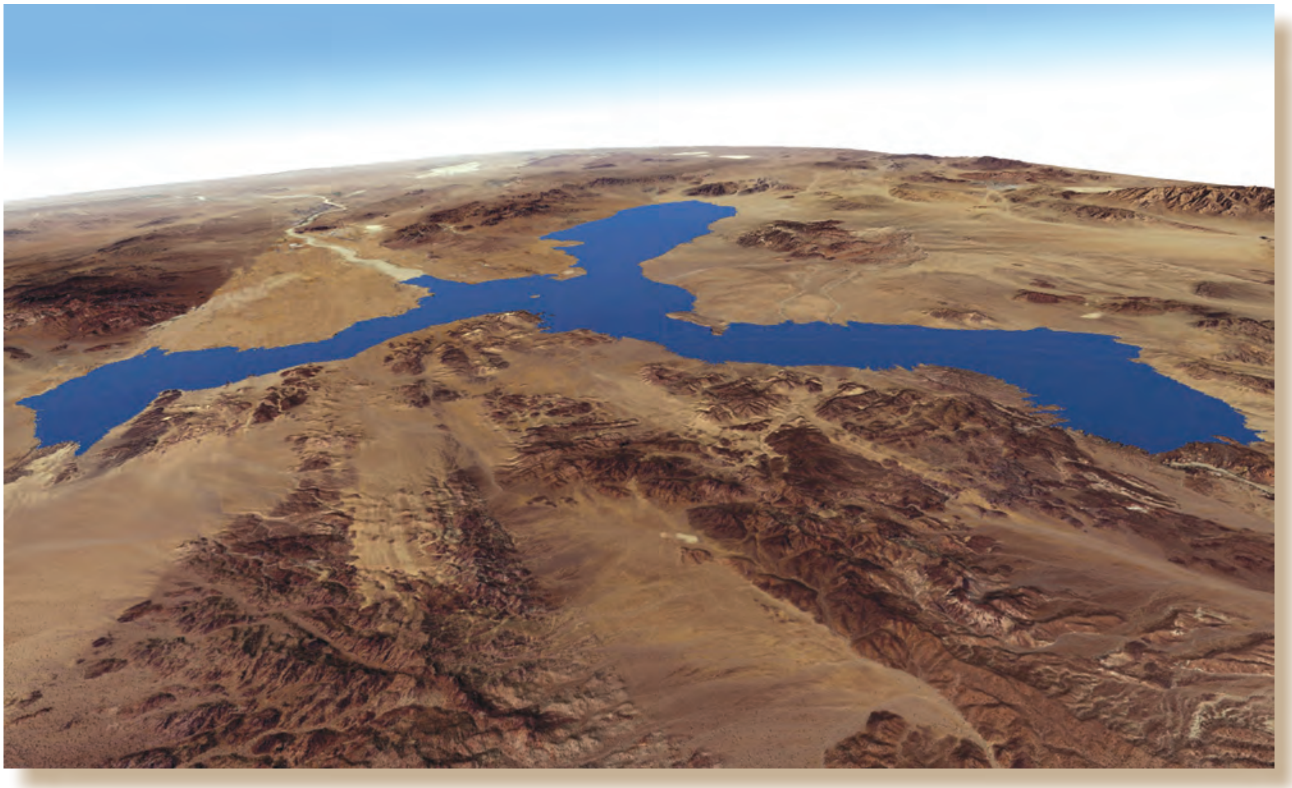
Quaternary Stratigraphy, Drainage-Basin Development, and Geomorphology of the Lake Manix Basin, Mojave Desert

Guidebook for Fall Field Trip, Friends of the Pleistocene, Pacific Cell, October 4–7, 2007



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Cover photo: A modern restoration of Lake Manix at the 543-m highstand level. View to the northwest from above the Cady Mountains. Clockwise from left center are the Troy Lake subbasin, Newberry Mountains, Mojave River, Calico Mountains, Coyote Lake subbasin, Tiefort Mountains (right skyline), and Afton subbasin. Modern-day Afton Canyon lies at the easternmost point of the Afton subbasin in this image. Eolian sand sheets east of the lake would have been less extensive prior to draining of Lake Manix. Visualization created in Visual Nature Studio (v. 2.53, 3D Nature Co.) by Paco Van Sistine (USGS) using 30-m DEMs and 1-m NAIP orthophotos.

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Principal Trip Leaders: Marith Reheis, Dave Miller, Joanna Redwine, Stephanie Dudash, and Jack Oviatt

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By Marith C. Reheis,[1] David M. Miller,[2] and Joanna L. Redwine[3]

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List of Annual Trips, Pacific Cell, Friends of the Pleistocene

[This section (or cell) was organized by Steve Porter with Linc Washburn, assisted by Eastern "Friends" and students of Dick Flint, in 1965 at the conclusion of INQUA Field Conference A in Bellingham, Washington. Due to growth and mitosis, the Pacific NW Cell was spawned in 1993]

Trip no.	Year	Date	Area or title and leaders
1	1966	Sept. 24–25	Glaciomarine environments and the Fraser glaciation in northwest Washington: Don Easterbrook
2	1967	Sept. 23–24	Pleistocene geology and palynology, Searles Valley, Calif.: George Smith, Estella Leopold, and E.L. Davis
	1968		No trip conducted
3	1969	Sept. 27–28	Pleistocene geology of the east-central Cascade Range, Wash.: Steve Porter
4	1970	Oct. 9–10	Cape Blanco sediments and terraces, Oreg.: Dick Janda
5	1971	Sept. 11–12	Glacial and Pleistocene history of the Mammoth Lakes Sierra: Bob Curry
6	1972	Oct. 6–8	Progress report on the USGS Quaternary studies in the San Francisco Bay area: Dave Adams, Dennis Burke, Jon Cummings, and others
7	1973	Sept. 8–9	Mount St. Helens, Wash., stratigraphy and eruptive history: D. Rocky Crandell, Don Mullineaux, and Jack Hyde
	1974		No trip conducted
8	1975	Nov. 21–22	San Diego coastal area, Calif.: Jeff Bada, George Carter, Dennis Nettleton, and George Borst
9	1976	Oct. 30–31	Archeology and tectonics, China Lake, Calif.: Stan Berryman, Wendell Duffield, Glenn Roquemore, and William Page
	1977		No trip conducted
10	1978	Nov. 10–12	Pluvial lake history of Searles, Panamint, and Death Valleys, Calif.: George Smith, Roger Smith, and Roger Hooke
11	1979	Aug. 22–26	Relative dating methods applied to glacial deposits, eastern Sierra Nevada, Calif.: R.M. "Bud" Burke, Pete Birkeland, and Jim Yount
12	1980	Sept. 18–20	Ice-sheet flooding in a portion of Columbia River Valley, Wash.: Richard Waitt, Jr.
13	1981		Quaternary tectonic deformation of Transverse Ranges, Calif.: Ed Keller, Tom Rockwell, George Dembroff, Andrei Sarna-Wojcicki, Ken Lajoie, Bob Yerkes, Malcolm Clark, and Don Johnson
14	1982	Aug. 5–8	Northern California coast, Humboldt basin, late Cenozoic deformation and stratigraphy: Debbie Harden, Donna Marron, and Anne McDonald
15	1983	Aug. 26–28	Glacial Lake Columbia basin, Wash. and McCall area, Idaho (joint trip with Rocky Mountain section): Brian Atwater, Richard Waitt, Steve Colman, Ken Pierce, and Maynard Fosberg
16	1984	Oct. 12–14	Holocene paleoclimatology and tephrochronology east and west of the central Sierran crest: Scott Stine, Spencer Wood, Kerry Sieh, and Dan Miller
17	1985	Oct. 25–27	Quaternary lakes of the eastern Mojave Desert, Calif.: G. Robert Hale, Steve Wells, John Ritter, and John Dohrenwend
18	1986	Oct. 31–Nov. 2	Quaternary tectonics of southern Death Valley: Roland Brady, III, Paul Butler, and Bennie Troxel
19	1987	Sept. 18–20	Pleistocene geology of northwestern Lake Lahontan, Nev.: Jonathan Davis and Rob Negrini
20	1988	Sept. 8–10	Central Oregon High Cascades: Willie Scott, Cynthia Gardner, and Andrei Sarna-Wojcicki
21	1989	April 7–9	Quaternary stratigraphy, soil geomorphology, chronology, and tectonics, western Transverse Ranges, Calif.: Ed Keller, Don Johnson, D.M. Laduzinsky, Tom Rockwell, D.B. Seaver, Rick Zepeda, and X. Zhao

Trip no.	Year	Date	Area or title and leaders
22	1990	January	Western Salton trough—Soils and neotectonics: Tom Rockwell, Robert Crisman, Jonathan Goodmacher, Ralph Klinger, Scott Lindvall, Andy Thomas, and others
23	1990	Sept. 21–23	Neotectonics of south-central coastal California: Bill Lettis, Kathryn Hanson, Keith Kelson, John Wesling, Michael Angell, Doug Clark, Tim Hall, Anthony Orme, and Tom Rockwell
24	1991	May 31–June 2	Fish Lake Valley, Calif.-Nev.: Marith Reheis, Janet Slate, Tom Sawyer, Andrei Sarna-Wojcicki, Jennifer Harden, Elise Pendall, Alan Gillespie, and Doug Burbank
25	1992	June 5–7	Northern coastal California—A look at the southern end of the Cascadia subduction zone and the Mendocino triple junction: Bud Burke, Gary Carver, Dorothy Merritts, Oliver Chadwick, and Ken Aalto
26	1993	April 23–25	The paleoseismic record of subsidence, tsunamis, liquefaction, and landslides from the northern Oregon coast: Evidence of subduction zone seismicity in the central Cascadia margin: Curt D. Peterson
27	1994	Sept. 30–Oct. 2	Transpressional deformation in the San Francisco Bay region: William Lettis, Kevin Clahan, N. Timothy Hall, Christopher Hitchcock, Keith Kelson, Jay Noller, David Schwartz, Gary Simpson, Janet Sowers, and Jerry Weber
28	1995	Oct. 6–9	Quaternary geology along the boundary between the Modoc Plateau, southern Cascade Mountains, and northern Sierra Nevada: Bill Page, Jeff Bachhuber, Duane Champion, Mike Clynn, Julie Donnelly-Nolan, Wendy Gerstel, Fraser Goff, Jim Humphrey, Keith Kelson, Marcia McLaren, Paul Renne, Tom Sawyer, Gary Simpson, Janet Sowers, Jeff Unruh, John Wakabayashi, and Jim Yount
29	1996	Sept. 27–29	Quaternary history, isostatic rebound, and active faulting in the Lake Lahontan basin, Nevada and California: Ken Adams, Marith Reheis, Steve Wesnousky, Nick Lancaster, Kurt Cupp, Steve Wells, Adrian Harvey, and Bruce Bills
30	1997	Sept. 26–28	Owens Valley, Calif.: Doug LaFarge, Fred Berman, Bud Burke, Paul Bierman, Malcolm Clark, Alan Gillespie, Liz Hearn, Marith Reheis, George Smith, and Paul Zehfuss
31	1998	Oct. 9–11	Quaternary geology of the Yucca Mountain area, southern Nevada: Emily Taylor, Ralph Klinger, Larry Anderson, Brian Andraski, John Bell, Jeff Coe, Pat Glancy, Scott Lundstrom, Shannon Mahan, Chis Menges, Silvio Pezzopane, Chris Potter, Alan Ramelli, Marith Reheis, Daniel Soeder, and Tim Sullivan
32	1999	Sept. 24–26	Quaternary geology of the northern Quinn River and Alvord Valleys, southeastern Oregon: Charlie Narwold, Dave Lindberg, Mark Hemphill-Haley, Marith Reheis, Silvio Pezzopane, Tom Sawyer, and Ken Adams
33	2001	Feb. 17–19	Quaternary and late Pliocene geology of the Death Valley region: Recent observations on tectonics, stratigraphy, and lake cycles: Ralph Klinger, Mike Machette, Jeff Knott, and Andrei Sarna-Wojcicki
34	2001	Oct. 12–14	Northern Walker Lane and northeast Sierra Nevada: Ken Adams, Rich Briggs, Bill Bull, Jim Brune, Darryl Granger, Alan Ramelli, Clifford Riebe, Tom Sawyer, John Wakabayashi, and Chris Wills
35	2002	Sept. 20–22	Historical faulting, chronostratigraphy, and paleoseismicity of the central Nevada seismic belt: John Caskey, John Bell, Alan Ramelli, Ken Adams, and Marith Reheis
36	2003	Oct. 3–5	Tectonics, climate change, and landscape evolution in the southern Sierra Nevada, California—Sequoia and Kings Canyon: Greg Stock, Bill Bull, Gary Weismann, Anthony Caprio, Nate Stephenson, John Wakabayashi, Bud Burke, and John Tinsley
37	2004		Santa Barbara fold belt: Larry Gurrola, Ed Keller, and others
38	2005	Oct. 8–10	Geomorphology and tectonics at the intersection of Silurian and Death valleys: Dave Miller, Chris Menges, Matt McMackin, Kirk Anderson, Jordon Bright, Richard Hereford, Heather Lackey, Shannon Mahan, Jennifer Mendonca, Joanna Redwine, Kevin Schmidt, Roger Smith, and Jonathan Stock
39	2006	Oct. 6–9	Signatures of Quaternary crustal deformation and landscape evolution in the Mendocino deformation zone, northwestern California: Mark Hemphill Haley, Tom Leroy, Bob McPherson, Jay Patton, Jay Stallman, Diane Sutherland, and Todd Williams, and many guidebook contributors
40	2007	Oct. 4–7	Quaternary stratigraphy, drainage-basin development, and geomorphology of the Lake Manix basin, Mojave Desert: Marith Reheis, Dave Miller, Joanna Redwine, Stephanie Dudash, Jack Oviatt, Darrell Kaufman, and Jordon Bright

General Field Trip Information

The Friends of Calico Early Man Site have graciously offered the Early Man Site facilities as our base of operations and campground for the entire trip, beginning Wednesday night (for those arriving early for the optional Pre-Trip Day) to Sunday morning. Please treat the facilities, both buildings and archaeology, with respect. The only power on-site is provided by a gasoline generator, and all water must be hauled in, so please provide your own water and power needs. We will have several portable toilets available for our use—please use them and *not* the BLM outhouse (permanent building). There is a small visitor center with artifacts on display, and the main staffer, Chris Christianson, can answer your questions about the site as well as sell you T-shirts and coffee cups (their main source of revenue, so please consider buying!). Chris will be at the camp during the day, so your belongings will be somewhat safe while you are out "FOPping."

To get there from I-15: Three exits north of Barstow, take Minneola Road exit. Turn north and follow the paved road past a few businesses. At about 0.1 mi from the exit, take a left on a graded road marked with "Calico Early Man Site," and follow signs to a right turn that leads you to the site.

To get there from I-40: Two exits west of Barstow, take Daggett exit. Turn north and follow the paved road through Daggett to Yermo, enter I-15 north, and proceed two exits. Refer to directions for I-15 above.

Camping is permitted in many places. Immediately after entering the site, some established camp sites are located on the left side of the road. Others (particularly those with campers) can use undesignated sites in the parking area beyond the buildings or continue farther around the loop road to bulldozed areas suitable for camping east of the buildings. Still others can walk north from the buildings to walk-in sites. Please ask if you are uncertain about sites. The group fire will be in the meeting area next to the two buildings. You can also build fires in the fire rings that already exist at some sites, but the staff has asked us not to build additional new fire rings or pits at the site.

If you prefer not to camp, motels and restaurants are available in Barstow and as close as the Yermo exit. Barstow is also the nearest source of significant supplies. Gas stations at several exits (Yermo, Minneola, and Harvard Road) also carry a few food items; no gas is available east of Harvard Road until Baker. Consult the road log for daily start times and rendezvous points.

Introduction to Lake Manix Basin

The following brief description and introduction to the literature is summarized from reviews in Enzel and others (2003) and Reheis and Redwine (in press). The Mojave River originates in the San Bernardino Mountains and in high-water years flows north and east to its terminus in Silver Lake playa north of Baker, Calif. Along this course, the river passes through or near several basins that were internally drained prior to integration by the Mojave River, including the Victorville, Harper, Manix, and Soda Lake basins (fig. 1; Cox and others, 2003; Enzel and others, 2003). Each of these basins contains a partial sedimentary record of integration, including fluvial and lacustrine sediments, indicating the arrival and ponding of the river and a record of climatic fluctuations

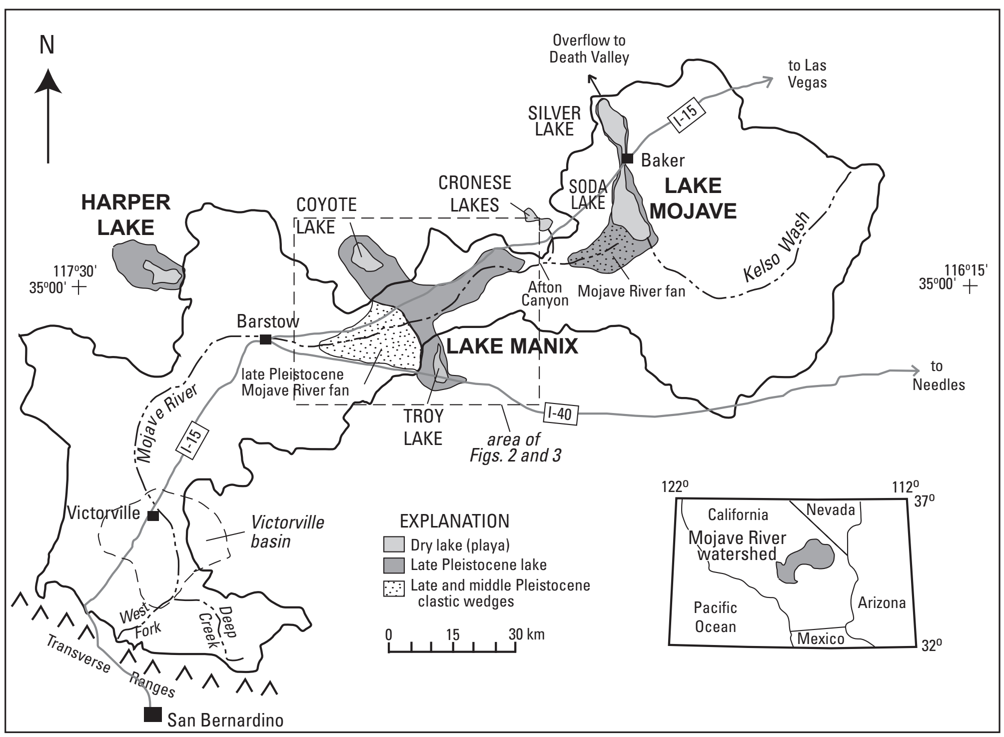

Figure 1. Mojave River drainage basin in southern California (modified from Enzel and others, 2003). During historic high-precipitation years, most recently in early 2005, the river flows into Silver Lake playa. In late Pleistocene time, after breaching of the Lake Manix basin, Lake Mojave episodically discharged northward into Death Valley. Dashed box is area of figures 2 and 3.

during the periods when a particular basin served as the river terminus. Sediments in the Lake Manix basin record Mojave River discharge and lake fluctuations that began during the middle Pleistocene and continued through most of the late Pleistocene (Jefferson, 2003).

