facing bluff of indurated fanglomerate ~5.4 mi down the wash.

Stop 3.1a: Miocene Fanglomerate. Many of the deposits exposed in Lost Cabin Wash evidently predate any influence from the developing Colorado River. The lowest part of the section consists of relatively fine alluvial-fan deposits composed almost entirely of clasts derived from the Newberry Mountains to the west, indicating that the preriver era fans extended from the mountain front to ~3 km east of the Arizona shore of Lake Mohave. Locally these fan deposits overlie older, tilted fanglomerates. The beheading of the Newberry Mountains–derived fans by the early river provided copious amounts of local gravel for fluvial transport and redeposition as the lower part of the alluvium of Bullhead City. There are exposures of reworked and intricately cross-stratified deposits of Newberry sand and gravel at the base of the Bullhead unit in southern Cottonwood Valley. Moving upsection to the east, we see a gravelly fluvial sequence that is dominated by Black Mountains volcanic clasts but also contains clasts from the Newberry Mountains. Structures in the gravels and their bedding suggest a NS alignment of the axial valley system similar to the modern one (minus the Colorado River).

Stop 3.1b: The Lost Cabin Bluffs. Continuing up the wash, the axial-valley gravel transitions into a prominent, bluff-forming sequence of interbedded sandstone and mudstone that we (informally) call the Lost Cabin beds (Fig. 21). They are a key piece of the latest Miocene stratigraphic puzzle in this area (Fig. 2C). The beds consist of ~100 m of fine-grained, flat-bedded clastic deposits. In locations near here to the north, the 5.5 Ma Connant Creek ash bed occurs within the upper third of the sequence (Fig. 22). This is the same tephra bed viewed at Stop 1.3. The Lost Cabin beds indicate a change in depositional conditions in southern Cottonwood Valley that preceded deep inundation and deposition of the Bouse Formation. More importantly, similar conditions did not exist in northern Mohave Valley, on the other side of the Pyramid hills. We interpret these relations as a strong case for the formation of a pre-Bouse body of standing water in Cottonwood Valley, eventual catastrophic drainage through the Pyramid hills, and inundation of both valleys by a second, deeper body of standing water into which the Bouse Formation was deposited.

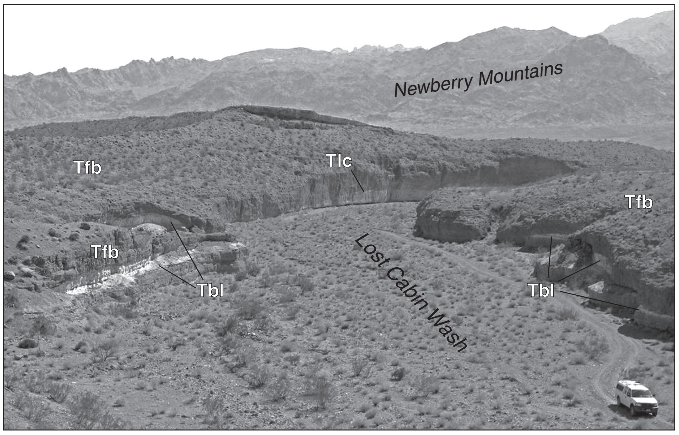

Figure 21. Oblique photograph of the Lost Cabin bluffs in Lost Cabin Wash, Arizona. Tfb—Black Mountains–derived fanglomerate; Tbl—Bouse limestone-marl; Tlc—Lost Cabin beds.

Continuing upsection while driving up the wash, look carefully along the south wall and you can see deposits of mud (Bouse?) in small erosional niches at the top of the Lost Cabin beds. Also evident are some intervening alluvial fan deposits derived from the Black Mountains, and then some unequivocal outcrops of the Bouse Formation appear as prominent tabular beds of buff to cream-colored sandstone and bright white lenses of marl, located mainly along the south wall of the wash. The fine-grained Bouse deposits are intercalated with tributary gravel deposits and possible turbidite deposits. It appears that this area was the focus of a dynamic interaction between the margins of the water body and the tributary alluvial fans.

