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Lake Manix shorelines and Afton Canyon terraces: Implications for incision of Afton Canyon

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ABSTRACT

Lake Manix, in south-central California, was the terminal basin of the Mojave River until the late Pleistocene, when it drained east to the Lake Mojave Basin. Based on new field observations, radiocarbon ages, and soil development, we propose modifications to previously published hypotheses on the timing of the last 543 m above sea level (masl) highstand of Lake Manix, the timing of the first discharge eastward, and the time required to cut Afton Canyon between the two basins.

Subtle beach barriers, wave-cut scarps, and lagged beach gravels indicate that Lake Manix reached highstands between 547 and 558 masl at least twice prior to its previously known 543 m highstands. Properties of soils formed on beach barriers at 547–549 masl compared to soils on dated deposits suggest an age of older than 35 cal ka for this highstand. Calibrated radiocarbon ages for three lacustrine highstands at or near 543 masl are ca. 40–35 ka, 33–30 ka, and 27–25 ka. Lake Manix periodically discharged down a drainage presently located on the north rim of Afton Canyon at 539 masl. Soil development estimated from multiple buried soils within fluvial deposits and overlying fan deposits suggests that discharge was coeval with or somewhat older than the 547–549 m highstand, and that fluvial aggradation in this drainageway was followed by a period of relative landscape stability and episodic burial by alluvial-fan deposits.

Strath terraces below these highest fluvial deposits, but above the canyon rim, record initial incision of the Lake Manix threshold. Surface and soil properties indicate that they are latest Pleistocene to early Holocene in age, similar to the previously studied strath terraces that are inset well below the rim and below the basal lake sediments. We suggest that the higher straths above the rim formed no earlier than ca. 25 cal ka. We interpret the soils, stratigraphy, and fluvial landforms in the canyon to indicate relatively rapid incision of Afton Canyon to the depth of the bedrock floor of Lake Manix, followed by intermittent, gradual bedrock incision.

Keywords: pluvial lake, Mojave River, soil development, fluvial incision.

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INTRODUCTION

The Manix Basin in south-central California is one of a chain of interconnected basins crossed and linked by the modern Mojave River (Fig. 1). The Mojave River headwaters are in the San Bernardino Mountains, and in high-water years (Enzel and Wells, 1997; personal observation, 2005), the river presently flows north and east to its terminus in Silver Lake playa north of Baker, California. Along this course, the river passes through or near several basins that were internally drained prior to being integrated with the Mojave River, including the Victorville, Harper, Manix, and Soda Lake Basins (Cox et al., 2003; Enzel et al., 2003). Each of these basins contains a partial sedimentary record of this integration, including fluvial and lacustrine sediments indicating the arrival and ponding of the river, and a record of paleoclimatic fluctuations during the periods when an individual basin served as the terminus of the river. Thus, records from several basins must be pieced together to make accurate and complete interpretations of paleoclimatic changes (e.g., Enzel et al., 2003). Sediments in the Manix Basin contain a record of Mojave River discharge and lake fluctuations during the middle Pleistocene and most of the late Pleistocene (e.g., Jefferson, 2003).

The progressive downstream integration of sedimentary basins, combined with the reversal of generally southward drainage of the region east of the Transverse Ranges during the Miocene and Pliocene (Cox et al., 2003), set the stage for potentially very complex interactions and migrations of aquatic species in this region. The biogeographic distributions of species of fish and aquatic snails in the western United States have been interpreted to indicate that (1) widespread distribution of species during early Tertiary time was followed by speciation as the region was disrupted by extensional tectonics (Taylor, 1985; Minckley et al., 1986; Hershler et al., 1999) during the Miocene and Pliocene; and (2) populations representing separate species or subspecies in topographically separated basins mixed and recombined episodically during pluvial periods of the Pleistocene when conditions were much wetter than today (Hubbs and Miller, 1948; Hershler and Sada, 2002; Smith et al., 2002; Hershler and Liu, this volume; Smith, this volume). Opportunities for both types of evolutionary processes were created during the evolution of the modern Mojave River. In the most recent example of potential mixing of populations, the Mojave River entered the Soda and Silver Lake Basins downstream of Manix Basin sometime during the late Pleistocene and intermittently discharged northward into Death Valley, where, together with the Amargosa River, it helped form Lake Manly (Anderson and Wells, 2003; Wells et al., 2003).

Meek (1989, 1999) interpreted the geomorphic record of Lake Manix overflow and incision of Afton Canyon to have occurred rapidly at ca. 18 ka (ca. 21.5 cal ka). From stratigraphic records of Lake Mojave downstream, Wells et al. (2003) and Enzel et al. (2003, for example) strongly disagreed and argued for slower 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 (ca. 26.5 cal ka). Regardless of whether the canyon was cut slowly or rapidly, there was potential for aquatic species to move downstream once discharge from Lake Manix began. In addition, 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 et al., 2003). This paper reports ongoing research on the stratigraphic and paleoclimatic record preserved in the Manix Basin and its relation to integration of the Mojave River. We present observations of previously unmapped shoreline features, fluvial deposits, and relict soils interpreted to indicate that Mojave River waters may have entered Soda Lake Basin far earlier than previously thought. If so, it is possible that aquatic species could have arrived in the Soda and Silver Lake Basins prior to 27 or 22 ka. Discharge toward Death Valley could only have occurred earlier if flow was sufficient to fill the much deeper Soda Lake Basin and to spill into Silver Lake (Brown, 1989; Wells et al., 2003).

PREVIOUS WORK

Deposits of Pleistocene Lake Manix have been studied for nearly a century. Enzel et al. (2003) reviewed much of this literature, and Wells et al. (2003) discussed the various conflicting interpretations of lake-basin and river-incision records; here, we describe those aspects most relevant to the present study. The lakebeds were first named, and associated vertebrate fossils identified, by Buwalda (1914). Ellsworth (1932) first studied in detail the pluvial lake history recorded in the Afton subbasin (the eastern arm of Lake Manix; Figs. 1 and 2A). He interpreted the stratigraphic sequence there to record two main lake phases, the younger lake mainly represented by nearshore sand and gravel, and the older lake represented by both nearshore and deep-water deposits. Blackwelder and Ellsworth (1936) inferred that the older lake did not overflow. The younger lake, which they believed reached a somewhat higher elevation due to progressive accumulation of sediment on the lake floor, eventually overflowed eastward toward the Soda Lake Basin. This discharge resulted in the formation of Afton Canyon, which Ellsworth (1932) believed was cut episodically based on his identification of inset terraces and deposits that he inferred to represent a shoreline within upper Afton Canyon. Topographic surveys suggested that there were two shoreline levels preserved, the higher at ~549 m and the lower at 543 m. However, Meek (1989) later showed that the higher measurement was based on an inaccurate bench mark.