The Lake Manix basin lies within a broad zone of faulting and folding that accommodates 20 percent or more of the Pacific-North American plate motion (termed the Eastern California shear zone by Dokka and Travis, 1990). Deformation within this zone has influenced basin geometry over the past 3 million years; Coyote Lake basin has lowered and the Alvord Mountains have risen since a distinctive Pliocene fluvial deposit was laid across their northern margins (Miller and Yount, 2002). This deposit is warped into steep dips adjacent to both the basin and the mountain, suggesting that much of today's topography is youthful. The informal Mojave River formation of Nagy and Murray (1991) is significantly deformed adjacent to the Manix fault. Faults that are known to cut Quaternary deposits of the Manix area are shown in figure 2; of these, we consider the Calico, Camp Rock, Dolores Lake, Pisgah, and Manix faults to have strong evidence for Holocene rupture.

All workers in the Lake Manix basin have noted that it currently consists of several subbasins. We use the following names (fig. 3) for these subbasins: Coyote Lake, Troy Lake, Manix, and Afton. As the lake evolved, fluvial and deltaic sediments were deposited progressively eastward into the lake, modifying the geometry of the subbasins and total lake volume. As a result, the current configuration may not accurately reflect the configuration of the early lake.

Jefferson (2003, and citations therein) conducted stratigraphic and paleontologic studies of the Pleistocene Manix Formation in the Manix subbasin near the confluence of the Mojave River and Manix Wash (fig. 3). He interpreted these deposits to represent at least four major lake cycles (fig. 4). Deposits of the oldest two lake cycles are poorly dated; the sediments have normal polarity, and one bone yielded an infinite uranium (U)-series age of >350 ka (J.L. Bischoff, U.S. Geological Survey, cited in Jefferson, 2003). Deposits that Jefferson interpreted as perennial-lake sediments and correlated with OIS 6 (his informal "upper Member C") contain a tephra layer near the base that has an assigned age of about 185 ka, based on a tentative chemical correlation with a rhyolite in the Sierra Nevada to the northwest; this tephra is overlain by a bed bearing a bone fragment that yielded a U-series age of about 184 ka (J.L. Bischoff, U.S. Geological Survey, cited in Jefferson, 2003). Sediments representing a sequence of fluctuating lake levels were correlated with OIS 4 (lower part of "Member D") on the basis of several U-series ages on bone ranging from about 74 to 50 ka and several mostly infinite radiocarbon ages, but several ages of both methods were not in stratigraphic order (Jefferson, 2003, p. 48). The youngest lake deposits at this site (upper part of "Member D"), coeval with OIS 2, consist mainly of sands interpreted as a delta that was deposited as the Mojave River prograded eastward. Numerous beach deposits at ~543 masl (meters above sea level) rim the basin and were taken by Jefferson (2003) and Meek (1990) as indicating multiple lake highstands.

Meek (1989, 1990) initially interpreted the geomorphic record of Lake Manix overflow and incision of Afton Canyon to have occurred rapidly at about 18 ka (~21.5 cal ka), but noted the presence of inset fluvial terraces suggesting the canyon was not all cut at once (Meek, 1990). Later, he (Meek, 2004) clarified his interpretation as inferring a rapid incision to the base of Lake Manix sediments, followed by a second phase of Afton Canyon incision that was slower than the initial incision. From stratigraphic records of Lake Mojave downstream, Wells and others (2003, and references therein) and Enzel and others (2003) strongly disagreed and argued for slower initial and later incision of Afton Canyon and integration of the Soda and Silver Lake basins to form Lake Mojave over a period of perhaps several thousand years, beginning >22 ka (~26.5 cal ka). An accurate understanding of the timing of these integration events is needed to reconstruct paleoenvironmental conditions during the late Pleistocene, because interpretations of past temperature and precipitation in the Mojave River drainage basin depend heavily on knowing the sizes of water bodies that may have been simultaneously maintained by the river (Enzel and others, 2003). Furthermore, the thick well-preserved sections of lake deposits in the Lake Manix basin offer the opportunity to develop a detailed record of paleoclimate variations prior to the latest Pleistocene; such records are rare in the Mojave Desert, with the exception of the Death Valley core (Lowenstein and others, 1999; Forester and others, 2005).

The principal trip leaders undertook mapping and stratigraphic investigations to improve understanding of the history of Lake Manix and to provide geologic context for a 45-m-long core obtained from the section preserved at the confluence of the Mojave River and Manix Wash. This field trip is intended to provide an introduction to the outcrop record of interbedded lake, alluvial-fan, and alluvial deposits, and to our interpretations of lake history based on this outcrop record and our new mapping, dating, and preliminary interpretations from the core. Significant revisions to the previously established stratigraphy include the following:

1. A subbasin integration event. For much of its history during the middle Pleistocene, Lake Manix was confined to the Manix, Troy Lake, and probably Coyote Lake subbasins to the west of Buwalda Ridge (fig. 3); the Afton subbasin during this time was an internally drained basin separate from the lake. At about the time of deposition of the Manix ash bed, thought to be about 185 ka (Jefferson, 2003), this lake overtopped a threshold located near the east end of Buwalda Ridge and entered the Afton subbasin in a catastrophic flood event. This event has profound implications for the interpretation of younger sediments deposited in the Afton and Manix subbasins.

2. After the subbasins were integrated, Lake Manix rose to a level as much as 10–15 m higher than its previously recognized highstands at about 543 masl, likely during

Figure 2. Map of principal Quaternary faults in the Lake Manix region, based on unpublished mapping of J.L. Redwine, D.M. Miller, and D.J. Lidke (U.S. Geological Survey) and Phelps and others (in press). Dashed faults are poorly exposed or covered. Field trip stops where faults will be discussed are shown. Background image is from Landsat 7.

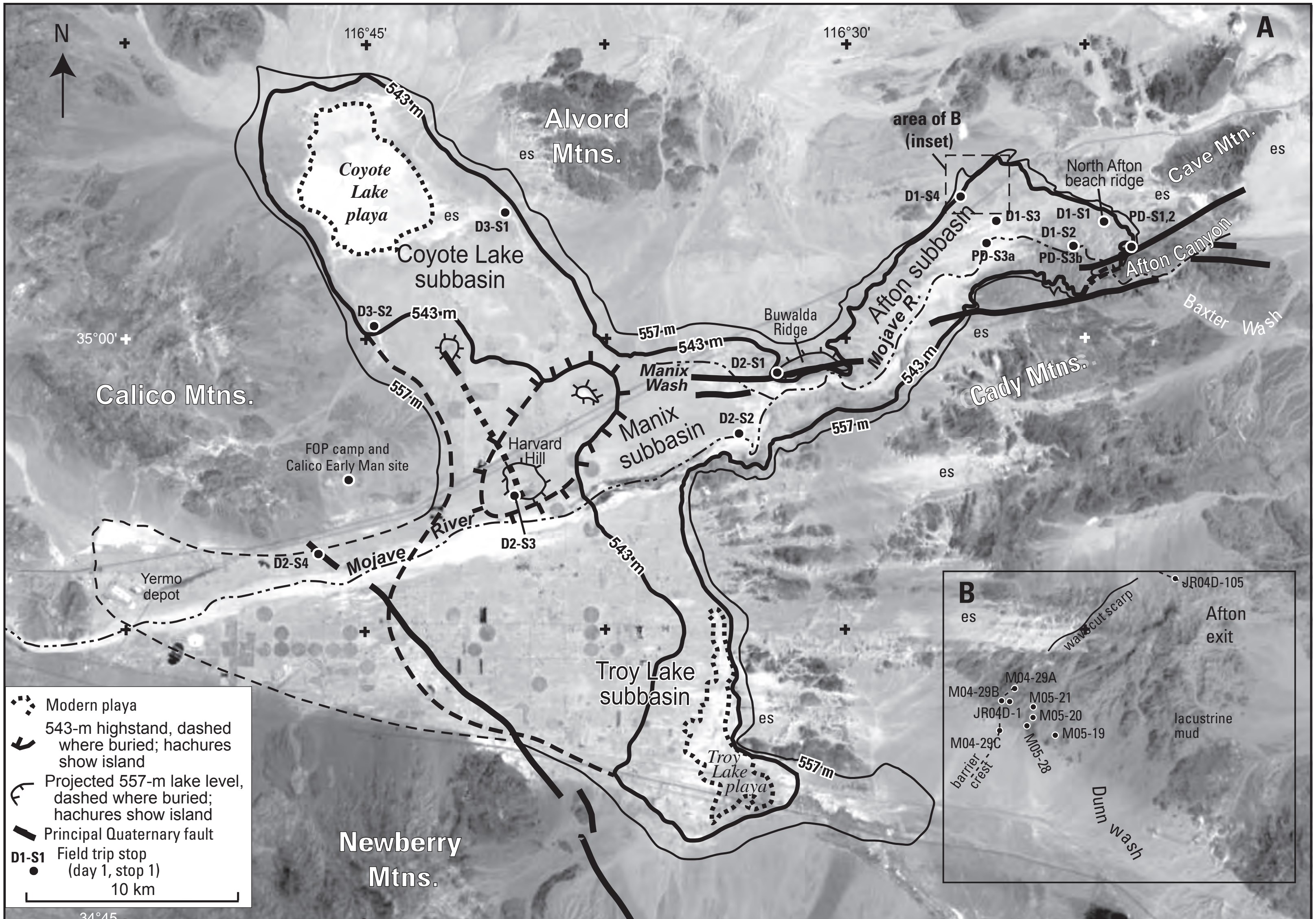

Figure 3. *A.* Geographic features of the Lake Manix basin, showing subbasins, playas (dotted), the Mojave River fluvial fan between Yermo and Troy Lake, and major faults (from Reheis and Redwine, in press). Field trip stops are also shown. Medium-weight line is the 543-masl highstand level that depicts the minimum extent of Lake Manix during the late Pleistocene; western margin is not known due to progradation during highstands and later burial by Mojave River alluvium. Thin line is the 557-masl lake limit projected from highest shoreline features recognized in this study. Study sites (dots) shown where not included on other figures. Note east-west streaks of eolian sand (es), derived from Mojave River and lake sediment, blanketing slopes of the Alvord Mountains, Cady Mountains, and Cave Mountain. *B.* Inset showing lacustrine features and study sites in upper Dunn Wash. Barrier crests and wavecut scarp lie at 543 masl.

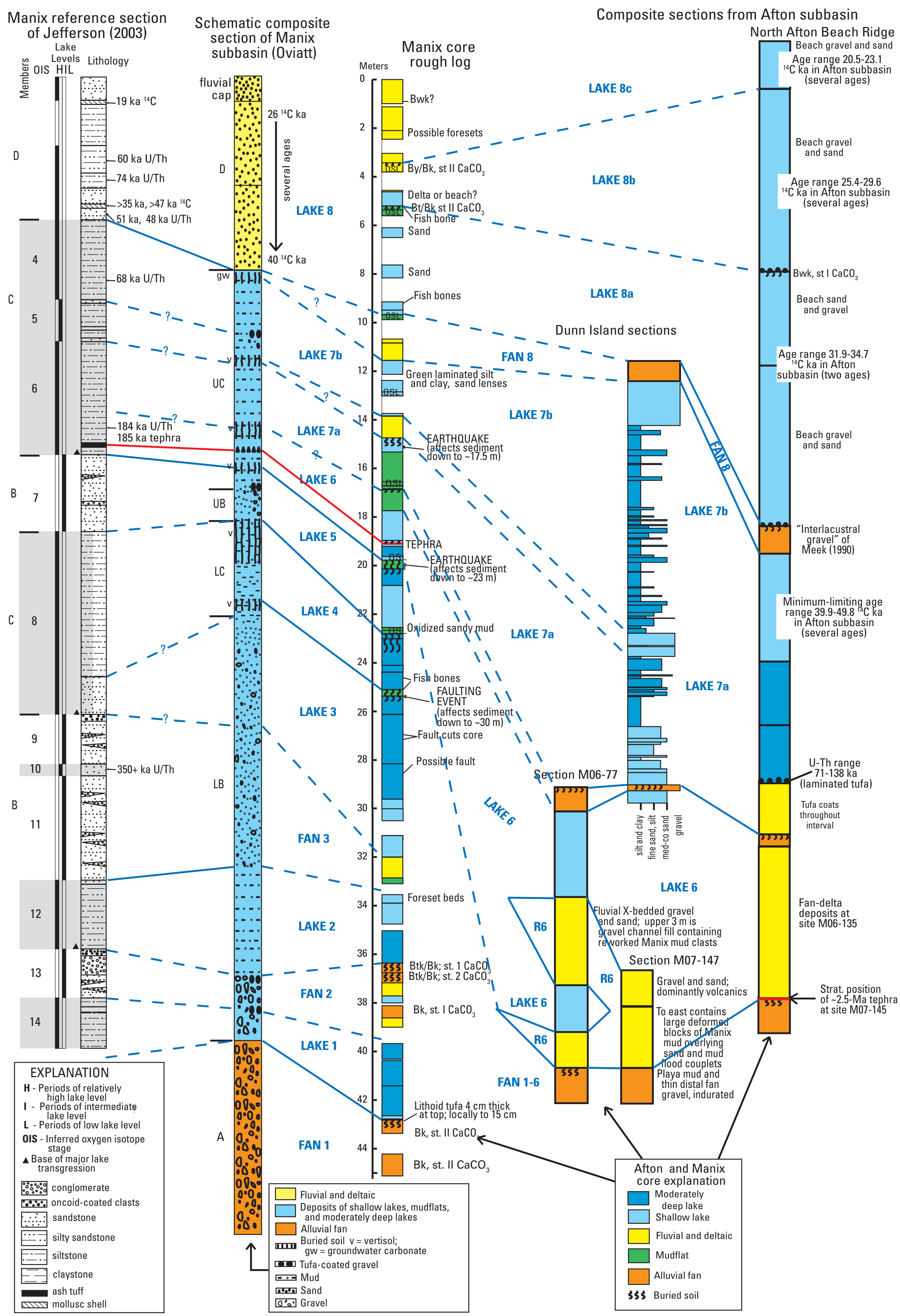
Manix reference section of Jefferson (2003)
Members
OIS
Lake Levels HIL
Lithology
19 ka ¹⁴C
60 ka U/Th
74 ka U/Th
>35 ka, >47 ka ¹⁴C
51 ka, 48 ka U/Th
68 ka U/Th
184 ka U/Th
185 ka tephra
350+ ka U/Th
EXPLANATION
H - Periods of relatively high lake level
I - Periods of intermediate lake level
L - Periods of low lake level
OIS - Inferred oxygen isotope stage
▲ Base of major lake transgression
conglomerate
oncoid-coated clasts
sandstone
silty sandstone
siltstone
claystone
ash tuff
mollusc shell
Schematic composite section of Manix subbasin (Oviatt)
fluvial cap
26 ¹⁴C ka
several ages
40 ¹⁴C ka
gw
Fluvial and deltaic
Deposits of shallow lakes, mudflats, and moderately deep lakes
Alluvial fan
Buried soil v = vertisol; gw = groundwater carbonate
Tufa-coated gravel
Mud
Sand
Gravel
Manix core rough log
Meters
Bwk?
Possible foresets
By/Bk, st II CaCO3
Delta or beach?
Bt/Bk st II CaCO3
Fish bone
Sand
Sand
Fish bones
Green laminated silt and clay, sand lenses
EARTHQUAKE (affects sediment down to ~17.5 m)
TEPHRA
EARTHQUAKE (affects sediment down to ~23 m)
Oxidized sandy mud
Fish bones
FAULTING EVENT (affects sediment down to ~30 m)
Fault cuts core
Possible fault
Foreset beds
Btk/Bk; st. 1 CaCO3
Btk/Bk; st. 2 CaCO3
Bk, st. I CaCO3
Lithoid tufa 4 cm thick at top; locally to 15 cm
Bk, st. II CaCO3
Bk, st. II CaCO3
LAKE 8c
LAKE 8b
LAKE 8a
LAKE 8
LAKE 7b
LAKE 7a
LAKE 6
LAKE 5
LAKE 4
LAKE 3
FAN 3
LAKE 2
FAN 2
LAKE 1
FAN 1
FAN 8
FAN 1-6
R6
Composite sections from Afton subbasin
North Afton Beach Ridge
Beach gravel and sand
Age range 20.5-23.1 ¹⁴C ka in Afton subbasin (several ages)
Beach gravel and sand
Age range 25.4-29.6 ¹⁴C ka in Afton subbasin (several ages)
Bwk, st I CaCO3
Beach sand and gravel
Age range 31.9-34.7 ¹⁴C ka in Afton subbasin (two ages)
Beach gravel and sand
"Interlacustral gravel" of Meek (1990)
Minimum-limiting age range 39.9-49.8 ¹⁴C ka in Afton subbasin (several ages)
U-Th range 71-138 ka (laminated tufa)
Tufa coats throughout interval
Fan-delta deposits at site M06-135
Strat. position of ~2.5-Ma tephra at site M07-145
Dunn Island sections
silt and clay
fine sand, silt
med-co sand
gravel
Section M06-77
Fluvial X-bedded gravel and sand; upper 3 m is gravel channel fill containing reworked Manix mud clasts
Section M07-147
Gravel and sand; dominantly volcanics
To east contains large deformed blocks of Manix mud overlying sand and mud flood couplets
Playa mud and thin distal fan gravel, indurated
Afton and Manix core explanation
Moderately deep lake
Shallow lake
Fluvial and deltaic
Mudflat
Alluvial fan
Buried soil

Figure 4. Preliminary correlation of lake and fan units; level of uncertainty is expressed by solid lines vs. dashed lines and queries. Three columns on the left are from the Manix subbasin; four columns on the right are from the Afton subbasin. From left to right, the first column is from Jefferson (2003), showing informal members of the Manix Formation and tentative assignments to oxygen-isotope stages (OIS). The second column is from unpublished mapping of C.G. Oviatt (Kansas State University, written commun., 2007), showing correlations to units of Jefferson (2003); UC is upper part of member C, and so forth. The third column is a condensed stratigraphic section from descriptions of a 45-m-long core acquired by the U.S. Geological Survey near the intersection of Manix Wash and the Mojave River (fig. 3). The four columns on the right are composite and individual measured sections (see Reheis and Redwine, in press, and this guidebook, fig. 5). Note that the five oldest lake units in the Manix subbasin are absent from the Afton subbasin.

and (or) after OIS 6, and probably discharged episodically eastward into the Soda Lake basin. During these discharges, the threshold at the head of the present-day Afton Canyon was gradually incised to about 543 masl.