Stop 3.1c: Thin, tenacious outcrops of Bouse marl. More exposures of the Bouse Formation are visible as you continue up the wash. At ~3 mi upstream of Stop 3.1a, a small tributary enters the main wash from the south. Park your vehicle and walk up this wash for ~0.2 mi. In the banks of this wash, the Bouse marl occurs as a very thin bed draped over a likely wave-worked paleosurface. The bed is generally less than 5 cm thick, but it can be easily traced up the tributary. We have noted fossil plant impressions in some of the marl, but have not investigated them in detail.

Stop 3.1d: Lost Cabin Beach. The final stop in Lost Cabin Wash is an enigmatic outcrop of cross-stratified, clean sand hemmed in between a bedrock outcrop and indurated, tilted Miocene fanglomerates along the margin of the wash. This site is ~5 mi from the Stop 3.1a. Beds of moderately well-sorted, locally derived gravel and some poorly exposed beds of greenish-yellow mud are also associated with the sand. We think that these sands and gravels are potential Bouse shoreline deposits. If this is the case, the fact that they are found at an elevation consistent with the highest Bouse deposits in Mohave Valley indicates a flat water surface at 550–560 m (1800–1840 ft) asl over an axial distance of more than 30 km, thus bearing no evidence of significant regional tilting. These are the highest Bouse-like deposits that we have yet found in Cottonwood Valley. About 2 km west of here we have found a series of unequivocal Bouse sandstone outcrops comprising a fan-delta sequence at ~490 m (1600 ft) asl.

Just down the wash from this site there is a distinct, nearly flat-lying shelf that crops out along the base of the fanglomerate bluffs along the south wall. We suspect that this feature may also be related to shoreline processes.

Directions and Highlights en Route to Stop 3.2

Retrace the route to U.S. Hwy 93 in Detrital Valley, and turn left (N) toward Las Vegas (Figs. 4 and 23). Note how high the alluvial fill of Detrital Valley is perched above the adjacent deeply incised Colorado River valley to the west. Was the Colorado valley equally filled following Miocene extension and subsequently exhumed? Proceed 22.8 mi to the Temple Bar Road and turn right toward Temple Bar. Proceed north 5 mi and park.

Stop 3.2: Pliocene Fluvial Detritus in Detrital Valley

This stop (Fig. 24) presents an overview of sediments and landforms involved in the early history of the river in the Lake Mead region. Detrital Valley debouches into Lake Mead (formerly the Colorado River), visible ahead to the north. The valley is one of several north-striking structural valleys that the river historically traversed westward across the Basin and Range province from the edge of the Colorado Plateau, before turning south in the area now occupied by Hoover Dam.

The earliest history of the Colorado River in the Lake Mead area and the mouth of the Grand Canyon to the east revolves around the upper Miocene Hualapai Limestone, the youngest unit to predate the river's arrival. This unit (Thl in Fig. 24) capped a series of nonmarine sediments that filled interior basins in this region at the close of Miocene tectonic extension (e.g., Tm). The highest outcrops of this limestone represent the level of the interior basin fill just before arrival of and incision by the Colorado River (Lucchitta, 1972; Longwell, 1936; Blair and Armstrong, 1979). The highest limestone outcrops can be traced by eye as light-colored mesas 6–10 km to the northeast and above our position, at an elevation of ~700 m (2300 ft) asl. They outline a bathtub ring along the southeast side of the valley that laps against dark Miocene volcanic rocks. The high limestone caps a sequence of mudstones, gypsum, more limestone, and unexposed halite deposits. This upper Miocene fill sequence evidently occupied a bolson not unlike many others in the modern Basin and Range province.