Jefferson (1968, 1985, 2003) investigated vertebrate fossils and conducted stratigraphic studies of the Pleistocene Manix Formation in the Cady subbasin (termed the Manix subbasin by previous authors) near the confluence of the Mojave River and Manix Wash (Fig. 2A). He interpreted these deposits to represent at least four major lake cycles, the younger two of which represented deposition during marine oxygen isotope stages (OIS) 6,

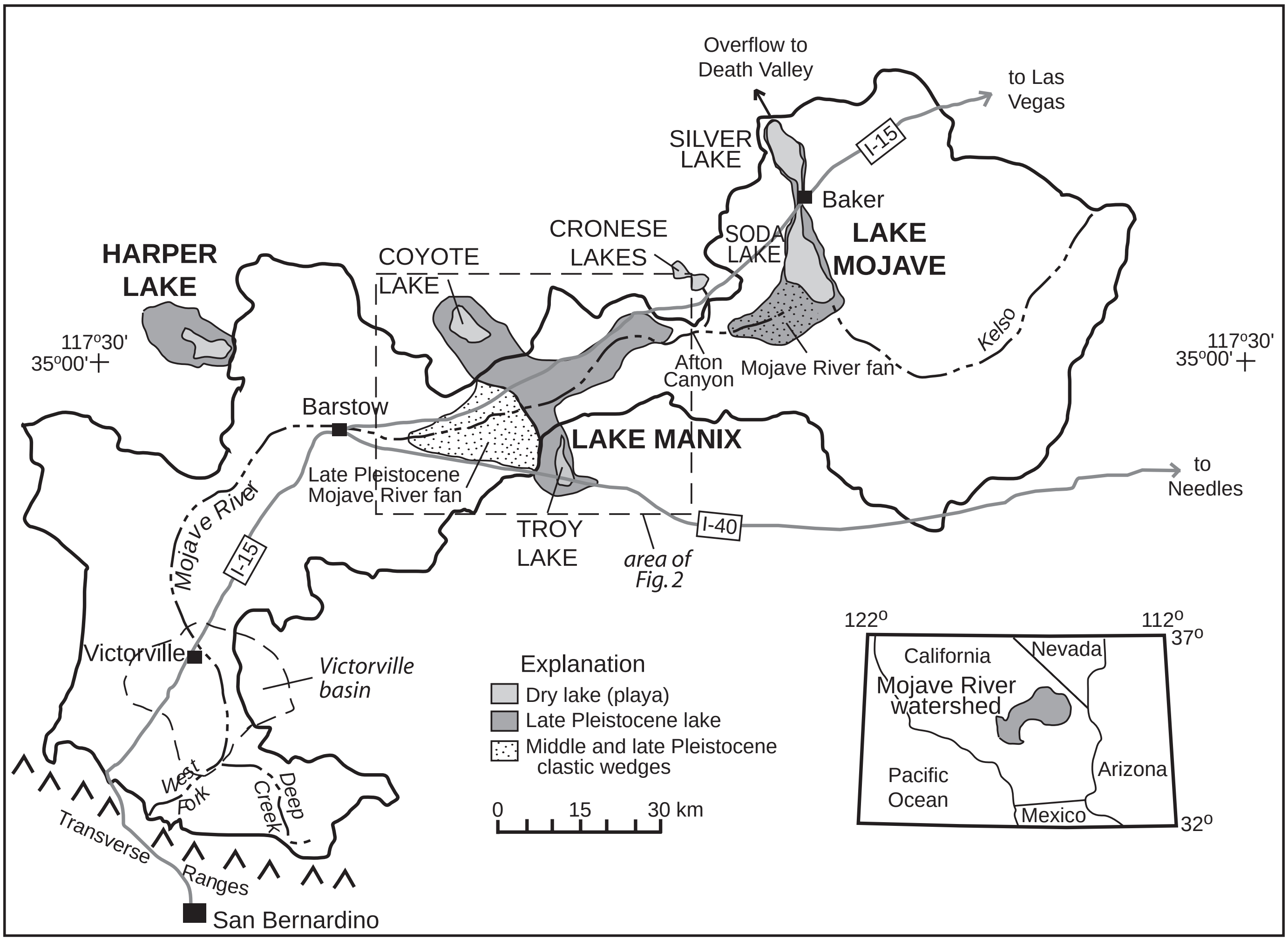

Figure 1. Mojave River drainage basin in southern California (modified from Enzel et al., 2003). During historic high-precipitation years, most recently in early 2005, the river flows to Silver Lake playa. In late Pleistocene time, after breaching of the Manix Basin, Lake Mojave episodically discharged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

4, and 2. Deposits interpreted as perennial-lake sediments and correlated with OIS 6 contain a tephra layer near the base that has an assigned age of ca. 185 ka based on tentative chemical correlation with a rhyolite in the southern Sierra Nevada to the west; this tephra is overlain by a bed bearing a bone fragment that yielded a uranium (U-) series age of ca. 184 ka (summarized in Jefferson, 2003). Sediments representing a sequence of fluctuating lake levels were correlated with OIS 4 on the basis of several U-series ages on bone ranging from ca. 74 to 50 ka and several mostly infinite radiocarbon ages, but several ages of both types were not in stratigraphic order (Jefferson, 2003, p. 48). The youngest lake cycle at this site, coeval with OIS 2, consists mainly of fluvial sands interpreted as a delta deposited as the Mojave River prograded eastward.

Meek (1989, 1990, 1999, 2000, 2004) studied the geomorphology and dated the highstands of Lake Manix, focusing primarily on the Afton subbasin and also examining nearshore deposits in the Coyote Lake and Troy Lake subbasins (Fig. 2A). However, as observed by Enzel et al. (2003), most of the dating sites were not tied to detailed stratigraphic sections. Closed-circuit surveys using a builder's level and rod (Meek, 1990) showed that maximum altitudes of beach ridges in all of the subbasins ranged from ~541 to 543.5 m except at Buwalda Ridge (informal name; Fig. 2A), where a shoreline feature lay at nearly 546 m. Meek suggested that this site recorded an older highstand that had been uplifted by deformation along the adjacent Manix fault. Ages reported in the early studies were mostly obtained by conventional ^{14}C dating of *Anodonta* shells and some lacustrine tufa. More recently, Meek (1999) redated some deposits using accelerator mass spectrometry (AMS) ^{14}C dating and revised his previous age estimates, concluding that radiocarbon ages of shells in lake sediments near the highstand level of 543 m clustered into two groups: ca. 36–33 cal ka (calibration performed for the present report) and 26.5–21.5 cal ka. The older ages consisted mainly of