3. During subsequent highstands of OIS 4(?), 3, and 2, the lake repeatedly rose to about 543 masl (Meek, 1990, 2000; Reheis and Redwine, in press), maintained there in part by an internal shallow threshold between the Manix and Coyote Lake subbasins (Meek, 2004) and perhaps in part by the eastern threshold at the head of Afton Canyon.

4. This eastern threshold failed sometime after about 21 ^{14}C ka and Afton Canyon was cut quickly enough that ages of soils on inset terraces are not distinguishable (Reheis and Redwine, in press); no recessional shorelines younger than this have been recognized.

Because the stratigraphic records preserved in the Manix and Afton subbasins are dissimilar due to the integration event (no. 1 above), we have developed a new preliminary system of nomenclature for the interbedded lake and fan deposits that differs from that of Jefferson (2003). This preliminary stratigraphic system may need to be modified in the future should more numerical dating show that our current correlations are incorrect. In the interim, the sequences are simply numbered upward as follows: L indicates lake deposits, F indicates fan deposits, and R indicates river or fluvial deposits. F1 is the oldest fan unit in the Manix subbasin and is equivalent to Jefferson's (2003) informal "Member A" of the Manix Formation; L1 is the oldest lake unit. L1 through L5 and the underlying and interbedded fan units (locally marked only by soils or unconformities) are exposed only west of Buwalda Ridge in the main Manix subbasin. L6 was the first lake to enter the Afton subbasin, and the fluvial deposits that locally mark the incursion of flood water from upstream are referred to as R6. In some places, these units are subdivided with subscript letters, for example, L7a (older) and L7b (younger). Figure 4 shows a very preliminary suggested correlation between the two subbasins and Jefferson's informal member designations of the Manix Formation. By this scheme, the youngest lake event is L8c, which is the OIS 2 lake for this basin. For those who wish to compare these units with those of regional surficial-map units used by Redwine (U.S. Geological Survey, unpublished mapping) in her map of the Afton Canyon area, see table 1.

In the following road log and field trip guide, we provide GPS locations for all stops in UTM units, NAD83 coordinate system. Altitudes are in meters above sea level (masl); most have been differentially corrected.

Pre-Trip Day (Optional): Early Incision of Lake Manix Threshold and Flooding of Afton Subbasin

YOU **MUST** RIDE IN A 4WD VEHICLE FOR THIS DAY!!! PLEASE CARPOOL!! *Only undertake this if you are reasonably fit and accustomed to hiking in rough, rocky, sometimes steep terrain.* We will start from Calico Early Man Site at 8 A.M., or if you prefer, you can meet us on the southeast side of the Afton (Dunn) exit at 8:30 A.M. The round-trip drive is about 65 miles. Follow the road log for Day 1 to Mile 26.0, at the north edge of the north Afton beach ridge. Continue straight ahead. The back (east) side of the beach ridge is in view to the southwest.

26.4 F653 route sign. Ridge to the right and bouldery hillslopes to left are composed of Tertiary(?) fanglomerate.

26.5 Greenish-tan sands to left in arroyo cut contain shell fragments that yielded a ^{14}C age of 20,810±130 yr B.P. Yet the sands lie at an altitude of 558 m, 15 m higher than well-preserved beach barriers that yielded similar ages. We interpret these as eolian sands and shell fragments reworked from the youngest highstand of Lake Manix, part of extensive sheets and ramps of sand in the Mojave River sand-transport corridor.

26.7 Road crosses over the fanglomerate ridge; wavecut terraces on Shoreline Butte are obvious at 1:00. Varnished surfaces in the middle ground and sloping toward north Afton beach ridge are the Afton F7 unit (F7 is the "interlacustral gravel" of Meek, 1990).

27.3 TURN RIGHT at fork and prepare to cross sandy wash. Engage 4WD **before** descending into the wash—we don't want to waste time digging or pulling your vehicle out! On the other side, bear right along the mountain front, and right again past tailings pile on an indistinct track heading for Shoreline Hill. STAY IN 4WD!

Table 1. Tentative correlation of J.L. Redwine's units (U.S. Geological Survey, unpublished mapping) to ongoing mapping and interpretation of Lake Manix stratigraphy.

Approximate OIS assignments based on radiocarbon ages (this guidebook), U-series ages reported by Meek (2000) and preliminary ages of J.B. Paces (U.S. Geological Survey, written commun., 2007), surficial mapping, and soil development	Nomenclature used in surficial geological map of Afton Canyon (Redwine, U.S. Geological Survey, unpublished mapping)	Nomenclature used in this guidebook
~OIS 2	Qya (Qya4 through Qya1)	Not discussed
OIS 2 to OIS 3	Qylg and Qylb	Lake 8a Lake 8b Lake 8c
OIS 3 to OIS 4?	Qia1	Not discussed
OIS 4(?)	Qilg1	Lake 8a?
OIS 4(?) to OIS 5(?)	Qia2	Fan 8
~OIS 5 and 6 ~OIS 6 and 7(?)	Qilf2	Lake 7 Lake 6

27.9 Road dead-ends on a sandy surface with old timbers scattered about. Park anywhere and prepare for a **minimum** 4-hour hike; take plenty of water and lunch or major snacks.

Walking Tour of Lake Manix Overflow Point and Highstands

Cross the wash headed southwest toward the left edge of Shoreline Hill; follow the remains of the jeep trail at first. In ~150 m, pause on a sand ramp for overview of stratigraphy and a panoramic view from Shoreline Hill to the north Afton beach ridge. Downslope are extensive varnished surfaces of F7 overlying greenish deposits of L6, which locally have thick tufa coats on clasts at the base, especially near Shoreline Hill where tufa cementation is so extensive it has formed an exhumed surface that is one of the apparent shorelines on the hill. These deposits overlie a reddish zone that is F7, which in turn overlies fan-delta deposits of L6; we will see these better on Day 1, Stop 1B. This same sequence can be found in the north Afton beach ridge, except that there are three subunits of L8 that overlie F7. L8 deposits are scarce to absent east of the beach ridge. F7 passes beneath the beach ridge forming a continuous planar surface coextensive with the one we see below us; these relations imply that the beach ridge was built entirely during L8 time.

Move east toward Shoreline Hill, dipping in and out of the nearshore sands of L7. Ascend to a saddle on the east side of the hill, composed of varnished pavement (with remnants of bar and swale morphology) that is probably a relict F8 surface. Follow this surface down to the southwest. Here the fan gravel overlies two sand units.

Stop 1

At site M06-156 (559072 E, 3877340 N), two units of fan gravel separated by a buried soil form the top ~1 m of the outcrop. These are underlain in sequence by 1.5 m of pale, well-bedded medium sand with interbedded minor gravel; 1.5 m of poorly exposed angular fan gravel; ~3 m of interbedded, moderately sorted sand and gravel fining down to mostly well-bedded, oxidized sand, locally with steep northeast dip; and bouldery angular fan gravel that pinches out upslope against bedrock. The basal sand unit locally has ripple cross-bedding with heavy-mineral laminae. A differentially corrected GPS altitude at the top of the upper sand unit is 551.2 masl. These two sand units are inferred to be two units of L7 nearshore sands representing a lake level as much as 8 m higher than the well-known 543-m barrier beach deposits. The multicolored badland-type hill due west consists of L7/F7/L6 (fan-delta deposits)/F1-6 with prominent paleosols. The extreme badland topography to the west-southwest is Tertiary(?) fanglomerate exposed along the trace of the Manix fault.

Take the sheep trail west down to the arroyo floor, then climb to the top of the steep mountain face due north. Once on top, catch your breath and look at the view. The upper part of the south wall of Afton Canyon runs from east to southwest. In the foreground, an inactive fault parallel to and north of the Manix fault strikes northeast through this valley (Redwine, U.S. Geological Survey, unpublished mapping). To the west, on the south side of the Mojave River, green beds of L7 are prominent. Near the river, they overlie (in sequence) a thin gravelly facies of L6, the fanglomerate of Cady Mountains (gray fanglomerate of Ellsworth, 1932, but it looks more brown), and the fanglomerate of Cave Mountain (brown fanglomerate of Ellsworth, 1932, but it looks reddish). Strath terraces are visible along the river to the west. To the northwest stretches the back (east) side of the north Afton beach ridge. Cave Mountain looms to the northeast.

Descend in a southerly direction into the valley and climb the red ridge ahead. Bear right along the ridge crest, and then take aim on two small bumps on a gentle ridge below and east of a rounded hill, bearing S25°W. A steep arroyo cut in bedrock bounds the east side of this ridge. Once down the hill partway, you can use a sheep trail that leads directly to the little bumps.

Stop 2

The two small bumps consist of interbedded alluvial-fan, colluvial, and fluvial deposits overlying metamorphic rocks; the following is summarized from detailed descriptions in Reheis and Redwine (in press) and Redwine (U.S. Geological Survey, unpublished mapping). Site JR04CM-87 (558726 E, 3876135 N) on the west side, at an altitude of 537.7 masl, about 130 m above the present river channel, exposes nearly 6 m of locally derived alluvial-fan deposits and contains an interval of fluvial gravel, including well-rounded volcanic and igneous clasts and quartz-rich sand (fig. 14 of Reheis and Redwine, in press). The outcrop comprises 18 depositional layers divided into 13 units that are separated and defined by buried soils (b1, b2, and so forth; table 2 of Reheis and Redwine, in press) overlying bedrock. Reworked fluvial deposits of unit 5 contain lacustrine ostracodes (R. Forester, U.S. Geological Survey, written commun., 2005) typical of those found throughout Manix Formation sediments (Steinmetz, 1987); thus, it is probable that these fluvial deposits originated by discharge from Lake Manix. A similar but thinner stratigraphic sequence is preserved at site JR04CM-88 on the east side.

We estimate the age of the fluvial deposits by summing the normalized profile development index (PDI) values of the overlying soils (surface soils and soils b1-b5, tables 2 and 3 of Reheis and Redwine, in press). This yields a value of 0.24, much larger than the PDI values of 0.01–0.05 that are typical of soils formed on last-highstand Lake Manix barriers (L8 deposits); however, these soils and PDI values are difficult to compare due to the vastly different parent materials, deposit thicknesses, and effects of ground water. In addition, a summed PDI value of 0.04 for soils b6–b9 that formed on the four fluvial units implies a lengthy period of fluvial aggradation with short episodes of stability. Cumulatively, these soils and the complex sequence of deposits represent a significant period of intermittent deposition, during which the surrounding landscape must have been stable with no rapid incision forming an adjacent Afton Canyon. The presence of four fluvial units separated by weak buried soils implies a stable, slightly aggrading river at this time. A sample from the fluvial deposits (fig. 14 of Reheis and Redwine, in press) yielded ages of 19.9±2.2 ka (IRSL, infrared stimulated luminescence on feldspar) and 15.0±1.5 ka (OSL, blue-light optically stimulated luminescence on quartz; S. Mahan, U.S. Geological Survey, written commun., 2006). The complex soil-stratigraphic sequence above the sampled unit, the large PDI values, and the poor preservation of the entire deposit suggest these luminescence ages are much too young. We suspect that disequilibrium in the dose rate caused by fluctuating ground water has affected the OSL ages. Comparison of the summed PDI value (0.24) to those of dated soils elsewhere and to those of older shorelines in the Lake Manix basin suggest these fluvial deposits represent discharge from Lake 7 (OIS 6–5?) or the earliest phase of Lake 8 (OIS 4?–3).

Inset below the 538-m fluvial and alluvial-fan deposits are two nested strath terraces sloping gently and stepping down toward the canyon rim. These terraces are similar in appearance and preservation to the straths below the canyon rim, and bear a similar suite of rounded clasts. The lower terrace slopes down from about 510 masl to about 490 masl at the rim (site JR04CM-84). A shallow pit excavated on the best-preserved surface exhibited weak soil development, similar to soils developed on the lower terraces. We interpret these high strath terraces to represent initial incision of the Lake Manix threshold at ca. 25 cal ka (Reheis and Redwine, in press).

Cross to the eastern ridge to descend to these lower strath terraces and a spectacular view of Afton Canyon. From here you can return to the cars the way we came, or you can take a different route if you are interested in seeing more evidence of shorelines higher than 543 m. *However, please do not attempt this route if you are not agile or if you are prone to vertigo!*

To continue the loop, backtrack upslope on the west ridge of fluvial deposits, then veer sharp left (southwest) along the flank of the dark hill, angling uphill (no need to go to the top, however). Cross a small gully to a rugged small red knob and regroup. Note that from here, looking southeast, the high fluvial remnants are visible, and to the northwest, just 25 m away, is a somewhat lower bench than the ridge we stand on. That bench is just above the easternmost remnant of Lake Manix deposits and represents a higher level, when the lake was at times discharging through the outlet whose deposits we just examined, long before Afton Canyon was cut. Thus, we are standing just above what was probably the lake threshold. Descend to that little bench (note the many bighorn sheep bedding places around here), and if you wish, very carefully (due to the steep outcrop and exposure) look at the small outcrop of probable beach sands exposed just below it (site M06-159, 558537 E, 3876617 N), at an altitude of 544.1 masl. We are looking down on a tufa-coated terrace (site M06-50; 558541 E, 3876690 N) at 530.7 masl. Preliminary U-series ages from tufa coats at this site are about 220 to 150 ka (J. Paces, U.S. Geological Survey, written commun., 2007) and thus may represent lake phase L6 and perhaps L7. Carefully descend to that terrace on a steep treacherous sheep path, then intersect a sheep highway that runs from here all the way back to Shoreline Hill.

Halfway to the next bench, look ahead at two wave-cut terraces. The lower, at a level below the trail on which we stand, has tufa-coated clasts at the base overlain by 3–4 m of lake sand banked against a steep riser or shoreline angle cut in bedrock. A higher shoreline angle and bench, above the sheep trail on which we stand, has a thin mantle, ~1 m thick, of possible lake sand buried by colluvium. The altitude of the bench descending from the lower shoreline angle is 530.7 masl; the highest outcrop of greenish sand on the upper bench is 544.6 masl. The sheep trail crosses the bedrock gulch ahead by climbing above the higher bench.

Cross the next gully and climb to the next lake bench. Here the sheep trail forks. The high trail climbs gradually, then eventually drops back to the arroyo floor just below Stop 1. The low trail drops northwest into a small valley, then climbs up through deposits of F7 and L7 (the little green-capped hill visible from here), then up a rocky arroyo and back to Stop 1.

From the saddle east of Shoreline Hill, either return to the cars via the up-and-down route we used in the morning, or for more lake stratigraphy and less scrambling, descend an arroyo to the northwest, then back up a northeasterly trending fork to the vehicles.

If you have seen enough for one day, retrace route back to camp via I-15. If you would like to continue to the sites at Stop 3A to see evidence for a very large flood that emanated from Lake Manix when it was confined west of Buwalda Ridge and filled the Afton subbasin with water for the first time, we will drive the Mojave Road (the dry riverbed)—4WD also required. Alternatively, those interested can take a look at soil development on two more fluvial terraces inset into Afton Canyon near the Afton Canyon campground (Stop 3B).

To go to Stops 3A or 3B, retrace route to Afton Canyon Road.

29.8 TURN LEFT (south) on Afton Canyon Road. For geology along this stretch, see notes in road log for Day 1 between Stops 1 and 2, Mile 27.1 to 27.8.

30.8 TURN RIGHT AND ENGAGE 4WD at fork near railroad bridge (BLM road sign) to go to Stop 3A. BEAR LEFT on main road to Afton Canyon campground for Stop 3B.

Directions To Stop 3A:

30.9 Pass under the railroad bridge and continue straight through a gate on F726 (last car please close gate). At 31.0, cross a shallow-water muddy wetland (it has a fairly firm sandy bottom) and continue straight. Perennial spring discharge exists at the head of Afton Canyon because the sands of the Mojave River aquifer terminate here against indurated Tertiary fanglomerate and bedrock, forcing the ground water to the surface locally.

31.5 The bluff on the left (9:00; site M06-17) exposes, from bottom to top, reddish fanglomerate of Cave Mountain; 15 m of tan to gray fanglomerate of Cady Mountains capped by a buried soil (Bwk horizon); 1.4 m of gray, moderately bedded, sandy cobble granitic gravel; 2.3 m of well-bedded pebble gravel interbedded with coarse, medium, and muddy fine sand that displays long sweeping east-directed crossbeds; and 0.9 m of carbonate-cemented coarser gravel capped by brown Cady Mountains-derived fan gravel. Greenish well-bedded sand and muddy sand underlie the capping fan gravel to the south. These deposits are interpreted to be derived from the influx of water from Lake Manix upstream.

We are now passing onto the dry sandy bed of the Mojave River. If you have not driven on loose sand before, keep your speed steady, do not drive too slowly, and stay on the tracked part of the sand—rude surprises await the unwary driver in the loose sand on either side! To accelerate from a stop, apply power gradually and smoothly to avoid digging in your wheels. Finally, never make a sharp turn in loose sand; turn gradually.

31.7 Strath terraces postdating the draining of Lake Manix on the left, and on the right at 2:00 near the railroad.

32.4 Mojave Road follows main channel traversing toward the north side of the valley floor.

32.9 Active sand dunes blanket the north valley wall on the right. The gravel-capped reddish bluffs straight ahead are the location of Stop 3A.

33.0 Veer to the right onto the gravel bars, just another 0.1 mi. Park in this area; **do not attempt to drive close to the bluffs!** The gravel bars here provide a stable surface and an easy place to turn around. Take water; the main deposits of interest are within a few hundred meters.