Spencer et al. (2001) dated a tuff in the Hualapai Limestone just beyond the field of view to the southeast, a few tens of meters below the highest outcrops. The date of 5.97 ± 0.07 Ma constrains the timing of the subsequent arrival of the river into the Basin and Range province. The highest exposures of the Hualapai occupy a similar elevation in the next valley to the east and over the top of the next adjacent range to the east. At the base of the Grand Wash Cliffs the limestone top has been uplifted along a fault to as high as 880 m (2900 ft) asl.

The Hualapai Limestone was suspected to be marine by Blair (1978), and nonmarine but deposited near sea level by Lucchitta (1979) and Lucchitta et al. (2001). Strontium isotope measurements show that the Hualapai is nonmarine and isotopically unlike the modern Colorado River, but the Sr values are consistent with a preriver origin from sources affected by the Precambrian bedrock (Spencer and Patchett, 1997; Patchett and Spencer, 2001). Oxygen isotopic values indicate that the Hualapai Limestone was mostly nonevaporative, and its basin of deposition therefore saw considerable through-flow of water (Faulds et al., 2001).

The oldest direct evidence of the river arriving in the Basin and Range province in the Lake Mead region are rare roundstone pebbles intercalated in a sequence a few meters thick of sand, silt, and clay that conformably overlies the Hualapai Limestone near the mouth of the Grand Canyon. Subsequent Colorado River sands and gravels are incised into the Hualapai Limestone and below it at a variety of levels from a few meters to hundreds of meters (Howard and Bohannon, 2001).

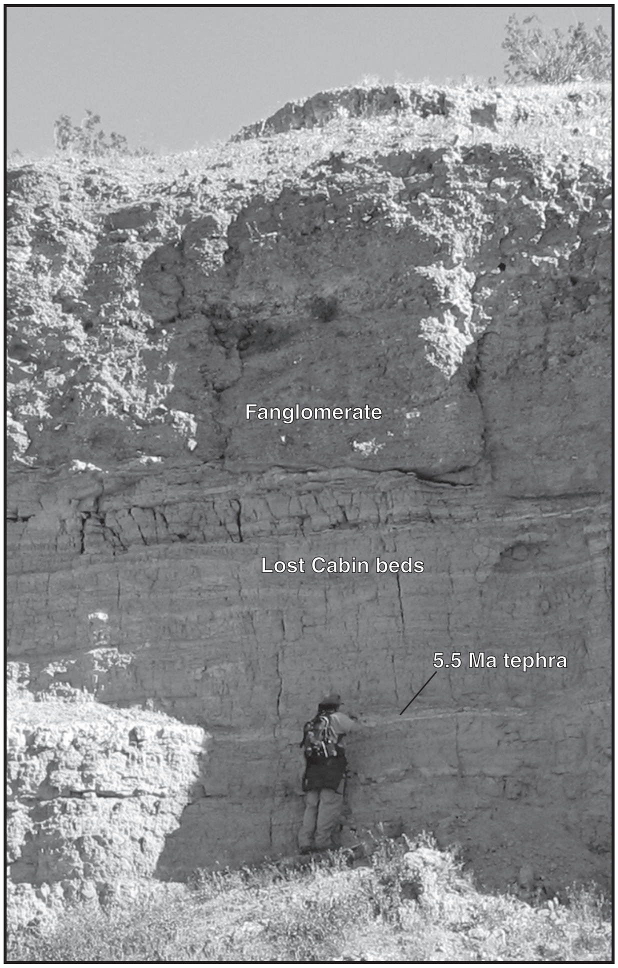

Figure 22. Photograph of the 5.5 Ma ash layer in the upper part of the Lost Cabin beds near Lost Cabin Wash, Arizona.