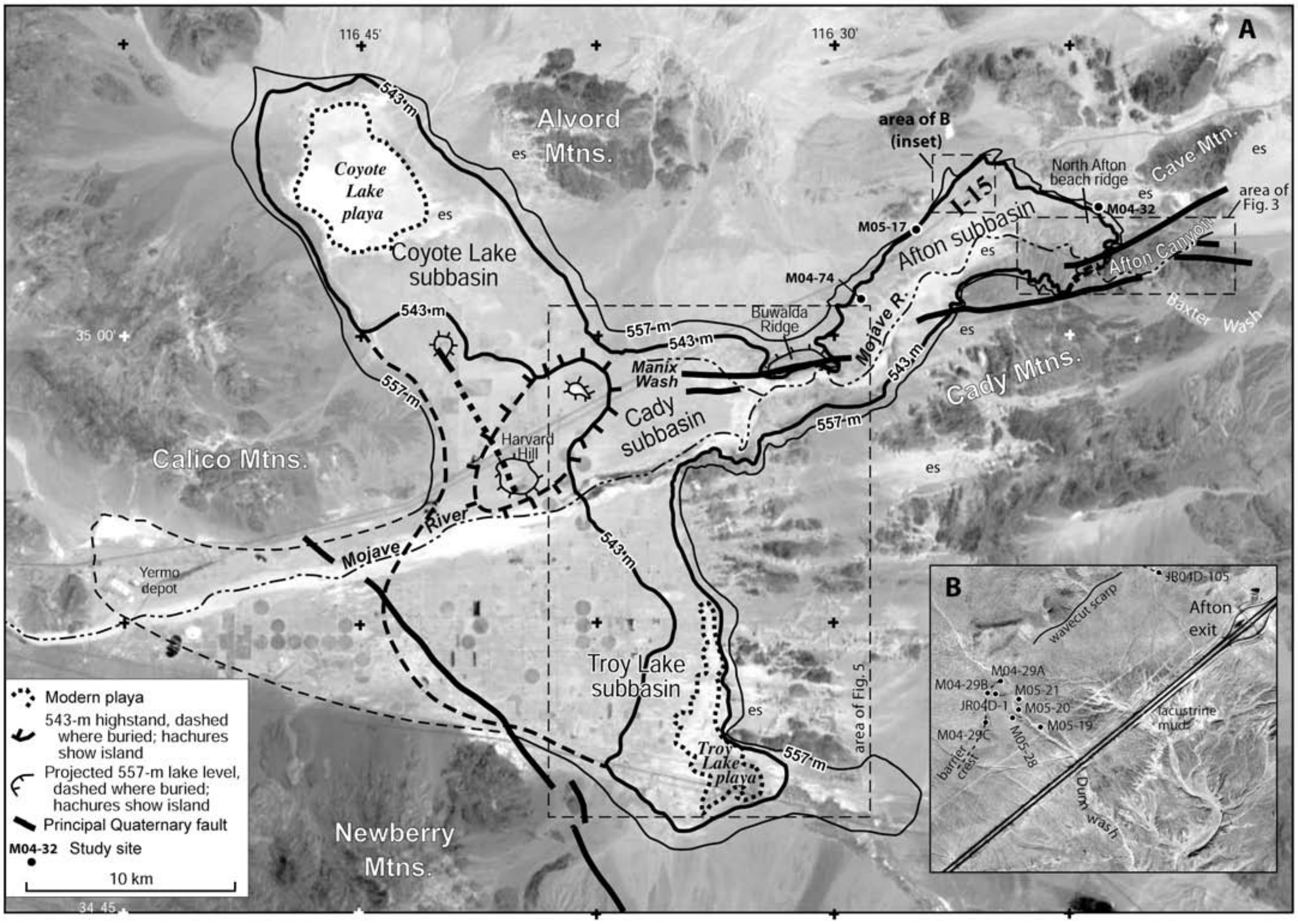

Figure 2. (A) Geographic features of Manix Basin, showing subbasins, playas (dotted), the Mojave River fluvial fan between Yermo and Troy Lake, and major faults. Medium-weight line is the 543 m highstand level that depicts minimum extent of Lake Manix during the late Pleistocene; western margin is not known due to progradation during highstands and later burial by Mojave River alluvium. Thin line is 557 m lake limit projected from highest shoreline features recognized in this study. Study sites (dots) are 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. Dashed boxes show areas of Figures 3, 5, and inset. (B) Inset showing lacustrine features and study sites (Table DR1 [see footnote 1]) in upper Dunn wash. Barrier crest and wave-cut scarp lie at 543 m above sea level (masl).

shell fragments collected on or near the beach ridge crests, whereas the younger ages came from abundant shells along beach foreslopes located 4 m or below the crests (Meek, 2004). Younger ages between ca. 20.7 and 13.4 cal ka were obtained only from deposits in the Coyote Lake subbasin and were interpreted to indicate that the Mojave River intermittently continued to feed a lake in that subbasin before headward erosion caused by the incision of Afton Canyon had reached far enough west to prevent the river from following this course. All of these ^{14}C ages, except those from Coyote Lake, were from deposits that lie stratigraphically above a nonlacustrine unit, widespread in the Afton subbasin, that Ellsworth (1932) and Meek (1990; and later reports) termed the “interlacustral fan gravel.” Meek (2000) reported a U-series age of ca. 80 ka on lacustrine tufa encrusting the uppermost clasts in this unit, which is overlain by lake sand and gravel.

Wells, Brown, and Enzel (Brown et al., 1990; Enzel et al., 1992; Wells and Enzel, 1994; Wells et al., 2003) have conducted extensive research on the history of pluvial Lake Mojave in the Soda and Silver Lake Basins and on paleoclimatic conditions required for the Mojave River to maintain lakes during the late Pleistocene and Holocene. Wells et al. (2003) summarized these studies, which were based on numerous sediment cores in the Silver Lake Basin combined with outcrop stratigraphy, ^{14}C ages of tufa and *Anodonta* shells in beach deposits, and an extrapolated sedimentation rate. They interpreted the results to indicate that episodic flooding of Silver Lake began as early as 26.5 cal ka, with two major perennial-lake episodes from 22.1 to 19.7 cal ka and 16.4 to 13.3 cal ka. They also pointed out that because of the low bedrock threshold between the Soda Lake and Silver Lake Basins and the much greater basin depth of Soda Lake, a lake could have existed only in the Soda Lake Basin for some time prior to ca. 26 ka before sedimentation or an increasing volume of Mojave River water triggered discharge into Silver Lake and integration of the two subbasins.