Stop 3A

The bluffs are underlain by a cliff-forming unit, about 10 m thick, of brown playa deposits composed of poorly sorted sandy mud and interbedded thin fan-gravel lenses. Above this is an abrupt change to a gentler slope. This slope is underlain by a section (fig. 5; site M07-147; 551913 E, 3877557 N, 463.0 masl) of horizontally bedded flood couplets composed of medium sand overlain by well-sorted, laminated silt and then clay (lacking sand grains, unlike the playa muds below). The uppermost mud displays soft-sediment deformation. This in turn is overlain by similar sand, silt, and clay layers, but they are dipping as much as 20° eastward. The deposits are capped by interbedded coarse sand and pebble-cobble beds dipping 10° eastward. The clasts are dominantly volcanic rocks similar to those exposed in Buwalda Ridge (the dark hump on the western horizon).

Moving to the west along the same outcrop (site M07-148; 551889 E, 3877524 N, 464.7 masl), the flood couplets and the steeply dipping sand, silt, and clay unit are still present, but the latter are dipping less steeply, and the overlying gravel contains a rip-up clast of green Lake Manix mud. Yet farther west, the dipping unit is replaced by a contorted zone of green sand, silt, and mud (site M06-66, 551871 E, 3877498 N, 463.9 masl).

We interpret the flood couplets to represent initial discharge from an overflowing Lake Manix that, at the time, was

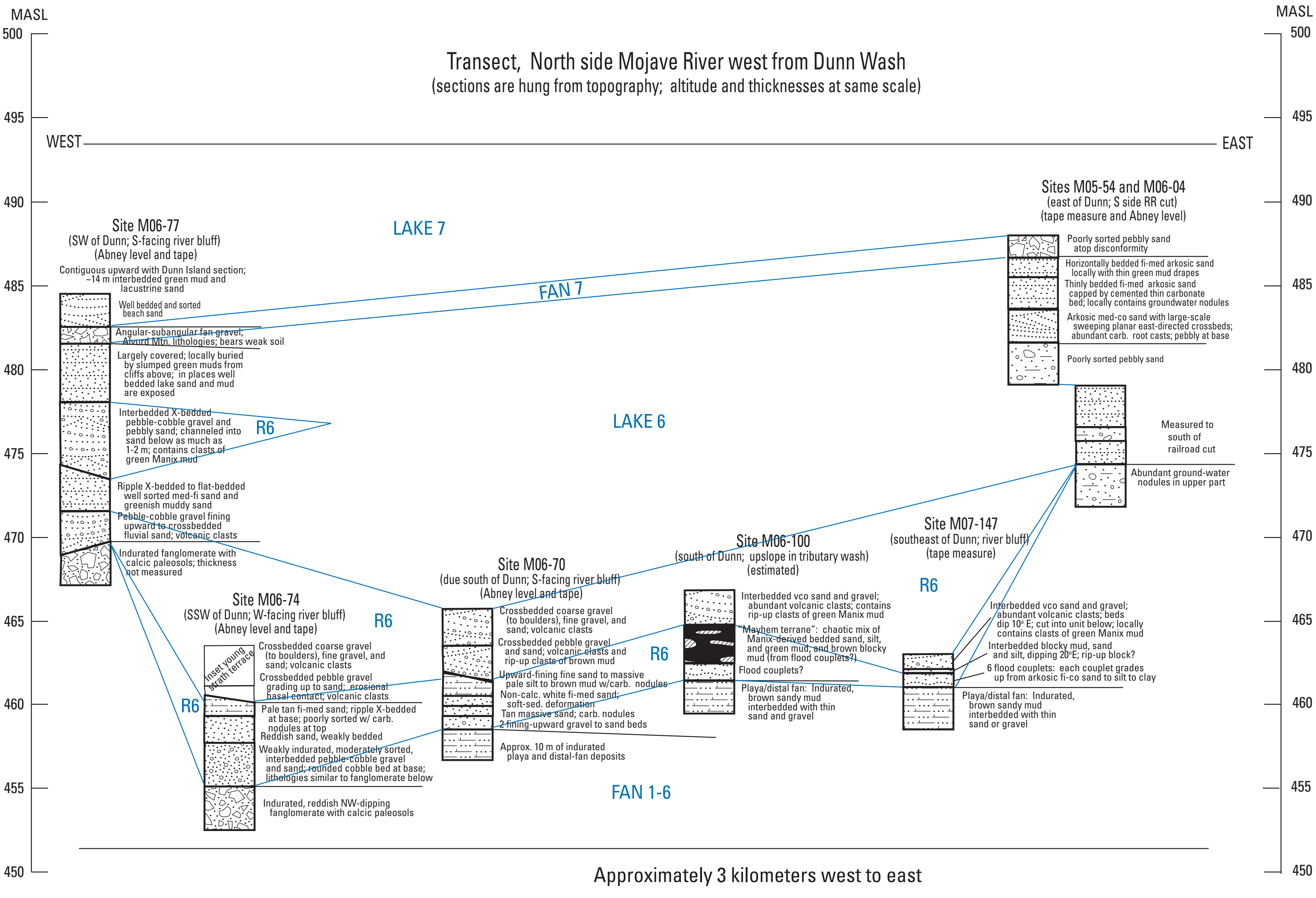

Figure 5. Sedimentology and stratigraphy of measured sections along the Mojave Road. Sites M07-147 and M06-100 will be visited at Stop 3A on the Pre-Trip Day . Site M05-54 will be visited at Stop 3 on Day 1.

confined to the area west of Buwalda Ridge; this discharge was transporting sediment eroded from the playa floor of the Afton subbasin. The deformed green sediments and the steeply dipping beds represent blocks of the Lake Manix deposits transported as much as 8 km, as well as more locally derived flood-couplet deposits, largely intact, brought down by flood water when the barrier at Buwalda Ridge failed catastrophically. The overlying coarse sand and gravel (R6) represents the establishment of through-flowing drainage emanating from the Manix subbasin upstream (in other words, a proto-Mojave River). This fluvial deposit elsewhere grades up into well-bedded lacustrine sand and silt of L6, the first lake in the Afton subbasin (Stop 3, Day 1; fig. 5). In the last outcrop we will examine, ~250 m to the west (site M06-100; 551658 E, 3877284 N, 466.8 masl), a similar stratigraphy is well exposed (after much shovel work). This outcrop displays a distorted assemblage of large, semi-intact, highly deformed, beach sand, green mud, and blobs of brown clay. These blobs are either paleosols formed on Manix muds or the early flooding clays, distinguishable from the underlying playa mud because the paleosols and (or) flooding clays are well sorted with no sand grains.

We will not go west of this outcrop, but if you wish to see more outcrops on your own someday, they are easily accessible along the Mojave Road. The unit of flood couplets gradually thickens and coarsens over a distance of 2 km (fig. 5) to become an entirely fluvial section of sand and pebble gravel with crossbedding indicating eastward flow; the overlying coarse sand and cobble gravel unit continues and locally contains rip-up clasts of green mud. Locally, however, the upper portion of the finer-grained fluvial beds is truncated by an inset strath terrace. In the westernmost outcrops (site M06-77; 550217E, 3876485N, 473.0 masl), the coarse sand and cobble unit is directly overlain by well-bedded and well-sorted granitic sand representing the L6 deposits in the Afton subbasin (we will see these at Day 1, Stop 3). This sand locally contains one or more wedges of fan gravel thickening to the north, and is overlain by a similar thin fan gravel, locally bearing a weak soil (Bwk horizon). This final fan gravel is directly overlain by beach sand and thick deposits of green muds representing L7 in the Afton subbasin (fig. 3).

Directions to Stop 3B:

Return to the directions from Stop 2 to Stop 3 of Optional Pre-Trip Day at Mile 30.8.

30.8 CONTINUE STRAIGHT for approximately 0.8 mi on the main road which leads to the Afton Canyon campground and park. This stop will likely take an hour or two at most and involves light to moderate walking (see map, fig. 6).

Stop 3B

The fluvial terrace sites near the Afton Canyon campground are the upper and lower terraces within a flight of about 10. These surfaces include an intermediate level of canyon incision (site JR04CM-95; 556872 E, 3877730 N, ~463 masl) and one of the lowest terrace remnants within Afton Canyon (site JR04CM-78; 557270 E, 3876966 N, ~439 masl). Soil development differences between these locations and the uppermost fluvial terrace seen at Stop 2 (site JR04CM-84) are minimal, do not correspond with elevation differences, and likely represent the natural variability of soil

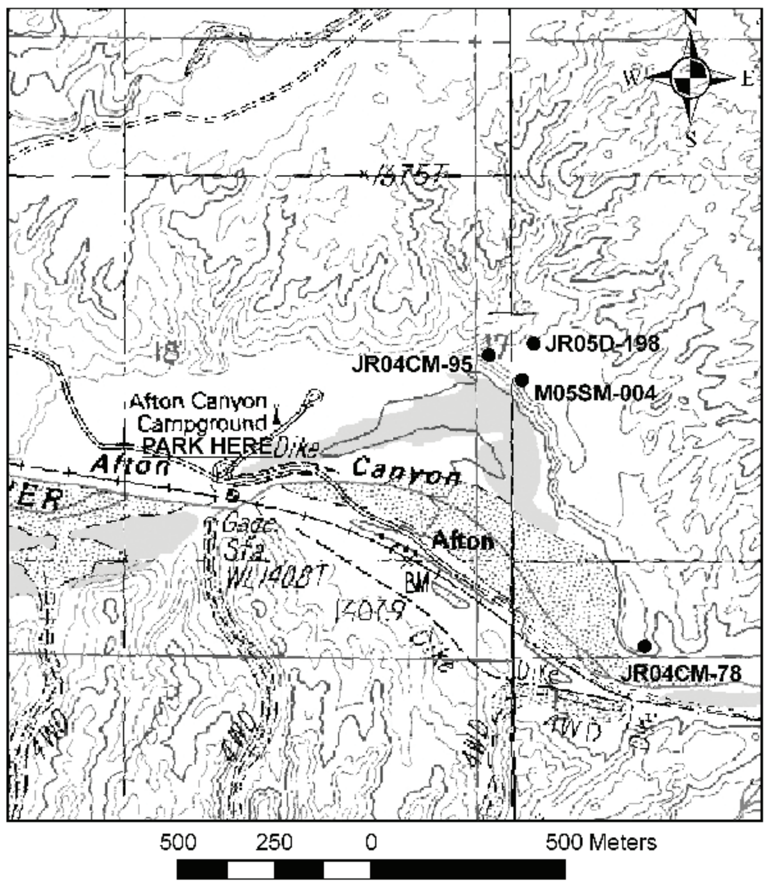

Figure 6. Map of Afton Canyon campground and area of Stop 3B, Pre-Trip Day.

development within fluvial deposits of similar ages. These deposits and soils are discussed in Reheis and Redwine (in press; see figs. 8, 9, and 11 therein).

Walk to the northeast end of the developed campground along the dirt road with campsites. Head past the farthest campsite and through the bushes for ~0.25 mi towards a narrow V-shaped canyon, bearing ~N60°E. Here, at the upstream end of this flight of fluvial terraces, strath terraces inset below basal Lake Manix sediments track incision to within about 12 m of the modern Mojave River. Overlying these strath terraces are 20–25 m of fluvial deposits, mudflows, and alluvium. We will climb up this deposit and glance at the soil development of the overlying Qya4 fan at site JR05D-198 (fig. 6; 556983 E, 3877763 N); this soil has an Av/Bwk/Ck profile with maximum stage I carbonate morphology and postdates much of the canyon incision (fig. 11 of Reheis and Redwine, in press).

We will then walk to the uppermost strath terrace within this terrace flight (fig. 6; site JR04CM-95; 556872 E, 3877730 N; figs. 8, 9, and 11 of Reheis and Redwine, in press) and examine the soil profile. Next we will proceed to a nearby site where Shannon Mahan and David Miller (U.S. Geological Survey) sampled a sand sheet that overlies a channel-shaped gap just southeast of site JR04D-95 (Miller site M05SM-004; 556939 E, 3877684 N) for luminescence analyses. The age of the OSL analysis on quartz is 12.6±1.2 ka and ages from IRSL on feldspars are 13.1±0.71 and 13.6±0.94 ka (S. Mahan, U.S. Geological Survey, written commun., 2006). This eolian deposit represents burial after the cutting and filling of this channel and likely pre-dates subsequent piracy and abandonment of these surfaces.

We will then walk about 0.5 mi to the southeast, down the flight of terraces, and look at the soil development in one of the lowest fluvial terraces inset into the canyon (site JR04CM-78; 557270 E, 3876966 N; figs. 8, 9, and 11 of Reheis and Redwine, in press). We will discuss what these soils, flights of terraces, and luminescence ages may mean in terms of timing and rate of incision of Afton Canyon.

Retrace route down the Mojave Road to the Afton Canyon Road (from Stop 3A) or upstream from the campground (Stop 3B) and return to camp via I-15.

Day 1: Afton Subbasin of Lake Manix and History of Afton Canyon

We will start from Calico Early Man Site at 7:30 A.M. (this will be the longest day); if you have not checked in and paid the previous night, please plan to arrive a half-hour early to pay the field trip fee and pick up a guidebook. The drive this day is about 60 miles round trip. Access to the first stop requires a high-clearance vehicle and parking space is limited. Please carpool as closely packed as possible from Calico Early Man Site, and be aware that at least 10 miles of the driving today will be on gravel and sand of lightly graded roads; *leave the sedans behind!*

0.0 Exit the gate at the Calico Site; set mileage to 0. We are driving across Holocene fan deposits, all derived from the nearby Yermo Hills. To the south, in the middle distance, the fluvial plain of the Mojave River forms a broad expanse. The Mojave River itself is marked by dunes of eolian sand derived from the river bed.

0.5 Cross riblets of Pleistocene fan deposits, marked by dark varnish, desert pavements, and a flat surface.

0.6 Left turn (south).

1.5 Fan merges with the Mojave River fluvial plain.

1.7 Right turn onto a paved road. Pass gas stations and the Minneola Store.

2.2 Cross I-15 freeway. The hills on the south side of the freeway are composed of folded gravels of the Mojave River (Reynolds and Kenney, 2004) that we will visit on Day 2. The hills mark an uplift at a restraining bend in the Calico fault (Dibblee, 1992).

2.3 Turn left to enter the freeway eastbound. Reset odometer to 0.

0.0 Eastbound freeway entrance. Much of the drive for the next dozen miles will be along the very flat Mojave River fluvial plain of latest Pleistocene age. Dated charcoal from fine-grained sediment (also bearing shells and bones) from excavations a few kilometers west of here yielded ages from 12.8±0.9 to 9.05±0.35 ^{14}C ka (Reynolds and Reynolds, 1985).

0.3 The Toomey Hills are visible at 10:00. The light-colored Miocene Barstow Formation contains a record of large lakes in this region (Reynolds and others, 2003; Reynolds and Woodburne, 2002), which were probably the aftermath of widespread extensional tectonism (for example, see Glazner and others, 1994). The linear front of the Toomey Hills is probably caused by faulting and uplift along the approximately east-striking Manix fault, a structure that played an important role in the evolution of Lake Manix.

3.0 Road cut on your left displays a spectacular exposure of the Manix(?) fault and associated folds. The main fault lies south of the white beds of the Barstow Formation. Faulted onto the Barstow Formation are gravels of unknown age, on top of which lie fluvial gravel of the Mojave River (Reynolds and Kenney, 2004). All of the gravels are folded and the Mojave River gravels lie well above the surrounding plain, indicating at least 8 m of uplift locally.

3.5 At 1:00 to 2:00 is Harvard Hill. It is composed of Miocene gravels and the Barstow Formation. Along its east and southwest sides, Mojave River gravels and gravels of Lake Manix form gentle slopes. We will visit some of the Lake Manix exposures on Day 2.

5.5 Ground on both sides of the freeway rises to the east, approximately where the Dolores Lake fault of Meek (1994) lies. Displacement along this fault apparently uplifts both Mojave River gravels and underlying Miocene strata, and therefore its latest offset may be Holocene in age. On the left is Dolores Lake, an example of a common perversion of deserts. The waterpark has never been seen in operation by us; rumors circulate of a new housing development at the lake.

7.5 Harvard Road exit. We will exit here for Days 2 and 3.

8.7 Miocene(?) gravel and fine-grained sediment in hills on the left are generally similar to those in the Toomey Hills, suggesting that the hills represent uplift along an unknown fault.

10.0 At 8:00 to 9:00 on the left is the broad divide between the Manix subbasin, in which we are driving, and the Coyote Lake subbasin to the northwest. Notice how flat the divide is. Much of the divide is underlain by a thin mantle of Mojave River fluvial sediment on Miocene deposits (Meek, 1994). At 9:00 to 10:00 lie the Alvord Mountains, which expose Mesozoic granitoids on the left with a prominent white streak of Paleozoic marble (Miller and Walker, 2002), and dark volcanic rocks on the right. The white rim of gravels in the distance on the right side of the mountains is Pliocene in age (Miller and Yount, 2002), and nicely marks vertical tectonics of the area since Pliocene time; it is domed up on the north side of the Alvord Mountains but sags down into the Coyote Lake basin on the west side of the Alvord Mountains.

11.0 Manix Wash overpass. Lake Manix muds and sands are exposed widely to the south.

13.6 At 2:30 is Buwalda Ridge, the west end of which we will visit on Day 3; it is informally named for J.P. Buwalda (1914), a paleontologist who first recognized the lake beds. The divide between the Manix and Afton subbasins in Lake Manix is located on the far side of the ridge, in an area now occupied by the Mojave River. Buwalda Ridge is an uplifted ridge of Pliocene fanglomerate that is intensely faulted on the south by shear along multiple strands of the Manix fault (McGill and others, 1988). During its earlier history, Lake Manix was apparently confined to the area upstream (west) of Buwalda Ridge, that is, the Manix, Troy Lake, and probably Coyote Lake subbasins. The lake entered the Afton subbasin downstream (east) by overtopping or by sapping through the divide, abetted by sheared zones along the fault. Later today (Stop 3) we will see evidence for the first lake in the Afton subbasin, which followed a catastrophic flood originating from the vicinity of Buwalda Ridge (Pre-Trip Day, Stop 3A).

15.0 Field Road exit. Pliocene(?) gravels are deformed into a broad fold and are exposed in freeway road cuts as east-dipping strata. These gravels differ from those on Alvord Mountain by having a different clast assemblage. On the north side of the hills we are driving across, a linear front is interpreted as fault-controlled by Phelps and others (in press), and that inferred fault is co-extensive with the Cave Mountain fault cutting Lake Manix sediment in the Afton subbasin (fig. 2), suggesting that the fault system has been active in the Quaternary.