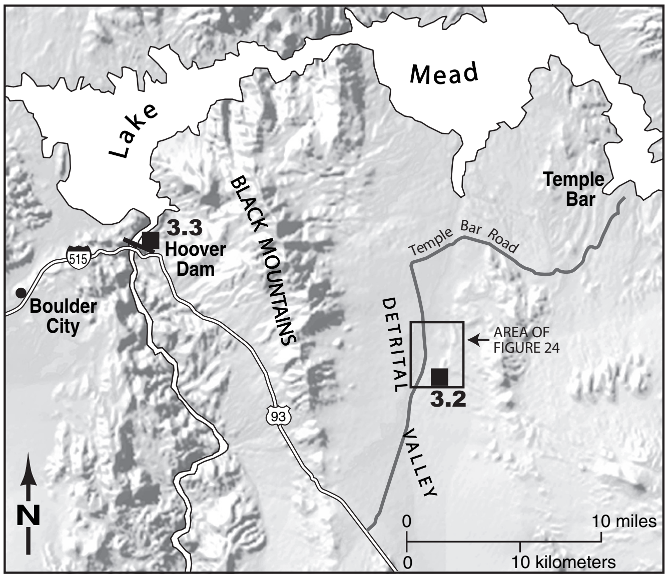

Figure 23. Map showing locations of field trip Stops 3.2 and 3.3.