Meek's studies (1989, 1990, 2004) and those of Wells and Enzel (1994), Wells et al. (2003), and Enzel et al. (2003) fundamentally disagree on the timing and rate of incision of Afton Canyon between the Manix and Soda Lake Basins (Fig. 2A), and these differences of interpretation are important to drainage integration scenarios and paleoclimatic reconstructions. Meek (1989, 2000, 2004) interpreted the dated beach ridges of Lake Manix, combined with the absence of recessional shorelines and fluvial terraces nested within lacustrine deposits of Lake Manix in the Afton subbasin, to indicate that Lake Manix began to overflow at ca. 21.5 cal ka, and that the incision of the upper part of Afton Canyon (below the lake highstand and above the elevation of the lake floor, or between 543 and 500 m above sea level [masl]) may have occurred very rapidly and perhaps catastrophically (10 h is suggested in Meek, 2000). Meek (1990) interpreted fluvial terraces at 465 masl near the west end of the canyon, below the lake-floor elevation and ~25 m above the modern river, to indicate later incremental incision. In contrast, Wells and Enzel (1994) and Wells et al. (2003) argued strongly for gradual and prolonged incision based on inset fluvial terraces and fans within and upstream of Afton Canyon, as well as features they thought were recessional shorelines of Lake Manix in the Afton subbasin. Wells and Enzel (1994) identified two sets of terraces lying 23–25 m and 29–31 m above the river in the western part of the canyon, and another terrace more than 45 m above the river at the eastern end. None of the inset terraces was dated, but soils and surface characteristics of tributary fans grading to near the floor of the canyon and of three fluvial terraces 10–12 km upstream of the canyon suggested late Pleistocene to Holocene ages (Wells and Enzel, 1994). These two scenarios basically differ in their interpretation of the rate of canyon incision between 543 and 500 masl. However, gradual downcutting following the initial discharge is required if the ages of ca. 21.5 cal ka for the last Lake Manix highstand and >26 cal ka for the appearance of episodic flooding in the Silver Lake subbasin of Lake Mojave are both correct. In the context of the ability of aquatic species to migrate along a newly opened corridor, the rate of downcutting is most relevant to upstream movement since steep gradients and fast water may inhibit such movement, especially for pool-adapted species like pupfish (e.g., Smith et al., 2002).

Possible recessional shorelines are also controversial. Ellsworth (1932) first suggested that fine-grained deposits inset within fanglomerates underlying Lake Manix beds at the head of Afton Canyon represented a younger lake, but Meek (1989) reinterpreted these deposits as slack-water flood sediments of the Mojave River. Wells and Enzel (1994) and Enzel et al. (2003) referred to observations of subtle, eolian-sand-draped recessional shorelines in the Manix Basin but did not give locations; Meek (2004) stated that such shorelines do not exist.

Several geologists have speculated on the possible flow paths and timing of the earliest discharges from Lake Manix eastward. Weldon (1982) first proposed that a pre–late Pleistocene highstand of Lake Manix discharged through an abandoned spillway on the south side of Afton Canyon into the Soda Lake Basin. Jefferson (1985) suggested this overflow channel lay on the south wall of the canyon at ~544 m. Meek (1990) commented that because the shoreline altitudes of pre–late Pleistocene highstands of Lake Manix were unknown, it was possible that one or more older lakes could have discharged via the proposed spillway across the southern rim of Afton Canyon and down Baxter Wash; such a spillway could have served to stabilize the lake at the spillway elevation. Wells and Enzel (1994) also suggested that Baxter Wash was the original overflow route, and headward erosion along the proto–Afton Canyon then triggered stream capture and deep incision of the canyon. None of these authors reported physical evidence to document Mojave River discharge down Baxter Wash.

METHODS

Initial reconnaissance in Manix Basin suggested that some sites contained lacustrine or reworked lacustrine deposits at higher altitudes than the known highstand shorelines at and below 543 m. In addition, comprehensive surficial-deposit mapping in the Afton Canyon area had not previously been done, and it promised to help unravel the incision history of the canyon. Study of aerial photographs indicated locations of deposits such as river terraces and beach ridges as well as subdued features suggestive of higher shorelines. Surficial deposits were mapped on 1:24,000-scale digital orthophotoquads (DOQs) in the Afton Canyon area (J.L. Redwine, 2007, unpublished geological mapping). *Anodonta* shells and ostracode-bearing sediments, suitable for radiocarbon dating and for interpretation of hydrologic environments, were collected from outcrop exposures. Positions of most study sites were recorded using a handheld global positioning system (GPS) device (Table DR1[1]). For features that represented shorelines at and above 543 m, measurements made using a high-precision instrument were differentially corrected to obtain altitudes with vertical errors of about ±50–100 cm.

Shells and shell fragments were isolated by soaking them in a weak Calgon solution for several hours. When necessary, the shells were sonicated in distilled water for 1 h to remove additional surface sediment. In certain cases, when the shell material was still encrusted in sediment or showed signs of surface alteration, the sample was soaked in dilute (0.1 *M*) HCl to etch the surfaces clean. Sample preparation and AMS radiocarbon dating were conducted through the Radiocarbon Laboratory of the U.S. Geological Survey by Jack McGeehin.

Most of the radiocarbon ages are older than ca. 22,000 ^{14}C yr B.P. (Table 1), the present limit of terrestrial-based calibration methods. Thus, we used the extended calibration of Fairbanks et al. (2005; http://www.radiocarbon.ldeo.columbia.edu/research/

[1]GSA Data Repository item 2008021, field locations and descriptions, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, or editing@geosociety.org, at www.geosociety.org/pubs/ft2008.htm.

TABLE 1. RADIOCARBON AGES ON SAMPLES FROM STUDY AREA

Site no.	Lab no.*	Figure	Material dated	^{14}C age†	±1σ	Calendar age§	±1σ	Notes on location and stratigraphy
M04-23	WW4771	5	*Anodonta* shells	21,780	70	26,230	90	Sampled in nearshore sands overlying weak Bt horizon formed on lacustrine mud; below 543 m shoreline.
M04-32A/B	WW4772	2A	*Anodonta* shells	20,810	60	24,960	130	Well-bedded sands containing broken *Anodonta* shells in individual layers; apparently eolian sand sheets reworked from late Pleistocene lake deposits.
M04-74	WW5279	2A	*Anodonta* shells	28,170	120	32,860	130	~2 m below surface of railroad cut in second unit down.
M04-75	WW5357	4, 5	*Anodonta* shells	22,470	70	26,960	110	Within Manix fault zone; uppermost lake sediments, about 2 m below surface.
M05-07	WW5339	5	*Anodonta* shells	32,690	210	37,650	610	North of Manix fault; uppermost limit of probable lake sediment in well-sorted sand about 05 m below distinct paleosol; above 543 m shoreline.
M05-19I	WW5340	2B, 4	*Anodonta* shells	34,680	260	40,080	480	Sampled ~80 cm below surface beneath uppermost buried soil; soil overlain by younger beach gravel.
M05-20	WW5628	2B, 4	*Anodonta* shells	49,800	2000	n/a	n/a	Just above basal tufa of green mud unit; minimum limiting age.
M05-21	WW5629	2B, 4	*Anodonta* shells	31,900	200	36,820	130	Sampled just below uppermost paleosol in muddy sand; in same stratigraphic position as M05-19I.
M05-22H	WW5341	3, 4	*Anodonta* shells	27,000	120	31,920	120	Top of beach ridge in youngest preserved lake unit; whole fragmented shells in growth position.
M05-23C	WW5342	3, 4	*Anodonta* shells	40,120	500	44,340	360	Shells are from base of oldest definite lake unit in measured section. Minimum limiting age.
M05-25J	WW5630	3, 4	*Anodonta* shells	45,500	1200	n/a	n/a	Shells are from top of oldest of three lake units in measured section. Minimum limiting age.
M05-26F	WW5631	3, 4	*Anodonta* shells	39,900	600	44,160	500	Shells are from top of oldest of three lake units in measured section and just below “interlacustral gravel” of Meek (1990). Minimum limiting age.
M05-26G	WW5632	3, 4	Gastropod shells	29,600	200	34,800	270	Gastropod shells and fish bones just below weak paleosol; top of middle lake unit, which overlies “interlacustral gravel” of Meek (1990).
M05-28B	WW5343	2B, 4	*Anodonta* shells	26,030	100	31,150	100	Uppermost lake unit above youngest paleosol.
M05-62	WW5633	3	*Anodonta* shells	28,440	160	33,090	180	Whole in situ shells 60 cm above a thickly tufa-coated bed.
JR04D-1	WW4924	2B, 4	*Anodonta* shells	25,420	120	30,660	110	Foreslope of beach barrier, adjacent to site M04-29B.
JR04D-68 248-255	WW5384	3, 10	Ostracodes	27,020	310	31,940	260	Bedded sand containing ostracode coquina; “slack-water” deposits, 248–255 cm below surface.
JR04D-68 331-338	WW5385	3, 10	Ostracodes	30,540	410	35,490	380	Laminated sand and clay; “slack-water” deposits, 331–338 cm below surface.
JR04D-68B 385-395	WW4909	3, 10	Ostracodes	28,020	160	32,740	150	Massive green clay with secondary gypsum and carbonate nodules; “slack-water” deposits, 385–395 cm below surface; Calgon used to disperse.
JR04D-68A 425-435	WW4908	3, 10	Ostracodes	30,180	210	35,200	140	Green silty clay with clay platelets; “slack-water” deposits, 425–435 cm below surface; Calgon used to disperse.
JR04D-68B 385-395	WW5077	3, 10	Ostracodes	29,280	320	34,340	560	Massive green clay with secondary gypsum and carbonate nodules; “slack-water” deposits, 385–395 cm below surface; only distilled water used.
JR04D-68A 425-435	WW5076	3, 10	Ostracodes	31,500	420	36,470	420	Green silty clay with clay platelets; “slack-water” deposits, 425–435 cm below surface; only distilled water used.
SL-830-Lb‡	WW4872	n/a	Ostracodes	18,040	70	21,510	110	Lake clays in USGS Soda-1 core, Soda Lake, 25.3 m depth.
SL-860-Lb‡	WW4873	n/a	Ostracodes	18,780	60	22,380	40	Lake clays in USGS Soda-1 core, Soda Lake, 26.2 m depth.