16.0 At 2:30, dark blocks at the low point in the valley are cuts along the south side of the Mojave River channel, exposing pre-Lake Manix deposits. From here to Afton Canyon, the river has incised through the Manix lake beds into underlying valley-fill deposits. The Cady Mountains lie in the distance to the south.

17.4 We are crossing a bridge over an arroyo that cuts into the uppermost, youngest lake deposits in the Afton subbasin.

18.7 Rest area exit. Potable water is available here at spigots next to the handicapped parking spaces. A beach deposit is preserved above the rest area on the north side of the freeway.

19.5 The mountain on the left has faults in old gravels near its southern base; these faults may have Quaternary offset because they align with others that cut Lake Manix deposits.

19.8 At 2:30, prominent green outcrops across the railroad tracks on the right are the “Dunn Island” area. They consist of sands and muds of L7, the second lake phase in the Afton subbasin (fig. 4). Beach and nearshore sands in the middle of the outcrop grade shoreward into fan deposits bearing a weak buried soil, indicating a notable fluctuation in lake level during the time represented by this outcrop. Sediment analyses by Jordon Bright (Northern Arizona University, written commun., 2007) suggest that the lower subunit commonly contains gypsum crystals but no fish bones and thus probably represents more saline lake water, whereas the upper subunit lacks gypsum and has many fish bones, and thus represents fresher water.

22.3 Cross the informally named Dunn Wash, where thick L7 green mud is capped by varnished F8 surfaces (Fan 8, exhumed) overlain by L8 sand and mud.

22.9 Take the Afton exit, which climbs to the L8 (late Pleistocene) highstand barrier beach.

23.2 TURN RIGHT (south) on the barrier beach crest. Cuts along the freeway and in drainage channels show that lagoonal deposits capped by weak soils are overlain by beach gravels, illustrating multiple lake occupations at this level. Drive south along the barrier, which is 543 masl (1,780 ft on the Dunn 7.5’ quadrangle).

23.6 The strike-slip Cave Mountain fault cuts the barrier beach at this position, although exposures have been destroyed by human bioturbation.

23.8 Holocene fan deposits, shed from the hill to the left, lie on F8 exhumed gravels (the varnished surfaces downslope) that once lay between L8 and L7 deposits. This relation is common in the Afton subbasin, where L8 fines are widely stripped away and subjacent alluvial fans are exposed; these were deposited atop L7 deposits during a lengthy hiatus and possibly lake desiccation. Ellsworth (1932), Blackwelder and Ellsworth (1936), and Meek (1990) refer to this fan as the “Interlacustral Gravel;” here we refer to it as “Fan 8” (fig. 4).

24.6 The fan surface to the right, past the power lines, bears scattered tufa coats on clasts that mark the transgressive base of L7; the rest of L7 and younger deposits have been removed.

24.8 Continue past the power line road (graded gravel); prepare to turn left.

24.9 TURN LEFT on the 4WD track. Only high clearance, not 4WD, is required as far as Stop 1; 2WD pickups will be fine. Leave smaller cars at the parking spot on the right after turning onto the road. We are again driving over very thin, young fan deposits and occasional patches of L8 gravels overlying F8 and L7 deposits.

25.4 On the right at about 2:00, the whole sweep of the 2-km-long north Afton beach ridge is visible. We will walk onto that ridge for Stop 1A. Green muds exposed across the valley on the south side of the Mojave River represent L7. Cave Mountain is visible at 11:00.

25.8 On the left are eroded Tertiary(?) gravels with huge boulders of granitoids. At 3:00 is Shoreline Hill; wavecut terraces formed on bedrock are visible.

26.0 Park on the pavement surface to the right of the road, OR take a right fork onto a fainter road; it parallels the main track and rejoins it to make a one-way parking loop. We will take a long walk, so carry water for two to three hours. Walk about 0.8 km southward on the linear beach ridge (to GPS coordinates 557525 E, 3878741 N) for this overview stop.

Stop 1A

Here we will discuss the general setting and review the lake-basin geography, tectonics, stratigraphic scheme, and lake-basin history (see Introduction to Lake Manix basin). Moving clockwise beginning due east of this point, a pale-green ridge, capped by a thin gravel remnant, consists of F8/L7/L6 (fig. 4); we will see this stratigraphy at Stop 1B. To the southeast, the same sequence is visible, but the L6 deposits lie atop a steeply dipping unconformity on older F1-6 beds (reddish due to buried soils; this is the fanglomerate of Cave Mountain). Next is Shoreline Hill, visited yesterday in the optional Pre-Trip Day (as if any day on an FOP field trip is ever mandatory…), and beyond that hill on the right is the overflow point and former threshold of Lake Manix. To the south is the Manix fault. To the south and southwest, across the river, are green L7 beds over thin L6 fan-delta deposits and two fanglomerate units. The upper “gray” fanglomerate, with abundant volcanic clasts, was sourced from the Cady Mountains to the south (Ellsworth, 1932; Meek, 1990). The lower “brown” fanglomerate, with red and white calcic paleosols and a granitic composition, was sourced from Cave Mountain to the north. To the west of the beach ridge, most of the surfaces are either F7 or F8 fan gravels exhumed from beneath younger deposits by erosion, but the perspective from here makes discrimination of these gravels difficult.

From the ridge we will drop down eastward through a depositional sequence of L8 (three subunits)/F8/L7/L6 fan-delta deposits; the main wash at the bottom lies atop, and is locally incised into, the Cave Mountain fanglomerate (F1-6). We will not examine the details of this section; a similar one, but in a fluvial-nearshore setting, will be the focus of Stop 4 today. Briefly, the L8 deposits seen here include, from top to bottom: L8c, ~1.5 m of beach pebbles; L8b, ~2 m of interbedded sand and pebble layers capped by a poorly sorted, indurated sand layer that represents a drop in lake level, and marked at the base by a gravel layer with thin tufa coats indicating a transgression over the next lower unit; and L8a, ~4–5 m of mostly medium sand at the top, slightly oxidized, grading downward and eastward into greenish fine sand and a few thin blocky muds (lagoonal?), underlain by 2–3 m of interbedded sand and gravel. This entire sequence rests atop fan deposits of F8 and a few meters of nearshore deposits of L7.

At the main wash (GPS point 557700 E, 3878740 N), go straight across and up a side wash leading north to see a spectacular section of fan-delta deposits of L6 overlain by finer-grained L7 deposits (site M06-135; GPS point lies on the capping F8 gravels at the top of the exposure, 557724 E, 3879018 N, 539.0 masl).

Stop 1B

Most of this outcrop (fig. 7) consists of sandy gravel and gravelly sand. Although at first glance, these deposits might appear to be of fluvial origin, most of them have bedding features that indicate they were deposited as an alluvial fan-lake interface; we interpret this section as fan-delta deposits of lake 6 (L6), the first phase of Lake Manix to fill the Afton subbasin. L6 deposits are nearly 7 m thick and are capped by 0.6 m of alluvial-fan deposits (F7) bearing a weak soil; 2.7 m of pale-colored bedded lacustrine silt and sand of unit L7, and 0.6 m of F8 fan gravel. Gravel clasts in the basal ~1.5 m of L6 commonly have tufa coats. L6 deposits can be traced up this drainage to a ~10–15° dipping line of large boulders, locally tufa-coated, that define the transgressive base of L6.

Return to the cars over the top of the fans, or walk back to the main wash and follow it upstream back to the cars.

Return to Afton Canyon Road.

27.1 TURN LEFT on main gravel road (Afton Canyon Road). We are driving on the interlacustral gravel (F8).

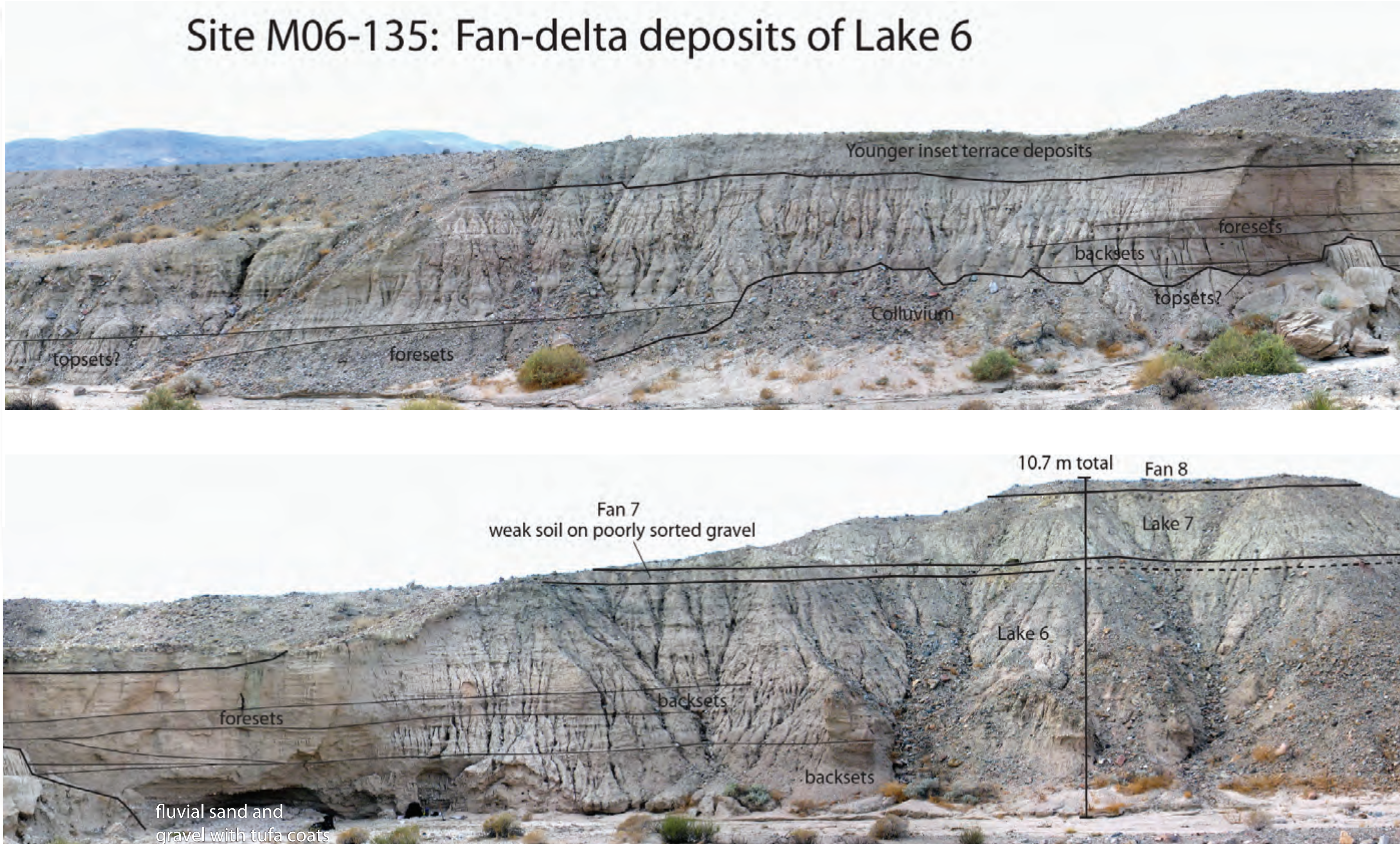

Figure 7. Stratigraphy of deposits at Stop 1B, Day 1. The panoramic view is a composite of nine original photographs. This arroyo cut exposes sediments of L6 and L7; fan gravel of F8 caps the top of the ridge. The top of the underlying fanglomerate of Cave Mountain emerges from the arroyo floor a few tens of meters downstream and is not visible in the panorama. Most of this outcrop consists of sandy gravel and gravelly sand. Most of these deposits have bedding features that indicate deposition at an alluvial fan-lake interface, and they are interpreted as fan-delta deposits of Lake 6, the first phase of Lake Manix to fill Afton subbasin. L6 deposits are nearly 7 m thick and are capped by 0.6 m of alluvial-fan deposits (F7) bearing a weak soil, 2.7 m of pale-colored bedded lacustrine silt and sand of unit L7, and 0.6 m of F8 fan gravel. Gravel clasts in the basal ~1.5 m of L6 commonly have tufa coats.

27.4 Road steepens as we drive down the scarp across F8 gravel and across L7 greenish mud and sand to the base of L7 deposits, marked by tufa-coated cobbles.

27.7 Road steepens again, cutting below the lake deposits into Tertiary(?) Cave Mountain fanglomerate (F1-6) bearing many soils. As you start to descend, sight downhill (south) along the surface marked by tufa-coated cobbles at the base of L7 to see a flat surface that intersects it. This surface, on both sides of the river, is a thin fan gravel (F7) that overlies sand and thin green mud of L6, the first lake phase to occupy the Afton subbasin.

27.8 Straight ahead, the upper 2–3 m of the canyon wall are greenish sands of L6.

28.3 On the left are strath gravels overlain by steeply dipping beds of sands and gravels, all deposited by the Mojave River as it incised below the former base of Lake Manix after Afton Canyon formed and the lake drained. Drive onto a flat fluvial terrace.

28.4 Drive up the back edge scarp of the next terrace. From this surface we can see the North Afton beach ridge at 12:00 (Stop 1, walking tour), composed of light-colored sediments weathering in badland forms. Drive down the back edge of the fluvial terrace. High fluvial straths are visible at 1:00 on the north rim of the canyon as you top the fluvial terrace (visited yesterday on the optional day hike). At 3:00 on the south side of the river, you can see the contact of the tan and red Cave Mountain fanglomerate with the overlying gray-brown Cady Mountain fanglomerate, both of which are overlain by green lacustrine muds of L7. The lower fanglomerate contains strong calcic soils, while the upper has very few.

28.6 Reverse fault is exposed in road cut on the right (N. Meek, Calif. State Univ. San Bernardino, oral commun., 2006).

29.0 TURN LEFT into Afton Canyon campground, where pit toilets are available. We'll eat lunch here and then take a short, strenuous hike to STOP 2.

Stop 2

See the detailed description and measured sections in the appended draft copy of Reheis and Redwine (in press; their figs. 3 and 14) and additional materials in Redwine (U.S. Geological Survey, unpublished mapping); the following is summarized from these reports.

Inset Strath Terraces West of Lake Manix Threshold

Fluvial deposits inset below Lake Manix deposits, west of the lake threshold, include strath terraces with both a veneer of gravel and much thicker alluvial fills that are variably re-incised. Terrace surfaces lie between 12 and 36 m above the modern channel and commonly exhibit meander scars. The terraces are almost entirely cut into the indurated, matrix-supported Cave Mountain fanglomerate. In contrast, the fluvial deposits overlying the strath surfaces are loose, clast-supported deposits, 1–4 m thick, of rounded to well-rounded gravel of primarily Cave Mountain lithologies with rare clasts of reworked, green lacustrine mud. The gravels are interbedded with quartz-rich sand and rare, thin, discontinuous beds of green clay and silt. In some deposits there are also well-rounded volcanic lithologies, mainly basalt and rhyolite, likely sourced from the Cady Mountains south of the Mojave River. Soils developed into the fluvial deposits typically have Av/Bwk/Ck or Av/Btk/Coxk horizon sequences. Normalized PDI values for these terrace soils range from 0.02 to 0.07, similar to values for soils on the 543-masl beach ridges in the eastern Afton subbasin (tables 2 and 3 of Reheis and Redwine, in press). Soil differences are not consistent relative to elevation above the river, and likely reflect a range of natural soil variation among soils that are similar in age. These terraces and their soil development show incremental incision of the canyon at a rate faster than can be recorded by differences in pedogenesis.

"Slack Water" Deposits

Fine-grained deposits are associated with valleys incised into the fanglomerate of Cave Mountain on the north side of Afton Canyon, west of the lake threshold (JR04D-68 and -70, fig. 3 of Reheis and Redwine, in press). Ellsworth (1932) inferred these deposits to represent the presence of a lake that formed after much or all of the canyon incision had produced the modern dendritic topography. However, Ellsworth (1932) and Blackwelder and Ellsworth (1936) were confounded by the absence of evidence for any damming of the canyon to the east by fan aggradation, fault movement, or landslides, which would be required to produce such a lake. Meek (1989, 1990) interpreted some of the deposits to represent slumping or reworking of overlying lacustrine clays when they were still present nearby (lake deposits are eroded far back from these sites today), and suggested that the thickest deposits represent side-canyon ponding or "slack water" deposits formed during floods that were transporting eroded lacustrine sediment.

Our study of these fine-grained deposits, concentrated in the largest and most complete exposure (JR04D-68), has yielded more data, yet the interpretation of their origin and age is still difficult. More than 5 m of deposits rest unconformably on pre-lake fanglomerate at and below about 478 masl. These deposits include, from bottom to top (fig. 10 of Reheis and

Redwine, in press): (1) sandy alluvium overlain by well-sorted sand; (2) blocky green mud, locally burrowed, with abundant secondary gypsum and other soluble salts, overlain by thinly interbedded green mud and laminated fine to medium sand; (3) thinly interbedded, laminated and ripple cross-bedded sand, locally with clay and silt; coarsens upward and intertongues toward adjacent hillslope with coarse fan sand and gravel; and (4) locally derived fan gravel.

Many beds in units 1 and 2 contain abundant to rare lacustrine ostracodes, abraded and winnowed near the base but including a coquina-like ‘death bed.’ The ostracode assemblages and their changes with stratigraphy appear to represent life assemblages in a perennial lake; the species represented are identical to those found in Lake Manix lake beds (R. Forester, U.S. Geological Survey, written commun., 2005; Steinmetz, 1987). Analyses of ostracodes from four strata in units 1 and 2 yielded ages in approximate, but overlapping, stratigraphic order from 31,500±420 to 27,020±10 ^{14}C yr B.P. In direct conflict with these ^{14}C ages is a luminescence age of 8.05±0.25 ka using OSL on quartz and a similar result using IRSL on feldspar (S. Mahan, U.S. Geological Survey, written commun., 2006); the surface soil properties of the capping fan gravel are consistent with such a younger age (Reheis and Redwine, in press).