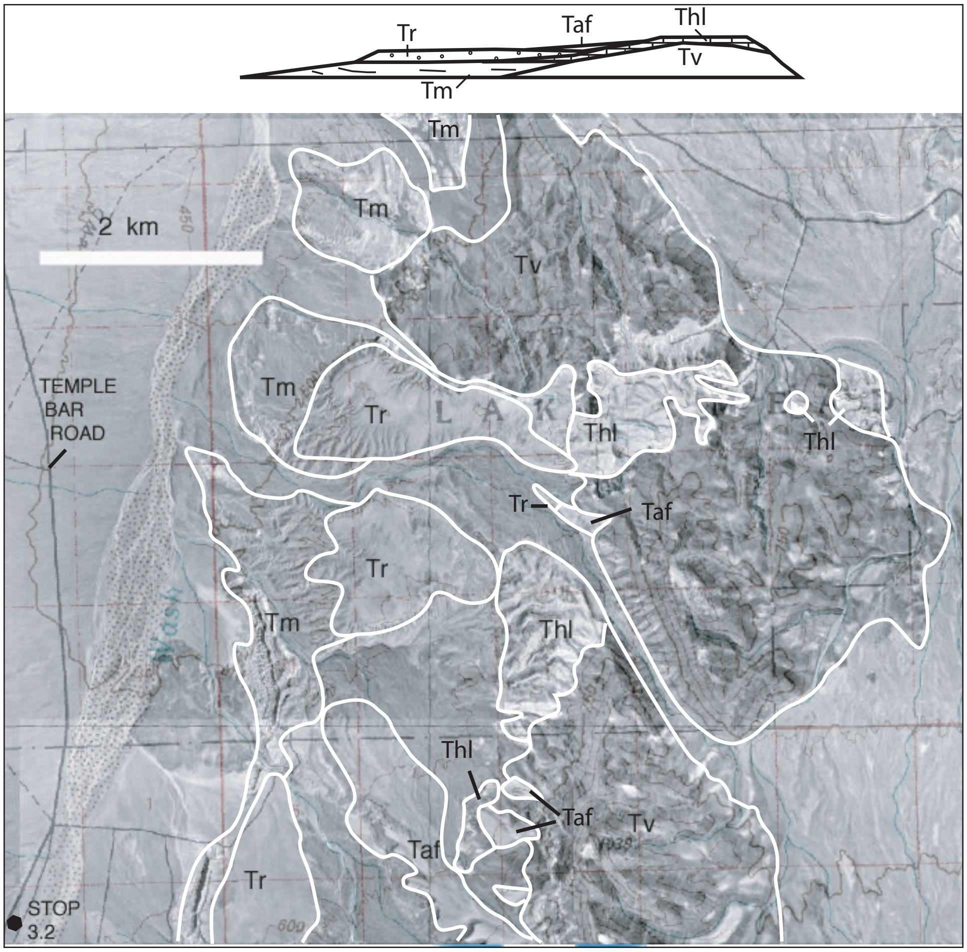

Figure 24. Air-photo map and conceptional cross-sectional sketch of the northeast side of Detrital Valley. Detrital Wash on the left drains northward to Lake Mead. The geologic units, in upward stratigraphic succession, are as follows: Tv—middle Miocene mafic volcanic rocks and ash-flow tuff; Tm—upper Miocene pink mudstone, limestone, and gypsum; Thl—upper part of the Hualapai Limestone (upper Miocene), which outcrops as a bathtub-like ring buttressed against the volcanic highland; Tr—riverlaid sand and gravel of the ancestral Colorado River, inset below the Hualapai Limestone (Pliocene?); and Taf—mesa-forming fanglomerate graded onto the Tr deposits and capped by a thick, resistant calcic soil (Pliocene?). Younger alluvial-fan deposits are not labeled.

One such packet of fluvial gravel and sand can be seen in front of and inset into the Hualapai Limestone exposures in the field of view, on the southwest flank of Detrital Valley. The undated river deposit (Tr) here is horizontal and lies at elevations between 520 and 620 m, 80 m below the floor of Hualapai Limestone. Its 100-m thickness represents an aggradational phase in the early river history. Whether the deposit reflects the same aggradation as the alluvium of Bullhead City is not yet resolved (Beard et al., 2005). Northward toward Lake Mead are other deposits at successively lower elevation. Because exposures concentrate at two or more distinct levels (Mel Kuntz, 1997, personal commun.) we suspect they are inset fills, younger than the 100-m-thick section before you; however it is also possible that they represent strath terraces cut into lower and deeper parts of an early, thick Bullhead-type aggradation.

Lee (1908) proposed that the river initially followed Detrital Valley far southward to Sacramento Valley and the Needles area, but there is no evidence to support this or any other course greatly different from the modern one. The existence of river gravels at high levels in this and other valleys and considerably away from the modern west-flowing channel, however, suggests that at times of aggradation the river wandered extensively on braidplains away from its most direct westward route, which was directly across these N-striking valleys.

Graded over the top of the river gravels are remnants of locally derived alluvial-fans capped by mesa-forming resistant, meters-thick soil carbonate horizons (Taf). The thick soil is consistent with a Pliocene age. As with the old fans discussed earlier in the trip near Golden Shores, these fans may record progradation over abandoned river deposits subsequent to incision of the river and erosion of river deposits. How many incision-aggradation sequences the river experienced in the Lake Mead area is yet to be determined. One important clue may come, however, from dating in progress by Ari Matmon of abandoned river potholes near Hoover Dam, at Stop 3.3.

Directions and Highlights en Route to Stop 3.3

Return southward up the Temple Bar Road and reset the odometer as you turn north onto U.S. 93 toward Hoover Dam (Fig. 22). In two mi you will leave the high detritus of Detrital Valley through Householder Pass and see the deep canyon of the Colorado River. This pass is barely higher than the Hualapai

Limestone and the inferred initial path of the river, yet there is no evidence that the early river took this shortcut southwestward. Instead the river coursed westward and incised precipitous Boulder Canyon through a high ridge of the Black Mountains 35 km north of here, then flowed westward through Boulder Basin before exiting southward into Black Canyon, the site of Hoover Dam, and continuing into the canyon in the foreground. This surprising incision, together with observations that old river gravels near Boulder Canyon are folded (Longwell, 1936; Anderson, 2003), suggest that the northern Black Mountains—and perhaps Boulder Canyon—have been uplifted since the river first established its course (Howard and Bohannon, 2001).

The views into Black Canyon give the viewer an appreciation of the magnitude of the river's incision. The drive northward along the east side of the canyon traverses basin-fill deposits—fanglomerate and megabreccia (avalanche) deposits—that have been deeply incised by the river (Anderson, 1978). In 8–9 mi the road cuts through a ca. 5-Ma basalt flow (Anderson et al., 1972) that slopes westward on a gradient consistent with deposition into a shallow pre–Colorado River or early Colorado River valley (Howard and Bohannon, 2001).