*Samples were pretreated at the ^{14}C laboratory of the U.S. Geological Survey (USGS) in Reston, Virginia (WW designation).

†^{14}C ages were determined at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory, Livermore, California, and at National Science Foundation–Arizona Accelerator Mass Spectrometry facility in Tucson, Arizona. Quoted age is in radiocarbon years (B.P.) using Libby half-life of 5568 yr.

§Ages were calibrated using program available at http://www.radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm (Fairbanks et al., 2005). Calibration was performed assuming no reservoir correction (see discussion in Methods); “n/a” indicates radiocarbon age is beyond current calibration limit of method.

‡Exact core location unknown; reported by Muessig et al. (1960) as NE/4 sec 1, T 12 N, R 8 E.

radcarbcal.htm), which was developed using U-series dates on marine corals. For comparison, we used the same technique to calibrate previously published age ranges of deposits in the Lake Manix and Lake Mojave Basins. Because the calibration method of Fairbanks et al. (2005) is experimental and may not be reliable for nonmarine deposits, we use the calibrated ages only for comparison in the Discussion section. Although Meek (1990) estimated a hard-water correction factor for Mojave River water of 480 ± 60 yr by dating shells with a true age of 30 yr, the age was obtained by averaging shells sampled from two sites, one of which lay west of the San Bernardino Mountains outside the Mojave River drainage basin. Thus, we did not include a hard-water effect in calibration.

Soil profiles were described and sampled on selected beach ridges and fluvial terraces using natural exposures and hand-dug pits. Soil descriptions and horizon designations followed Soil Survey Staff (1975) as modified by Birkeland (1999). Carbonate stage morphology was described using nomenclature introduced by Gile et al. (1966). Gypsic stage development was described as in Reheis (1987). Relative age estimates for soils are based on calculations of profile development indices (PDI) using the method of Harden and Taylor (1983) and Taylor (1988). Calculations included eight soil properties: texture, clay films, dry and moist consistence, carbonate morphology, and structure, and depending on the soil, various combinations of two of the following: rubification, paling, lightening, and melanization. C horizon properties were used as initial parent material properties for a profile.

STRATIGRAPHY AND DATING

Incision by the Mojave River and its tributaries has locally provided extensive outcrops of deposits of Lake Manix and prelake deposits, especially near the Mojave River within the Afton subbasin and the area south of Buwalda Ridge (Fig. 2A). Numerous strath terraces capped by fluvial deposits are preserved along the river course, inset below the lacustrine deposits (J.L. Redwine, 2007, unpublished geological mapping). However, erosion has also been so pervasive that lake deposits have been entirely removed in many places. In addition, the prevailing westerly winds and the ready availability of sand along the river and within the exposed sediments have resulted in burial of many shorelines by eolian sand, especially along mountains and escarpments bounding the east side of Troy Lake, Coyote Lake, and Afton subbasin (Fig. 2A). This area is part of a sand-transport system described by Zimbelman et al. (1995). Thick sheets and sand ramps of reworked, lake-derived sediment locally contain well-sorted, stratified sands with fragments of *Anodonta* shells and concentrations of broken or frosted lacustrine ostracodes. Such outcrops commonly extend rangeward and are higher than beach ridges and wave-cut scarps marking the late Pleistocene 543 m highstand of Lake Manix, complicating the identification of shoreline features connected to previous highstands that might have represented a larger lake. Hence, solid identifications require a conservative approach to rule out wind-reworked deposits.

Lake Manix Shorelines near 543 m

Lake Manix reached highstands at or just below 543 m 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. Such barriers typically are flat-topped with sloping, gently rilled flanks, excepting the North Afton beach ridge (Figs. 2A and 3), which is highly dissected due to its proximity to Afton Canyon; some are unbreached and retain fine-grained sediments deposited in back-barrier or lagoonal settings on the landward side. Exposures northwest and southeast of the Afton exit on Interstate 15 (Figs. 2 and 3) contain deposits formed during multiple highstands within beach barriers with crests at 543 m.

At the Dunn wash sites (Fig. 2B), at least four lake fluctuations are recorded (Fig. 4). 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 (1 in section M05-19, Fig. 4) 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 m. This unit is overlain by alluvial gravel (unit 2) 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) that rise and thin shoreward, typically with tufa-coated clasts at the base of each package separated by weak soils or alluvial units. Lake units 4 and 5 can be traced to an altitude of ~543 m, directly beneath a beach crest (three remnant beach crests in the vicinity yielded a mean altitude of 543.5 m; Table DR1 [see footnote 1]). *Anodonta* shells near the base of unit 1 at site M05-20 yielded a finite but minimum limiting age of 49,800 ± 2000 ^{14}C yr B.P. (Table 1). The overlying lake unit 3 is only locally preserved and may represent a minor fluctuation. Shells within unit 4, 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 (JR04-D-1, immediately below a 543 m beach crest, and M05-28B), the uppermost lake unit 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, though with much thicker packages of lacustrine sediments, in the North Afton beach ridge (Figs. 3 and 4; Table 1), where Meek (1990) surveyed the highest preserved beach deposits at 542.5 ± 0.11 m.