The majority of our new evidence supports a fluvial origin for the “slack water” deposits at site JR04D-68, as first suggested by Meek (1989, 1990), rather than a shallow young lake as posited by Blackwelder and Ellsworth (1936). In support of the lake hypothesis, the stratigraphy, ^{14}C ages, and life-like ostracode assemblages appear to indicate deposition in a perennial but short-lived lake that occupied a valley that had been incised below the bottom of Lake Manix, but significantly before the last highstand of the lake (about 22,000 ^{14}C yr B.P. in this study). However, no other stratigraphic or geomorphic data support such a hypothesis; the ~8-ka luminescence ages are in conflict, and no remnants of a damming mechanism once Afton Canyon was partially or completely incised have been identified. In addition, the calibrated ^{14}C ages overlap and do not show a consistent age progression with depth. In support of the fluvial hypothesis, some of the alluvial and fine-grained deposits and the intertonguing of some of the upper beds with coarse local sand and gravel suggest “slack water” deposition during Mojave River floods. Soil development (JR04D-157, table 2 of Reheis and Redwine, in press) and surface characteristics of the overlying alluvial fan are similar to those of other inset strath terraces and suggest an age younger than the last highstand of Lake Manix, consistent with the 8-ka luminescence ages. If the deposits have a fluvial origin, then a life-like assemblage of mostly unabraded, well-preserved ostracodes was fortuitously redeposited at this site.

Retrace route out of Afton Canyon.

30.3 As we rise out of the canyon incised into pre-Lake Manix gravels, the view upslope along the former L7 lake bottom emphasizes scarps interpreted by Meek (1990) as representing erosion-resistant alluvial gravels that encroached over lake deposits during climatic intervals characterized by no or small lakes. The scarps are not at constant elevation, making another suggested interpretation of the scarps as wave-cut features (Wells and Enzel, 1994) unlikely.

31.0 TURN LEFT on power line road.

31.3 Drive along an erosional scarp exposing green muds of L7.

32.0 Route AF 313 and a pink shack on left. Continue straight on the power line road. Do not take AF 2423. We are driving on the base of L7, as indicated by the tufa-coated cobbles.

32.4 Drop down into a large wash (east fork of Dunn Wash).

32.6 Under the power lines, at 11:00 are excellent exposures of L6 deposits overlying distal fan deposits, also exposed at Stop 3.

33.2 Complex intersection. Fixer-upper home on left. Take the middle road.

33.4 TURN LEFT toward the fixer-upper. Pass it and park in the open spot north of the railroad cut for STOP 3.

Stop 3

The railroad cut (site M05-54; 552284 E, 3878805 N, 478 masl) exposes, from top to bottom, a thin fan gravel (F7) overlying ~4.5 m of well-sorted sands exhibiting long sweeping crossbeds indicating east-directed flow. The sands are quartz- and feldspar-rich and similar to modern Mojave River sand. Green muddy sand forms a few thin (centimeters) layers in the upper part of the exposure on the south side of the cut; although these muds contained no ostracodes, deposits in similar stratigraphic positions (for example, M05-20 and M05-65 west of the north Afton beach ridge) contain *Limnocythere ceriotuberosa* (J. Bright, Northern Arizona University, written commun., 2006) typical of Lake Manix deposits. The basal sand contains carbonate-cemented layers and nodules that resemble root casts. The sand overlies poorly sorted, indurated, distal alluvial-fan deposits (F6), and represents a valley-axis facies of L6, the first lake to occupy the Afton subbasin. In other locations to the south and west (fig. 5), this sand is thicker and contains thin interbeds of distal-fan deposits, lacking soils, suggesting brief fluctuations in lake level. To the southwest, along the Mojave River, this same sand directly and conformably overlies fluvial gravel and sand, with clasts of dominantly mafic volcanic rocks probably derived from older fan deposits upstream near Buwalda Ridge (fig. 3). In turn, these fluvial deposits overlie the “Mayhem terrane,” a zone of chaotically mixed and plastically deformed blocks of Lake Manix muds and sands mixed with locally derived playa muds (fig. 5). These were seen at Stop 3 on the Pre-Trip Day, and can be accessed with a 4WD vehicle along the Mojave Road (the river bed), or by hiking 1.5 km heading S25°W from the railroad cut.

Return past the fixer-upper.

33.6 Continue straight on the good road. Head uphill (northwest) toward the freeway.

33.7 Cross under the power line, continue straight.

34.0 Cross under a smaller power line, continue straight.

341 TURN RIGHT on a paved frontage road. Cross Dunn Wash and climb to the Afton exit beach ridge.

36.0 TURN LEFT across the freeway and cross the cattle guard ahead (DO NOT take freeway); turn left on the paved frontage road. The store at this intersection offers water and minimal food, as well as long stories about the desert experience!

36.3 We are crossing through F8 and L8 deposits.

36.8 Tufa-coated cobbles are nicely displayed at the base of L7 greenish mud on both sides of the roads in steep road cuts. Cross the east fork of Dunn Wash. Climb onto a surface underlain by complicated thin sequences of L8 gravels and younger fan deposits.

37.1 Road takes a right-angle turn to the north and turns to gravel.

37.4 TURN LEFT onto the pipeline road to park in an open area on the right.

Stop 4

Stop 4 is shown on inset figure 3B. See the detailed description and measured sections in Reheis and Redwine (in press; their figs. 2 and 4); the following is summarized from that report. GPS coordinates for site M05-19 are 551615 E, 3880169 N and mark a long bulldozer cut; other sites on those figures lie to the north, up the west fork of Dunn Wash.

Lake Manix reached highstands at or just below 543 masl at least three times during the late Pleistocene, as suggested by Meek (1990, 2000). Highstands at this altitude are marked by well-preserved constructional beach barriers and locally by well-defined wave-cut scarps. Most such barriers are flat-topped with sloping, gently rilled flanks; some are nearly unbreached and retain fine-grained sediments deposited in back-barrier or lagoonal settings on the landward side (for example, the Afton exit barrier). At the Dunn Wash sites, at least four lake fluctuations are recorded (fig. 4 of Reheis and Redwine, in press). Dunn Wash was an active drainage during these fluctuations, and therefore lacustrine and alluvial sediments are interbedded. These two depositional environments are very difficult to distinguish in places where alluvial gravel was only slightly reworked during a subsequent lake-level rise.

The oldest lake unit (unit 1 in section M05-19, fig. 4 of Reheis and Redwine, in press; equivalent to L7) has basal lacustrine gravel with thick tufa coats on clasts, overlain by green mud, silt, and sand that coarsen and thin shoreward. The tufa-coated gravel persists to an altitude of at least 539 masl. This unit is overlain by alluvial gravel of unit 2 (F8) and a buried soil with a Btk horizon. The buried soil is overlain by three packages of beach gravel and sand (units 3, 4, and 5, all fluctuations within L8) that rise and thin shoreward, typically with tufa-coated clasts at the base of each package and separated by weak soils or alluvial units. Lake units 4 and 5 (L8a and L8b) can be traced to an altitude of about 543 masl. *Anodonta* shells near the base of L7 at site M05-20 yielded a finite but minimum-limiting age of 49,800±2,000 ^{14}C yr B.P. (table 1 of Reheis and Redwine, in press). A single preliminary U-series age on the basal tufa is 71±25 ka (J. Paces, U.S. Geological Survey, written commun., 2007). Lake unit 3 is only locally preserved and may represent a minor fluctuation within L8a. *Anodonta* shells within unit 4 (L8a), below a weak buried soil, yielded ages of 34,680±260 and 31,900±200 ^{14}C yr B.P. (sites M05-19I and M05-21). At two other sites in this drainage (JR04-D-1, immediately below a 543-m beach crest, and M05-28B), the uppermost unit 5 (L8b) contained *Anodonta* shells that yielded ages of 25,420±120 and 26,030±100 ^{14}C yr B.P. A similar stratigraphy with comparable ages is preserved in the North Afton beach ridge. A younger highstand (L8c) that reached minimum elevations of 534 masl on the north Afton beach ridge and 536 masl on the south Afton beach ridge (south of the river) has yielded ages ranging between 20.6 and 21.8 ^{14}C ka on *Anodonta* shells. Deposits of L8c have not yet been identified in the upper Dunn Wash area.

Retrace the route to the I-15 freeway and drive south to Minneola Road and campsite.

Day 2: Manix Subbasin of Lake Manix and Tectonic Disruptions

We will start from Calico Early Man Site at 8:00 A.M. The drive this day is about 30 miles round trip. Please carpool as closely packed as possible from camp, and be aware that at least 20 miles of the driving today will be on gravel and sand of lightly graded roads. High-clearance vehicles are not required, but there are two crossings of washes with loose sand.

Follow the Day 1 road log to Harvard Road and EXIT. Set odometer to 0 at stop sign.

0.0 TURN RIGHT on Harvard Road (south). Notice the flatness of the Mojave River fluvial plain. In this area, the gradient eastward is approximately 2 m/km.

0.1 TURN LEFT on Yermo Road, old Highway 40, now the frontage road for I-15.

0.8 Road climbs over cemented gravels of Tertiary age.

3.2 TURN RIGHT at Alvord Mountain crossroad, and cross the railroad tracks. Bear left along the dirt road fronting the railroad on the south; ignore the three other roads.

4.3 L7 beds on the right are capped by reddish sand of L8.

4.6 Manix Wash, where strath terraces consist of gravel of the Alvord Mountains.

6.6 Park in the wide area on the right as we cross an obscure boundary between Lake Manix gravels and alluvial fan gravels sourced from the low hills to the northeast. Buwalda Ridge lies to the south, with eolian sand decorating its gullies.

Stop 1

Walk about 1 km to the west tip of Buwalda Ridge to view shoreline deposits that lie above the common 543-masl shoreline of L8, as well as exposures of Manix fault splays. During the walk, we will cross dissected beach ridges composed of arkosic beach gravel and sand of L8. Note that the beach ridges are underlain by F8 deposits bearing a pavement of varnished volcanic clasts derived from Buwalda Ridge. Arroyo cuts both west and east of the beach ridges expose green sorted sands and local muds equivalent to L7 in the Afton subbasin and to “upper Member C” of Jefferson (2003). Our observations suggest that the broad divide north of Buwalda Ridge was probably submerged by shallow water at the highest levels of L7, but evidence for this is patchy and largely covered by younger fan and colluvial deposits shed from both sides of the divide.

At Stop 1, refer to the detailed description and measured section in Reheis and Redwine (in press; their figs. 2, 4, and 5); the following is summarized from that report. Outcrops on the southwest flank of Buwalda Ridge, adjacent to the Manix fault, expose two lake units separated by fan deposits (sites M04-75 and M05-06). At both sites, the older unit bears a moderately developed soil that formed prior to burial by the younger unit (figs. 4–7, Reheis and Redwine, in press); a similar moderately developed soil crops out at the surface on the north side of a strand of the Manix fault at the soil-pit site M04-76 (542395 E, 3870999 N) at 546 masl. The top of the outcrop south of the fault strand at M04-75 lies at about 542 masl (542443 E, 3870921 N). *Anodonta* shells from the younger of two units in this outcrop yielded an age of 22,470±70 ^{14}C yr B.P.

On the west end of Buwalda Ridge, two nested beach ridges (figs. 5, 6A, and 6B of Reheis and Redwine, in press) lie north of the Manix fault. The upper, moderately dissected beach ridge (soil pit M04-76) lies a minimum of 2 m higher than 543 masl. This upper barrier extends as high as 550 masl and once formed a loop attached to the hill to the east, but has been eroded to form two separate arms. A low, more sharply defined scarp, trending perpendicular to the Manix fault strands, is incised into the upper beach ridge at 543 masl, and this scarp grades downslope into a gravel-covered platform at 537 masl (soil-pit site M04-77; 543356 E, 3870981 N).

The upper beach ridge has a packed desert pavement and clasts mostly covered with desert varnish, in contrast to the lower beach platform. Soil pits excavated in both surfaces showed significant differences in soil profile development. At site M04-76 on the upper beach ridge, stratified gravel overlies well-bedded, coarse sand at a depth greater than 62 cm, and the sand contains lacustrine ostracodes *(L. ceriotuberosa)* and fish bones (R. Forester, U.S. Geological Survey, oral commun., 2005). Our observations at several nearby sites both south of the fault and near Troy Lake, all with altitudes higher than 543 masl, indicate that these higher shorelines were deposited by higher lake levels, not by fault displacement. The surface soil at M04-76 has a normalized PDI value of 0.11, and at site M05-46, a value of 0.07. The buried soil at M05-06 (542705 E, 3871027 N, 543 masl), in a deposit on the south side of the Manix fault, has a PDI value of about 0.13. Adding this value to that of the surface soil at M04-75, which formed on the overlying younger beach gravel, yields a total normalized PDI value of 0.17 as an estimate of cumulative soil development since deposition of the older gravel; this value is higher than that of the unburied older gravel nearby, perhaps due to erosion of the surface soil.

Retrace route west along railroad.

7.1 BEAR LEFT at a gate and take the road west toward the power line; DO NOT take the right fork after passing through the gate.

7.5 Road drops into Manix Wash.

7.6 Gravel surface is probably an exhumed fan between two lake deposits.

7.7 BEAR LEFT.

7.8 Cross Manix Wash. Beware the loose sand; 4WD is sometimes needed (we will scout in advance).

8.0 Exposures here are mud and sand of L7 (“upper member C;” fig. 4) with tongues of gravel and tufa-coated pebbles near the base. L8 (“member D”) forms a reddish slope above the greenish muds; it is composed of Mojave River gravel and sand.

8.4 White sand beds are visible in the sandy greenish muds of L7 on the right.

9.0 Cross road. Continue straight.

9.7 TURN LEFT onto main graded road.

10.3 We are at the base of a former stream channel that forms an incised meander valley in the fluvial plain. The channel evidently marks the route of the ancestral Mojave River that started to downcut locally after most or all of Lake Manix had drained, indicating that the knickpoint had migrated from Afton Canyon to somewhere near here at this time. Alternatively, the river may have made a local incision soon after the lake level dropped as it adjusted to the steepening of gradient to the east, from the delta top to delta slope. The river later initiated a channel in its present position to the south of this location. Strath terraces are composed of Mojave River gravels (granitic grus, rounded reddish quartzite, and volcanic rocks) on the south side of this channel; a preliminary quartz OSL date on sand beds is 21.1±2.0 ka (S.A. Mahan, written commun., 2007). Cosmogenic dates on surface pebbles of the strath yielded Pleistocene ages from 70.4±5.8 ka to 121.5±11.0 ka (L. Owen, Univ. Cincinnati, written commun., 2007) that we interpret as inherited ages from previous depositional sites in the Mojave River system.

10.8 BEAR LEFT at Vortek station (big bowling pin). Eolian sand ramps visible on the crest of the hills to the south are part of the Soldier Mountain ramp system, mostly out of sight. Note the broad swath of sand far to the east. All sand is sourced from the Mojave River. On windy days, this entire sand pathway is active (and you don't want to be in it).

11.1 BEAR LEFT along the fence line. Prominent shorelines are visible to the south.

12.1 Park at the abandoned trailer.

Stop 2

Manix reference section stratigraphy and core interpretations. We will hike a short distance on rough terrain to examine the exposed Lake Manix section along the Mojave River channel to the south. George Jefferson (2003, and papers cited therein) established a sequence of members in the Manix Formation and contributed greatly to our knowledge of the stratigraphy and paleontology of the formation. Figure 4 shows schematically the stratigraphy we studied in outcrop and compares it to the core stratigraphy (drilled 0.5 km to the north) and the reference section by Jefferson (2003). Prepare for a sometimes-strenuous short hike and bring water for two hours.

The following summary of our findings regarding the stratigraphy in this area is quoted directly from an abstract in press by Oviatt and others (in press):

> "We have found that, except for Member A of Jefferson, which consists of alluvial fan deposits, and Member D, which consists of fluvial-deltaic sands, most sediments in the Manix Formation were deposited in shallow lacustrine to mudflat environments punctuated by short episodes of deeper water. Although some units can be traced for kilometers and are relatively uniform in character, some units undergo facies changes over short distances. For example, unit Upper B of Jefferson is a sandy gravel unit along the Manix Wash bluffs, a mud unit in the core several hundred meters away, and a widespread sand bed for several km to the west of the core site. Tufa-coated gravel beds mark episodes of lake deepening or lake transgression, and are found capping both lacustrine and alluvial gravels. Buried soil profiles or soil horizons within the lacustrine section can be identified in the core and outcrops, and suggest multiple periods of non-deposition on the low-gradient floor of the Manix subbasin during the Pleistocene.
>
> Recently obtained radiocarbon ages of *Anodonta* shells in the uppermost stratigraphic unit range from 31.6 to 44.2 cal ka. The Manix tephra bed (approximately 185 ka) serves as a valuable marker in the lower part of unit Upper C (Jefferson, 2003) in the Manix subbasin. We have evidence for seven paleomagnetic excursions and estimate the bottom of the Manix core to be ~450 ka. Additional studies of geochronology, including amino acid racemization, OSL, and U-Th, are in progress. Our studies suggest some refinements to Jefferson's interpretations, including shorter lake cycles and somewhat different timing for parts of the section. The data suggest that the sediment record is reflecting Mojave River discharge and proximity of the Mojave River deltaic system."

"Member D" of Jefferson (2003) ranges from 8.5 to 10 m thick, and its surface is nearly planar at an altitude of 535 m, about 8 m below the 543-m Lake Manix highstands. It crops out only in this immediate area, and is not known east of Buwalda Ridge. The unit (fig. 4) is composed of reddish-brown grus-derived sand and fine gravel, with less common mud beds and laminae; the clast composition is strikingly similar to that of modern and latest Pleistocene Mojave River deposits. Sedimentary facies and structures also mimic those of the Mojave River, including cross-bedded channel-fill deposits, crevasse-splay deposits, marsh, and floodplain deposits. Foreset beds expected for a delta environment are largely absent. However, thin intervals of very well sorted silt or sand beds may represent brief lacustrine deposition, and a few micro-delta beds are present.

Radiocarbon results range from 40.0±0.6 ^{14}C ka from a shell 0.5 m above the base to 26.3±0.2 ^{14}C ka 1.2 m from the top. This time period spans 2 or 3 highstand beach-forming events elsewhere in the basin. We interpret the lake stands as brief to account for the lack of lacustrine facies in "Member D," which apparently represents an active Mojave River fluvial plain during marine oxygen isotope Stage 3.

Retrace the route west along the fence line.