Beyond the Temple Bar Road 22–23 mi you will begin to see evidence of a massive construction project for a highway to bypass Hoover Dam and reestablish Hwy 93 as an important commercial route. The bypass will culminate in a 900-ft-high bridge across Black Canyon. In another mile, just before beginning to descend switchbacks to Hoover Dam, turn right into the parking area for an overview of Hoover Dam, and park. Note: Visiting Stop 3.3 requires pre-approval from the Hoover Dam Police.

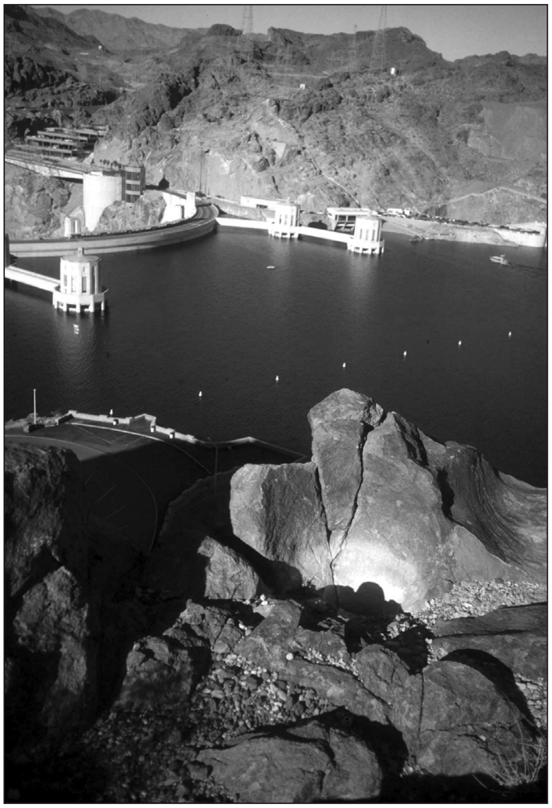

Figure 25. River-sculpted potholes in dacite, overlooking Hoover Dam.

Stop 3.3: Potholes Just too Pretty to Repair

A small and unique exposure of river-sculpted potholes and overlying fluvial gravel deposited by the early Colorado River lie stranded on the rim of Black Canyon 275 m above the river bed (Fig. 25). This exposure records a time when the river sculpted and exposed this site and partly buried it under gravels before ultimately abandoning this course and further incising the deep canyon in which Hoover Dam was built.

Ransome (1923) recognized the significance of these high-level potholes as evidence of the river's course before the adjacent river canyon had been fully cut. In what may be one of the earliest practical applications of paleoseismology, he observed that the potholes cut across faults in the volcanic bedrock, and inferred from the depth of subsequent canyon incision that the potholes are old and that such faults near the dam site therefore must be ancient enough to pose no earthquake risk to a future dam. The dam was built, and time has confirmed his inference so far.

The river-sculpted pothole surfaces record an incision depth on the order of 200 m below the earliest Pliocene preriver topographic surface, which is recorded by basin fill including the 5 ± 0.4 Ma Fortification basalt flow a few miles to the northwest of our position (Anderson et al., 1972; Damon et al., 1978; Mills, 1994) and by a paleogroundwater table mapped by Anderson (1969). Since pothole formation, the river has incised another 275 m. As much as 25 m of vertical relief can be seen on river-sculpted bedrock and in river gravels that line and overlie the bedrock paleochannel (Howard et al., 2004). Cemented gravel at the same level is exposed in a cut for the new bypass highway ~1 km downstream.

The sculpted rock gorge filled by river sediment here may have a modern analog under Hoover Dam. During excavation for the dam, the discovery of sawn plank buried in river fill 15 m below the low river level at a bedrock bench led Berkey (1935) to conclude that the river bed was recently reworked to that depth. A narrow inner gorge notched another 22 m deeper was lined with potholes and vertically fluted bedrock surfaces, features that led Berkey (1935) to conclude that the inner gorge was cut by pothole incision.

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Printed in the USA