Outcrops on the south flank of Buwalda Ridge and adjacent to the Manix fault (Figs. 2, 5, 6A, and 6B) expose two lake units separated by fan deposits (sites M04-75 and M05-06). At both sites, the older unit includes a moderately developed soil that was formed prior to burial by the younger unit (Figs. 4, 7C, and 7D); notably, however, a similar moderately developed soil crops out at the surface on the north side of a strand of the Manix fault at significantly higher altitude (discussed later). The top of the outcrop south of the fault strand at M04-75 lies at ~542 masl. Shells

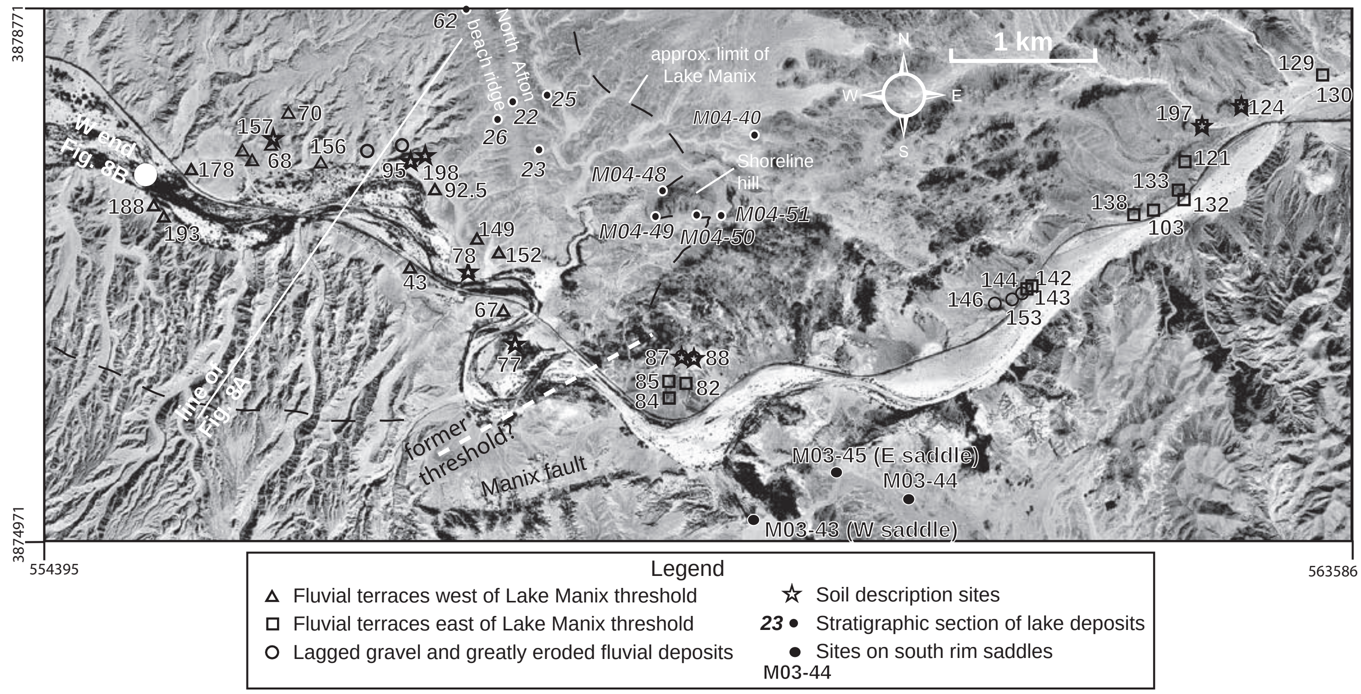

Figure 3. Study sites near Afton Canyon (alluvial deposits and straths) and on North Afton beach ridge (lacustrine). White line is approximate line of cross section in Figure 8A; white dot is west end of transect in Figure 8B. Dashed line shows limits of known lacustrine features of Lake Manix; likely position of threshold also shown. Note prominent faults and shear zones (discontinuities in photo) north of canyon and subparallel to Manix fault. See Table DR1 (see text footnote 1) for site information and Tables 2 and 3 for soil descriptions and index data. Coordinates are in UTM units, NAD 83, Zone 11.

from the younger unit in this outcrop yielded an age of 22,470 ± 70 ^{14}C yr B.P. (Table 1).

Two other sites below the 543 m highstand yielded relevant ages. North of the Mojave River, shells in beach gravel exposed in a railroad cut (M04-74) at ~535 masl gave an age of 28,170 ± 120 ^{14}C yr B.P. (Fig. 2A; Table 1). South of the river, shells in beach sand that abruptly overlies a buried soil formed on green lacustrine mud at site M04-23, ~536 masl (Fig. 5), gave an age of 21,780 ± 70 ^{14}C yr B.P. Significantly, none of our samples from the Cady and Afton subbasins yielded younger ages than this except at site M04-32 (Fig. 2A; 20,810 ± 60 ^{14}C yr B.P.; shell fragments in an eolian sand sheet), in contrast to ages on similar *Anodonta* shells as young as ca. 18 ka reported by Meek (1999) and ca. 19 ka reported by Jefferson (2003).

Our surveys at several sites in the Afton, Cady, and Troy Lake subbasins (Table DR1 [see footnote 1]) confirm Meek's (1990) results that shoreline deposits of the 543 m highstand lie at essentially the same altitude throughout the Manix Basin. However, the angles of wave-cut scarps that are seemingly closely associated with the 543 m beach barriers, such as those at sites M05-17, M04-20A, and M06-55A (Figs. 2 and 5), and sites on Shoreline Hill (e.g., M04-48, M04-49, Fig. 3), commonly lie at the same or higher altitudes (as much as 3 m). Such positions are counter to the accepted model of beach cliff–platform development (e.g., King, 1972) in which the erosional shoreline angle is typically slightly lower than barrier crests formed by storms. Survey measurement errors and difficulty in locating scarp-angle positions due to burial by scarp-derived colluvium may account for those anomalous scarp angles that are within 1 m of the barrier crests. However, some of the higher shoreline angles may have been formed when Lake Manix stood at levels higher than 543 masl, and their proximity to younger 543 m barriers is fortuitous.

Lake Manix Shorelines above 543 m

In contrast to shoreline features associated with altitudes of ~543 m, higher features were significantly more subdued and difficult to recognize. To be confidently identified as lacustrine features, sites were required to exhibit at least two of the following: (1) a scarp at higher altitude that closely resembled an adjacent wave-cut scarp identified as belonging to the 543 m highstand; (2) barrier beach morphology; (3) rounded clasts that could not be attributed to reworking from nearby alluvial deposits or to subsoil weathering; (4) outcrops above 543 m that exhibited distinctive lacustrine bedding and sorting, such as steeply dipping beds with well-sorted sediment; and (5) fine-grained, well-bedded sediment containing lacustrine fossils (fish bones, *Anodonta* shells, or ostracodes).