13.1 CONTINUE STRAIGHT along the fence.

13.6 BEAR LEFT along the power line road.

13.9 BEAR RIGHT on a main road skirting Camp Ironwood, which lies on a broad abandoned terrace of the Mojave River.

14.0 BEAR RIGHT.

14.2 BEAR RIGHT. Don't take the sharp right turn. Look over your shoulders to read the signs for eastbound traffic entering Camp Ironwood. Any guesses on what kind of camp this is?

15.3 We are along the edge of the same incised meandering channel that we crossed earlier.

16.2 This is an uplift bordering the apparent trace of the Manix fault. Several anomalous topographic features occur in an east-west zone in this part of the fluvial plain.

16.6 BEAR LEFT along the power line road.

17.2 BEAR LEFT.

17.3 TURN RIGHT past the barn.

17.6 TURN LEFT along the power line road.

17.8 Cross Harvard Road. Watch for high-speed traffic.

18.8 We are now driving on local fan deposits shed from the Harvard Hills, ahead and to the right. The Harvard Hills are composed of Miocene fine- to coarse-terrigenous deposits, partly of the Barstow Formation.

19.6 Stop near the crossroads. We will need to simply park in the road and stop any local traffic because adjacent fans are very soft with eolian sand. DO NOT PULL OFF!

Stop 3

Uplifted and faulted nearshore deposits of Lake Manix. The outcrops between the crossroads and Harvard Hill are mostly well-sorted, thin-bedded sands of Mojave River composition. Interbedded muds contain lacustrine ostracodes. Exposures locally show well-sorted and well-bedded pebble to cobble gravels, suggesting they are beach gravels. We interpret the assemblage of deposits to be nearshore Lake Manix deposits. The complex geometries of several exposures are due to approximately east-striking near-vertical faults that disrupt the section. Near here, one of these faults cuts latest Pleistocene or early Holocene alluvial-fan deposits that postdate the Mojave River fluvial plain. We consider these faults to be part of the Manix fault zone. Lake Manix deposits can be traced as high as 593.1±0.2 masl here, requiring a minimum of 50 m of uplift, if they date to a time when the lake levels were a maximum of 543 masl. The nearest Lake Manix deposits, deposits similar to "Member D," are exposed about 700 m to the south along the Mojave River cliffs; the top of that unit is at ~552 masl and the base of the exposure is ~539 masl. If older lake deposits equivalent to these exposed deformed deposits underlie "Member D," then the uplift here would have been greater than 54 m. The uplift is probably a consequence of up-to-the-north displacement along the Manix fault and up-to-the-east displacement along the Dolores Lake fault, which lies a short distance west of this location as originally interpreted by Meek (1994). The geometry of the faults, location of uplift at

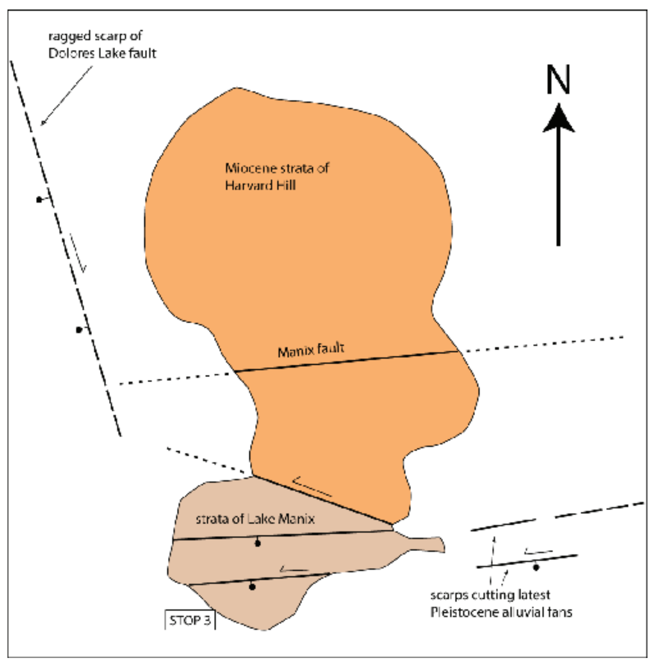

Figure 8. Sketch of geology at intersection of the Dolores Lake and Manix faults near Harvard Hill (Day 2, Stop 3). Based on unpublished geologic mapping of D.M. Miller and D.J. Lidke (U.S. Geological Survey).

the intersection of the faults, and evidence that both faults are active support the model of Dokka and Travis (1990) for uplift in block corners undergoing contraction (fig. 8); although a complex stepover is a possible explanation as well.

Continue west on the power line road.

19.8 Veer right through the poles, heading due west.

21.6 Drive along the edge of a small housing development.

22.1 TURN RIGHT on Coyote Lake Road, cross railroad tracks.

22.2 TURN LEFT on Yermo Road. Note the pale-colored east-dipping sands of the freeway cut (north side of the freeway). These are uplifted Mojave River deposits, probably analogous to those we saw at Stop 3 but fluvial rather than lacustrine in origin.

25.5 TURN RIGHT on Minneola Road and return to camp. If time permits, stop and park along the right side of Yermo Road before turning on Minneola Road for optional Stop 4.

Optional Stop 4

Uplifted and faulted gravels and sands of the Mojave River. The roadcuts here expose south- and west-dipping strata of the Mojave River, identifiable by the granitic grus, volcanic rocks, and well-rounded reddish-quartzite-pebble assemblage. Faults disrupt the beds in several places in cuts along the east side of Minneola Road. The Calico fault borders the east side of this hill and is prominent to the southeast as a zone of splaying faults that generally step strata of the fluvial plain down to the east (fig. 2). Latest Pleistocene terrace deposits bordering the Mojave River appear to be offset tens of meters in a dextral sense. The Calico fault cuts early and middle Holocene deposits south of here (Phelps and others, in press; Oskin and others, 2007). The Calico fault is interpreted by most workers to bend to the west-northwest at the north edge of these hills, in an apparent restraining bend, to cause the uplift of the Calico Mountains that can be seen to the northwest. However, the faults bordering the Calico Mountains do not show evidence for Holocene slip, raising the possibility that slip is transferred to other fault systems north of here. Recent surficial geologic mapping in this area (Phelps and others, in press) indicates that east-striking faults parallel to the Manix fault exist on both sides of the Calico fault, and hence complex interactions are likely. In addition, the Tin Can Alley fault of Dudash (2006) strikes nearly southerly, and is last visible just a few kilometers north of this hill (Miller and others, 2005). None of these faults are known to have Holocene activity. The fault configuration presents a major puzzle, to which answers are not completely known.

Day 3: Coyote Lake Subbasin of Lake Manix and Post-Lake Manix Lake and River History

We will start from Calico Early Man Site at about 8:30 A.M. The drive this day is about 25 miles. Most of the driving today will be on lightly graded roads and across a playa; high-clearance vehicles are not required.

Follow the Day 1 road log to Harvard Road and exit. Set odometer to 0 at stop sign.

TURN LEFT over the freeway on Harvard Road.

0.3 Pavement ends. Continue north. We are heading toward the Alvord Mountains, with dark granitoids and a white streak of marble straight ahead.

1.8 Bear right (continue on Harvard Road).

2.4 TURN RIGHT on the power line road.

3.2 TURN LEFT on the Fort Irwin haul road. Watch for tank convoys! This road traverses the broad divide between the Coyote Lake and Manix subbasins. Much or all of the divide is underlain at shallow depth by fine-grained Miocene strata (Meek, 1990, 1994). Playas have formed between the encroaching dunes on the west and the broad aggrading Alvord alluvial fan on the east.

5.9 Cross a big longitudinal dune.

7.7 Crest of a broad compound barrier beach at about 543 masl. Our view is northwest to the Coyote Lake subbasin, whose floor is about 7 km wide and at 520 masl. This barrier was built from northeast to southwest, based on morphology and clast composition. Its elevation suggests that it probably has a history similar to that of the north Afton beach ridge and was built during several lake phases. The broad divide between Coyote Lake and the rest of the Lake Manix basin may have been only 1 to 2 m deep at highstands of Lake Manix, so the waves that built this beach were derived solely from wind energy generated in the Coyote Lake subbasin.

8.0 STOP along the road.

Stop 1

A regressive shoreline on the flank of the southeast Coyote Lake beach (fig. 9) at this location mantles lake deposits dated with *Anodonta* shells. At this elevation, about 530 masl, a thin gravel beach deposit overlies sand that has *Anodonta* at its base; the shell yielded an age of 15,590±40 ^{14}C yr B.P. We interpret the unconformably underlying ripple-laminated sand,

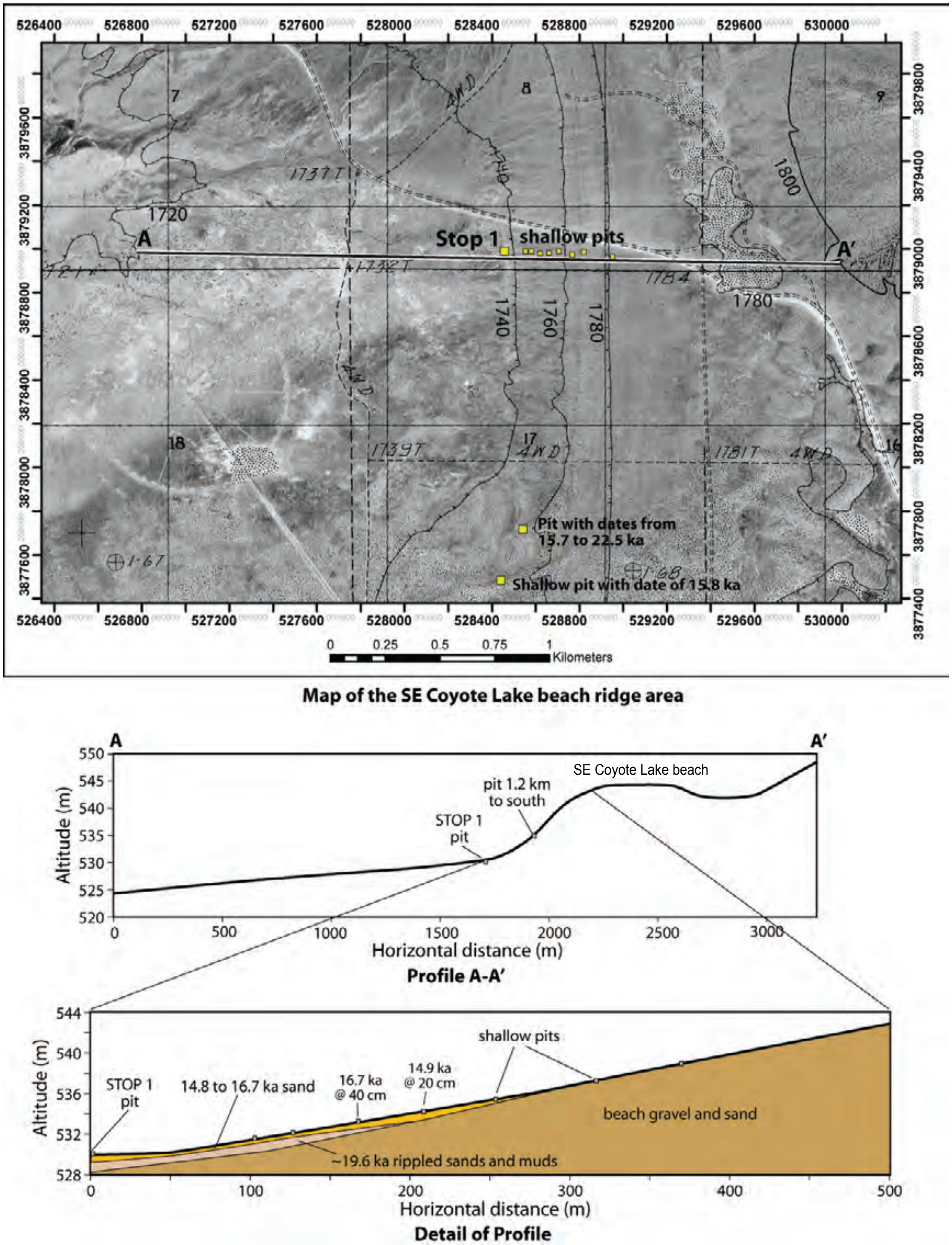

Figure 9. Map of the southeast Coyote Lake beach (Day 3, Stop 1), locations of sites referred to in text, and profile with sites and dated strata. Base map is USGS digital orthophotoquad.

sandy mud, and massive muddy sand to represent shallow lake deposits. Many of the beds fine upward, suggesting periodic lake deepening. Mud cracks occur at the top, beneath the unconformity. An age of 19,660±70 ^{14}C yr B.P. on *Anodonta* in fine laminated sand near the base of the exposure suggests that the entire deposit postdates the draining of Lake Manix.

We explored lateral continuity of these deposits in a series of shallow pits along the wash extending upslope from this exposure. The gravel-over-rippled-sands stratigraphy extends east about 150 m as a thin gravel and sand cap on underlying fines (fig. 9). About 160 m to the east, rippled sand is absent, and the gravel cap overlies shelly sand on muddy sand. There, *Anodonta* yielded an age of 16,710±90 ^{14}C yr B.P. At about 210 m to the east, the gravel fingers out into a sand that has several shelly layers; *Anodonta* at 20-cm depth yielded an age of 14,880±80 ^{14}C yr B.P. This shelly sand unit continues east about 270 m (altitude about 537 masl). Farther east, most near-surface strata are gravel and coarse sand.

At 1.2 km south of this location and slightly higher, at an altitude of about 536 masl, we excavated a deep pit in similar lacustrine units (also dated in a range of 20–15 ^{14}C ka), below which lay a possible weak soil on sands bearing *Anodonta* that yielded an age of 22,490±170 ^{14}C yr B.P., evidently representing the last of Lake Manix deposition. Deposits in this pit contain lacustrine ostracodes, in many places reworked as shown by abrasion and infilling with mud. Some have secondary carbonate accumulation. Articulated valves suggest only modest reworking in some cases. *L. ceriotuberosa* and *Limnocythere bradburyi* are present in all strata. It is possible that the ~19.6 ^{14}C ka deposits represent a slow decline from Lake Manix highstand levels as Afton Canyon was cut, separating Coyote Lake from Lake Manix. Alternatively, the Mojave River may have fed Coyote Lake at 19.6 ka, causing a brief lake in the otherwise dry lake basin. Preliminary dating of ostracodes in the Soda Lake core of Lake Mojave suggests that the lake was large before 19.6 ka, which requires that Afton Canyon was partly cut before that time, and hence the latter interpretation for an ephemeral Coyote Lake at 19.6 ka is preferred.

We interpret the ~19.6-ka rippled sands and sandy muds as near-wave-base deposits of an ephemeral lake fed by the Mojave River. These beds are overlain by a package of shelly sand with one prominent beach gravel that dates from ~16.7 to ~14.9 ^{14}C ka, suggesting a period of fluctuating lake levels in a second, longer-lived, ephemeral lake fed by the Mojave River. At this location, evidence for yet younger ephemeral lakes in this basin are not supported from our studies, but Meek (1994) provided evidence for younger lakes in the form of dates on *Anodonta* of 13.6 ka and 11.8 ^{14}C ka near here. Our overall interpretation of the deposits in this area is very similar to that of Meek (1990, 1994), except the timing differs.

We will next travel across the playa to a location where lacustrine landforms permit lake levels to be assigned for dated lake sediments, and we will show that beaches were formed just 1 to 2 m below the Lake Manix highstand during the Coyote Lake ephemeral lake stands.

Continue north on the haul road.

8.5 TURN LEFT on a small track that leads toward the playa. We are driving on thin-bedded lacustrine sands of OIS 2 (L8) lakes.

10.4 Turn left from the ruts and head southwest across the playa. Watch for fissures, sinkholes, channels, and ridges. *This is NOT a high-speed playa! You have been warned!*

11.4 Near here, personnel from the U.S. Geological Survey and California State University Bakersfield obtained some exploratory short cores in the playa. Dates on *Anodonta* shells are 48 to 49 ^{14}C ka (probably minimum ages for the sediment) at a depth of ~5 m, which we interpret to indicate that these deposits significantly predate the OIS 2 Lake Manix. Evidently, several meters of deflation have occurred on this playa.

12.8 VEER LEFT at an obvious two-track and leave the playa, climbing the southern playa-margin scarp of late Pleistocene muds and sands. Faults exposed in places along the south edge of the playa suggest either slumping down to the north or faulting along a zone coincident with the south margin of the playa, or both. The fault probably is related in part to perched ground water south of the playa (Hagar, 1966), which may be dammed by the fault.

14.2 VEER RIGHT on a smaller road.

14.8 Park along and near the road.

Stop 2

We will take a two- to three-hour hike from here over easy terrain. Bring water and a snack. The tour will visit several landforms recently highlighted spectacularly in LiDAR flown by University of Texas at Austin. We will discuss the origin of fluvial channels, now inverted topographically, as well as lacustrine beaches and platforms and closed depressions. The deposits and landforms bear evidence for several brief lake cycles that postdate the demise of Lake Manix after Afton Canyon developed.