Several sites along the east side of the Afton subbasin exhibited one or two of these characteristics, notably well-bedded and

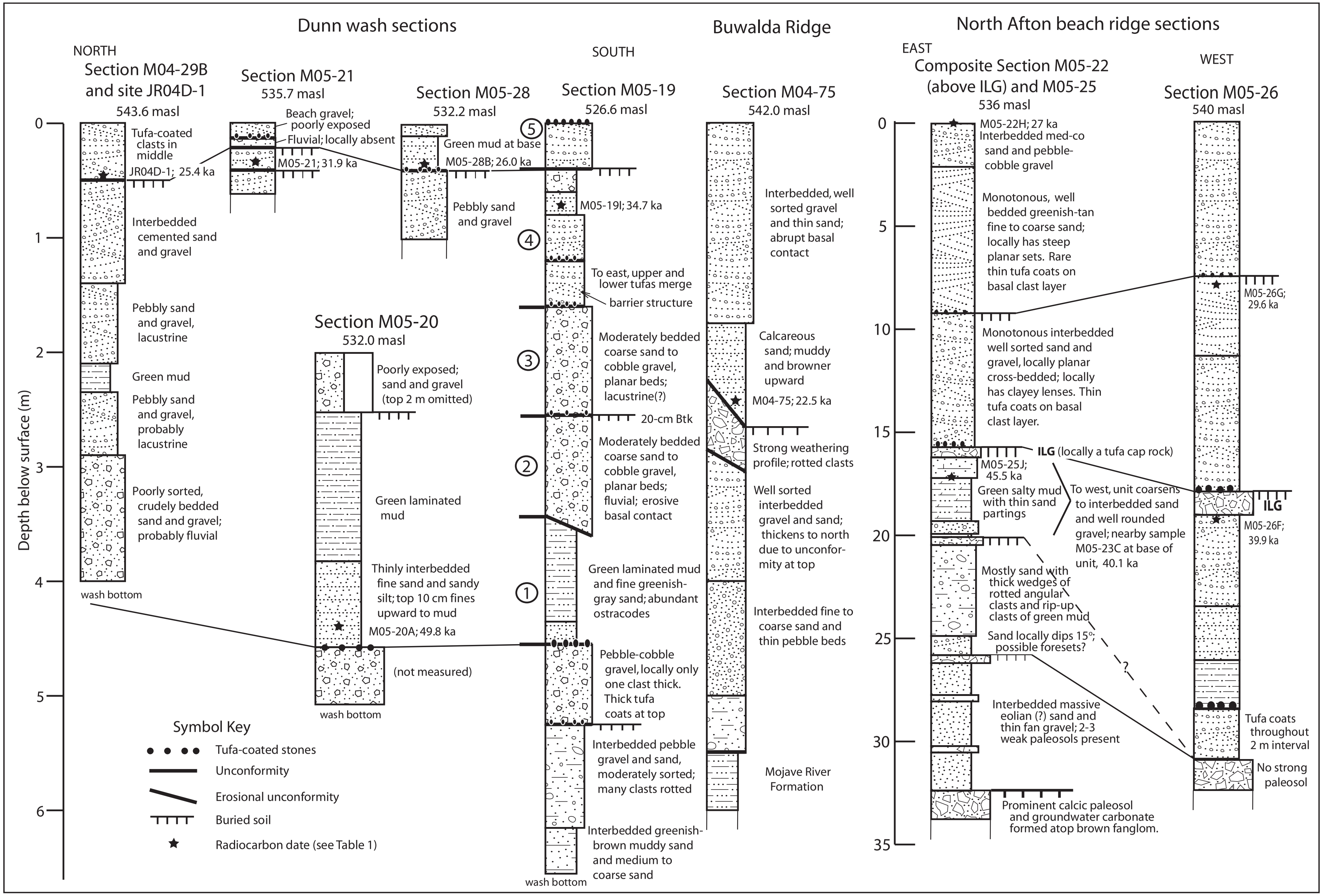

Figure 4. Selected stratigraphic sections of late Pleistocene deposits grading to 543 m highstand of Lake Manix. Global positioning system (GPS) altitudes are shown for section tops. Ages are in ^{14}C yr B.P.; see Table 1 for data and calibrated ages. ILG is "interlacustral gravel" of Ellsworth (1932) encrusted with tufa that at another site (not shown) has a reported U-series age of ca. 80 ka (Meek, 2000). Note scale change for North Afton beach ridge sections (masl—m above sea level).