Walk west along the ridge crest (fig. 10), watching the north and south sides as topography changes westward. The ridge becomes better defined with increasing height above basins on both sides. We will examine the clast composition of gravel in the ridge; the “grussy” composition strongly supports an interpretation of a Mojave River source. At the west termination of the ridge, examine the topography: a bench exists in this area and extends northeast and southwest. To the southwest, the bench (at 541.6 masl) closes off a lagoon-like feature that flanked the ridge on which we walked. We interpret the ridge as an inverted fluvial channel of the Mojave River, and that the adjacent flats were composed of fines that

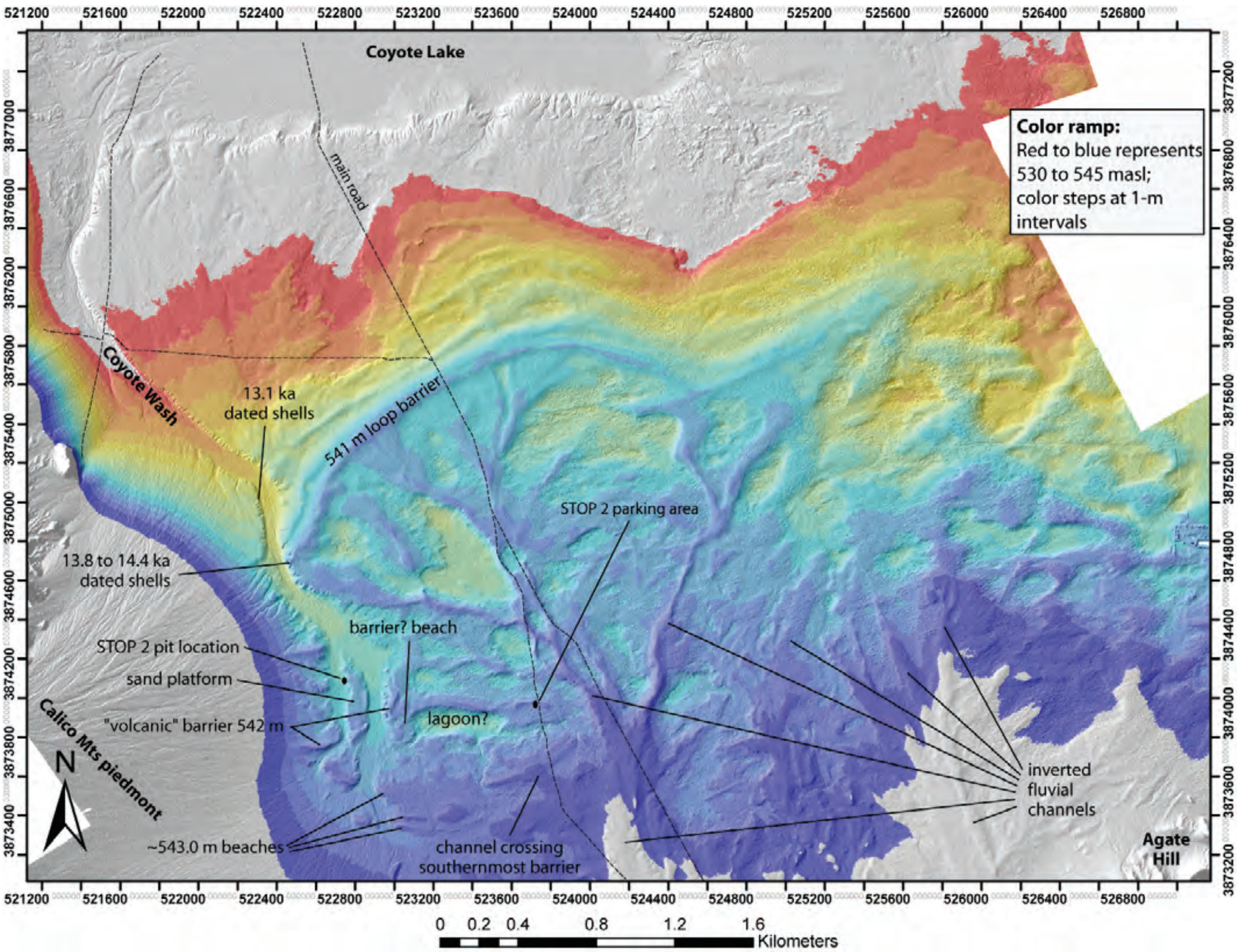

Figure 10. Map of hillshade derived from 1-m LiDAR, southwestern Coyote Lake basin, flown and processed by University of Texas Austin. Landforms and sites mentioned in the text are identified, along with altitudes of several features.

eroded after deposition and cessation of river activity. We interpret the bench, which closes off the deflated area, at the truncated front of the ridge as a lacustrine wave-formed beach. By this interpretation, fluvial channels formed, followed by rapid deflation, and then the lake rose to truncate the channel and build a small barrier. However, deflation may also have postdated the new barrier construction. A narrow barrier beach formed on this bench farther to the southwest and is notable for its clast content: abundant volcanic rocks derived from local fans of the Calico Mountains. This barrier beach lies at 542.2 masl according to LiDAR data.

Above and south of the "volcanic" barrier beach lie three more barrier beach remnants, each with crest altitudes of 543.3 masl, and each bearing volcanic clasts. We interpret these as earlier beaches that formed during highstands of Lake Manix, although we have no direct dates or other evidence for their timing. Each barrier must have been abandoned as more northerly barriers formed, providing relative ages for the beaches. At least one time, Coyote Wash cut through a barrier after it was formed and before the lake rose again. The southernmost barrier has a bench cut into it at 542.5 masl adjacent to the modern Coyote Wash channel. We interpret the bench as having been cut as the lake rose to highstand after abandoning the southernmost beach, and before the next beach to the north formed to close off the area from wave energy.

Stretching below the "volcanic" barrier at 542.2 masl is a broad sand and fine-gravel platform that we have excavated to examine stratigraphy and chronology. *Anodonta* shells recovered from four positions in the ~3 m of section range from 16.2 to 15.1 ^{14}C ka, and thus are similar in age to the upper sequence we examined at southeast Coyote Lake beach. The deposits contain the ostracodes *L. ceriotuberosa* and *L. bradburyi*, confirming a lacustrine origin for many beds. Preliminary quartz luminescence ages (S.A. Mahan, written commun., 2006) in this section are younger than the calibrated radiocarbon ages, similar to mismatched dates described for lacustrine deposits cross-dated by Owen and others (2007) at Silver Lake. Here, the deposits lie between 538 and 541 masl, and are associated with a barrier beach at 542.2 masl, providing direct evidence that the ~16–15 ka lake level was about 542 masl at its highest. This lake level may indicate a threshold control for overflow from Coyote Lake, as suggested by Meek (1990).

Farther north down Coyote Wash, a prominent loop-shaped barrier beach (fig. 10) is cut by Coyote Wash. The beach crest is at 541.4 masl. Prominent inverted channels leading to the beach lie on older, higher beaches, including beaches at the altitude of this 16–15 ka site (fig. 9). The 541-m beach is built across a 3-m-thick sequence of grus sand and muddy sand that contains *Anodonta* dated at 14,335±40 to 13,810±35 ^{14}C yr B.P. About 300 m farther down the wash, we recovered *Anodonta* dated at 13,145±45 ^{14}C yr B.P. These dates, stratigraphy, and landforms indicate that Mojave River fed one or more ephemeral Coyote Lakes that created beaches at ~541 masl between about 13.8 to 13.1 ka. We have not found evidence for younger lakes.

Meek (1994) outlined stratigraphic evidence for Mojave River deltas farther east (east of the informally named Agate Hill) where spectacular exposures of deltaic foreset beds were created along the wall of a giant trench (now filled in). He obtained a date of 17,140±1,500 ^{14}C yr B.P. on *Anodonta* in sands below the delta unit. We speculate that this delta may coincide with our dated record of ~19.6 ^{14}C ka lake sediments (noting that many of our dated shells appear to yield ages older than those reported by Meek as collected at the same localities). West of Agate Hill, most Mojave River interaction with ephemeral lakes appears to be one of distinct fluvial channels forming and later being truncated along shore zones. We found no distinctive deltaic sediments in this area, although thin intervals of cross-bedded sands are present at low altitudes near the south margin of Coyote Lake.

The available data point to two or more ephemeral lakes occupying Coyote Lake after the demise of Lake Manix, the first being at about 19.6 ka (uncalibrated) and perhaps being quite brief. Another period of ephemeral lakes appears to be 16.7 to 14.9 ka and perhaps as young as 14.4 ka. The stand that formed the loop barrier in lower Coyote Wash apparently occurred about 13.8 to 13.1 ka. These times permit a single protracted period of lake occupation with fluctuating levels (~16.7 to 13.1 ka) or may represent numerous short-lived lakes. Regardless of the number of lakes, the point made by Meek (1994), that downstream Lake Mojave must have experienced periods of low water flow due to diversion of the Mojave River to Coyote Lake basin during the latest Pleistocene, is critical for interpreting climate history from Lake Mojave.

Continue south on the road.

15.0 Cross the 543-masl highstand beach of Lake Manix, here marked by coarse pebbles of volcanic rock derived from the Calico Mountains piedmont to the west.

16.4 Veer south on the main graded road.

Major parting point. For those headed EAST AND NORTH to Las Vegas, turn left (east) along the power line road to Harvard Road.

18.1 Slight jog left on gravel road.

20.1 Jog south to big power lines.

20.3 Turn sharp left on the power line road.

21.5 Turn sharp right, which is southbound on Harvard Road.

23.7 Intersection with freeway I-15; cross overpass and enter I-15 northbound.

For those headed WEST AND SOUTH to Los Angeles, continue south.

17.4 Complex branching of roads; stay on the center of the three roads.

19.2 Cross the power line road.

20.3 End at the paved road. Turn right.

20.7 Turn right on Yermo Road.

24.0 Turn right on Minneola Road.

24.2 Turn left, entering freeway I-15 southbound.

References Cited

Blackwelder, E., and Ellsworth, E.W., 1936, Pleistocene lakes of the Afton basin, California: American Journal of Science, v. 231, p. 453–463.

Buwalda, J.P., 1914, Pleistocene beds at Manix in the eastern Mojave Desert region: Bulletin, Department of Geology, Berkeley, University of California, v. 7(24), p. 443–464.

Cox, B.F., Hillhouse, J.W., and Owen, L.A., 2003, Pliocene and Pleistocene evolution of the Mojave River, and associated tectonic development of the Transverse Ranges and Mojave Desert, based on borehole stratigraphy studies and mapping of landforms and sediments near Victorville, California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and paleohydrology of the Mojave and southern Great Basin Deserts: Boulder, Colo., Geological Society of America Special Paper 368, p. 1–42.

Dibblee, T.W., Jr.,1992, Neogene movements on Calico and Camp Rock faults, Mojave Desert, California, *in* Richard, S.M., ed., Deformation associated with the Neogene eastern California shear zone, southwestern Arizona and southeastern California: Redlands, Calif., San Bernardino County Museum Special Publication 92-1, p. 24–27.

Dokka, R.K., and Travis, C.J., 1990, Late Cenozoic strike-slip faulting in the Mojave Desert, California: Tectonics, v. 9, p. 311–340.

Dudash, S.L., 2006, Preliminary surficial geologic map of a Calico Mountains piedmont and part of Coyote Lake, Mojave Desert, San Bernardino County, California: U.S. Geological Survey Open-File Report 06-1090, 48 p. pamphlet, scale 1:24,000.

Ellsworth, E.W., 1932, Physiographic history of the Afton Basin: Palo Alto, Stanford University, Ph.D. dissertation, 99 p.

Enzel, Y., Wells, S.G., and Lancaster, N., 2003, Late Pleistocene lakes along the Mojave River, southeast California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and paleohydrology of the Mojave and southern Great Basin Deserts: Boulder, Colo., Geological Society of America Special Paper 368, p. 61–77.

Forester, R.M., Lowenstein, T.K., and Spencer, R.J., 2005, An ostracode based paleolimnologic and paleohydrologic history of Death Valley: 200 to 0 ka: Geological Society of America Bulletin, v. 117, p. 1,379–1,386.

Glazner, A.F., Walker, J.D., Bartley, J.M., Fletcher, J.M., Martin, M.W., Schermer, E.R., Boettcher, S.S., Miller, J.S., Fillmore, R.P., and Linn, J.K., 1994, Reconstruction of the Mojave block, *in* McGill, S.F., and Ross, T.M., eds., Geological investigations of an active margin: Geological Society of America Cordilleran Section Guidebook, 27th Annual Meeting, Redlands, Calif., San Bernardino County Museum Association, p. 3–30.

Hagar, D.J., 1966, Geomorphology of Coyote Valley, San Bernardino County, California: Amherst, University of Massachusetts, Ph.D. dissertation, 210 p.

Jefferson, G.T., 2003, Stratigraphy and paleontology of the middle to late Pleistocene Manix Formation, and paleoenvironments of the central Mojave River, southern California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and paleohydrology of the Mojave and southern Great Basin deserts: Boulder, Colo., Geological Society of America Special Paper 368, p. 43–60.

Lowenstein, T.K., Li, J., Brown, C., Roberts, S.M., Ku, T.-L., Luo, S., and Yang, W., 1999, 200 k.y. paleoclimate record from Death Valley salt core: Geology, v. 27, p. 3–6.

McGill, S.F., Murray, B.C., Maher, K.A., Lieske, J.H., Jr., and Rowan, L.R., 1988, Quaternary history of the Manix fault, Lake Manix basin, Mojave Desert, California: San Bernardino County Museum Association Quarterly, v. 35, nos. 3 and 4, p. 3–20.

Meek, N., 1989, Geomorphic and hydrologic implications of the rapid incision of Afton Canyon, Mojave Desert, California: Geology, v. 17, p. 7–10.

Meek, N., 1990, Late Quaternary geochronology and geomorphology of the Manix basin, San Bernardino County, California: Los Angeles, University of California Los Angeles, Ph.D. dissertation, 212 p.

Meek, N., 1994, The stratigraphy and geomorphology of Coyote Basin, central Mojave Desert, California: San Bernardino County Museum Association Quarterly, vol. 41, no. 3, p. 5–13.

Meek, N., 2000, The late Wisconsinan history of the Afton Canyon area, Mojave Desert, California: San Bernardino County Museum Association Quarterly, vol. 47, no. 2, p. 32–34.

Meek, N., 2004, Mojave River history from an upstream perspective, *in* Reynolds, R.E., ed., Breaking up—the 2004 Desert Symposium Field Trip and Abstracts: Fullerton, Calif., California State University Fullerton, Desert Studies Consortium, p. 41–49.

Miller, D.M., and Yount, J.C., 2002, Late Cenozoic evolution of the north-central Mojave Desert inferred from fault history and physiographic evolution of the Fort Irwin area, California, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., eds., Geologic evolution of the Mojave Desert and southwestern Basin and Range: Boulder, Colo., Geological Society of America Memoir 195, p. 173–197.

Miller, D.M., Menges, C.M., Amoroso, L., Schmidt, K.M., Phelps, G.A., Lidke, D.J., and Dudash, S.L., 2005, New Quaternary geology map of faults, northern Mojave Desert, California: Geological Society of America, Abstracts with Programs, v. 37, no. 4, p. 98.

Miller, J.S., and Walker, J.D., 2002, Mesozoic geologic evolution of Alvord Mountain, central Mojave Desert, California, *in* Glazner, A.F., Walker, J.D., and Bartley, J.M., eds., Geologic evolution of the Mojave Desert and southwestern Basin and Range: Boulder, Colo., Geological Society of America Memoir 195, p. 59–77.

Nagy, E.A., and Murray, B.C., 1991, Stratigraphy and intrabasin correlation of the Mojave River Formation, central Mojave Desert, California, *in* Reynolds, R.E., ed., San Bernardino County Museum Association Quarterly, v. 38, no. 2, p. 5–30.

Oskin, M., Perg, L., Blumentritt, D., Mukhopadhyay, S., and Iriondo, A., 2007, Slip rate of the Calico fault: Implications for geologic versus geodetic rate discrepancy in the eastern California shear zone: J. Geophys. Res., 112, B03402, doi:10.1029/2006JB004451.

Oviatt, C.G., Reheis, M.C., Miller, D.M., and Lund, S.C., in press, Stratigraphy of Lake Manix beds in the Manix subbasin, Mojave Desert, CA: Geological Society of America Abstracts with Programs, v. 39, no. 7.

Owen, L.A., Bright, Jordon, Finkel, R.C., Jaiswal, M.K., Kaufman, D.S., Mahan, Shannon, Radtke, Ulrich, Schneider, J.S., Sharp, Warren, Singhvi, A.K., and Warren, C.N., 2007, Numerical dating of a late Quaternary spit-shoreline complex at the northern end of Silver Lake playa, Mojave Desert, California: A comparison of the applicability of radiocarbon, luminescence, terrestrial cosmogenic nuclide, electron spin resonance, U-series and amino acid racemization methods: Quaternary International, v. 166, p. 87–110.

Phelps, G.A., Miller, D.M., Schmidt, K.M., Bedford, D.R., and Lidke, D.J., in press, Surficial geologic map database of the Newberry Springs 30' x 60' quadrangle, San Bernardino County, California: U.S. Geological Survey Scientific Investigations Map.

Reheis, M.C., and Redwine, J.L., in press, Lake Manix shorelines and Afton Canyon terraces: Implications for incision of Afton Canyon, *in* Reheis, M.C., Hershler, R., and Miller, D.M., eds., Late Cenozoic drainage history of the southwestern Great Basin and Lower Colorado River Region: Geologic and biotic perspectives: Boulder, Colo., Geological Society of America Special Paper.

Reynolds R.E., and Kenney, M., 2004, Breaking up!—The Desert Symposium 2004 field trip road guide, *in* Reynolds R.E., ed., Breaking up: Fullerton, Calif., California State University Fullerton, Desert Studies Consortium, p. 3–31.

Reynolds, R.E., Miller, D.M., and Bishop, K., 2003, Land of lost lakes: The 2003 Desert Symposium field trip, *in* Reynolds, R.E., ed., Land of lost lakes: Fullerton, Calif., California State University, Fullerton Desert Studies Consortium, p. 3–26.

Reynolds, R.E., and Reynolds, R.L., 1985, Late Pleistocene faunas from Daggett and Yermo, San Bernardino County, California, *in* Reynolds, R.E., ed., Cajon Pass to Manix Lake: Geological investigations along Interstate 15: Redlands, Calif., San Bernardino County Museum Association Special Publication, p. 175–191.

Reynolds, R.E., and Woodburne, M.O., 2002, Marker bed correlations between the Mud Hills, Calico Mountains, and Daggett Ridge, central Mojave Desert, *in* Reynolds, R.E., ed., Between the basins: Fullerton, Calif., California State University Fullerton, Desert Studies Consortium, p. 82.

Steinmetz, J.J., 1987, Ostracodes from the late Pleistocene Manix Formation, San Bernardino County, California, *in* Reynolds, J., ed., Quaternary history of the Mojave Desert: San Bernardino, Calif., San Bernardino County Museum Association Quarterly, v. 34, nos. 3 and 4, p. 70–77.

Wells, S.G., Brown, W.J., Enzel, Y., Anderson, R.Y., and McFadden, L.D., 2003, Late Quaternary geology and paleohydrology of pluvial Lake Mojave, southern California, *in* Enzel, Y., Wells, S.G., and Lancaster, N., eds., Paleoenvironments and paleohydrology of the Mojave and southern Great Basin deserts: Boulder, Colo., Geological Society of America Special Paper 368, p. 79–114.

Wells, S.G., and Enzel, Y., 1994, Fluvial geomorphology of the Mojave River in the Afton Canyon area, eastern California: Implications for the geomorphic evolution of Afton Canyon, *in* McGill, S.F., and Ross, T.M., eds., Geological investigations of an active margin: Geological Society of America Cordilleran Section Guidebook, 27th Annual Meeting: Redlands, Calif., San Bernardino County Museum Association, p. 177–182.