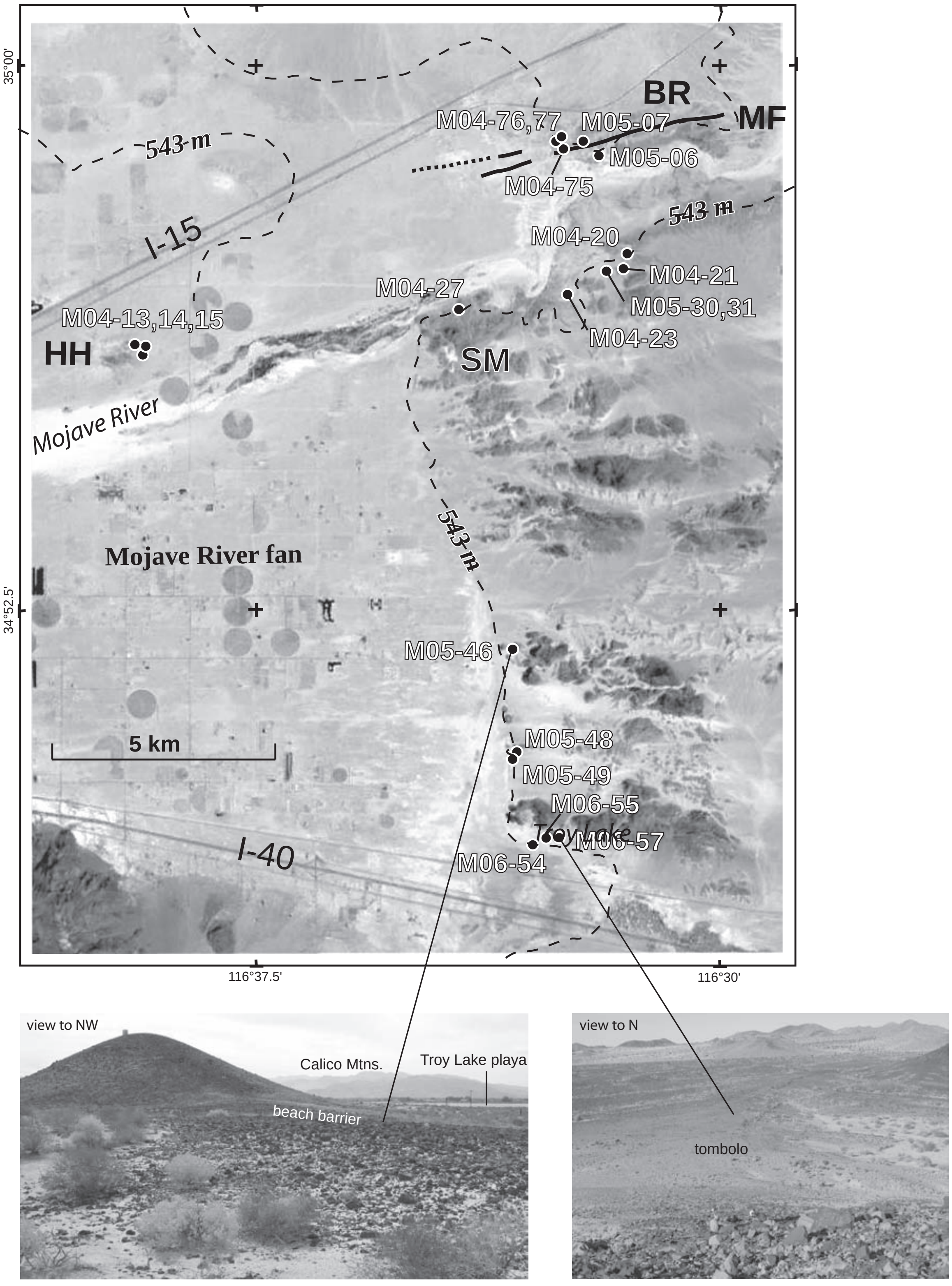

Figure 5. Sites within Cady and Troy Lake subbasins. Dots are locations of lacustrine or probable lacustrine deposits; see Table DR1 for site information (see text footnote 1). BR—Buwalda Ridge; MF—Manix fault; SM—Soldier Mountain; HH—Harvard Hill. Note streaks of active eolian sand (white) south of Soldier Mountain; these are superimposed on large sand sheets and sand ramps. Photograph of site M05-46: beach barrier at 547 m above sea level (masl) attached to basalt hill, which is the source of the mostly angular clasts on barrier surface. Site M06-57: from flank of basaltic hill forming an island in Lake Manix, looking down on tombolo, which is a beach barrier connecting the hill to a nearby landward edge. The tombolo extends to an altitude as high as 558 masl.

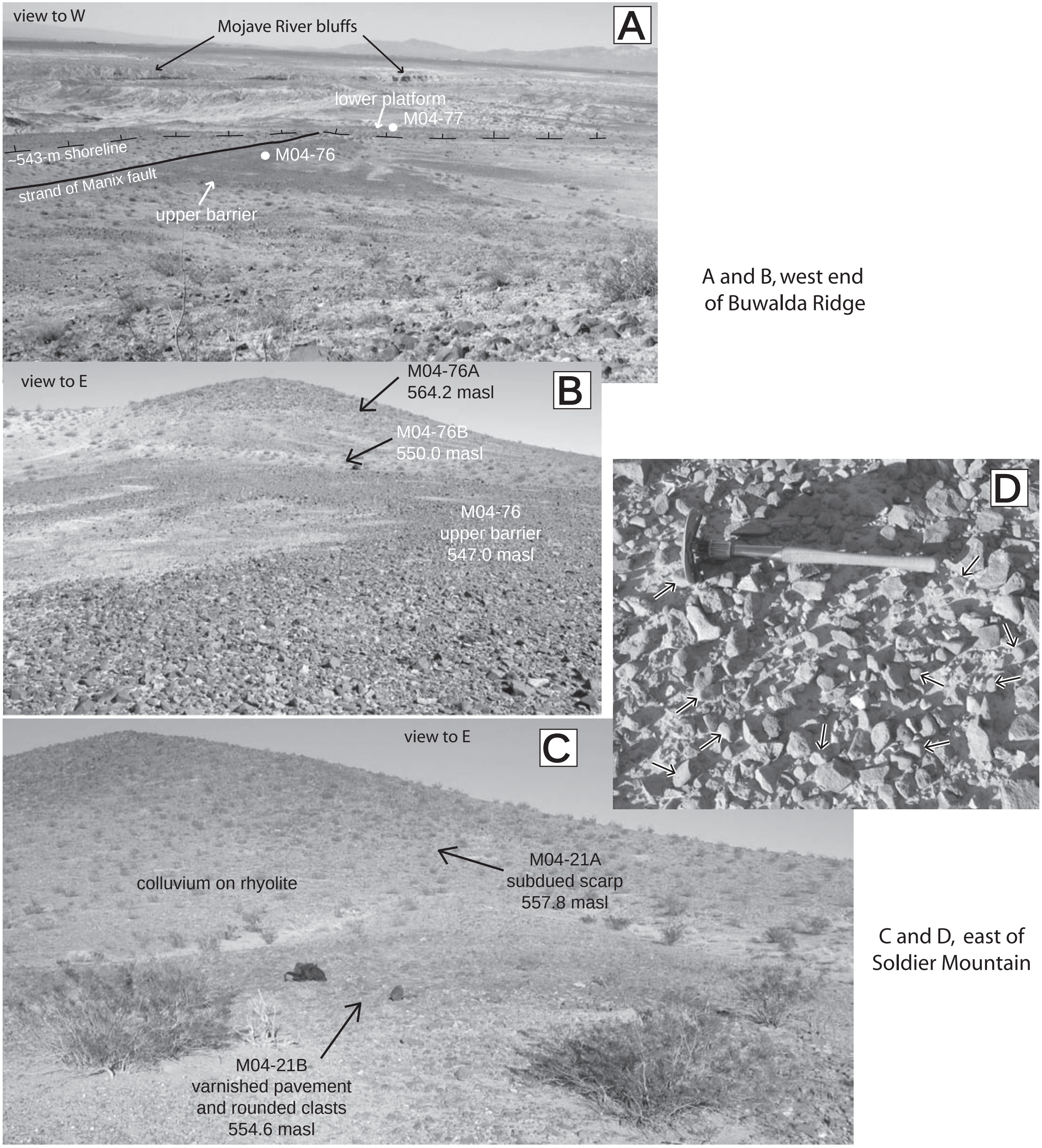

Figure 6. Photographs of lacustrine deposits above 543 m highstand (see Fig. 5). (A–B) Beach barriers and study sites on west end of Buwalda Ridge. M04-76 lies on upper barrier with higher scarps (M04-76A and M04-76B) to the east; upper barrier is truncated on the west by erosional scarp at 543 m above sea level (masl). M04-77 lies on lower platform below this scarp. (C–D) Site M04-21 east of Soldier Mountain. (C) Varnish and pavement (daypack for scale) on remnant surface against rhyolite hill; clasts on hillslope and outside of pavement area are angular to subangular. (D) Close-up of rounded clasts (arrows) comprising part of pavement (shovel ~0.5 m long).

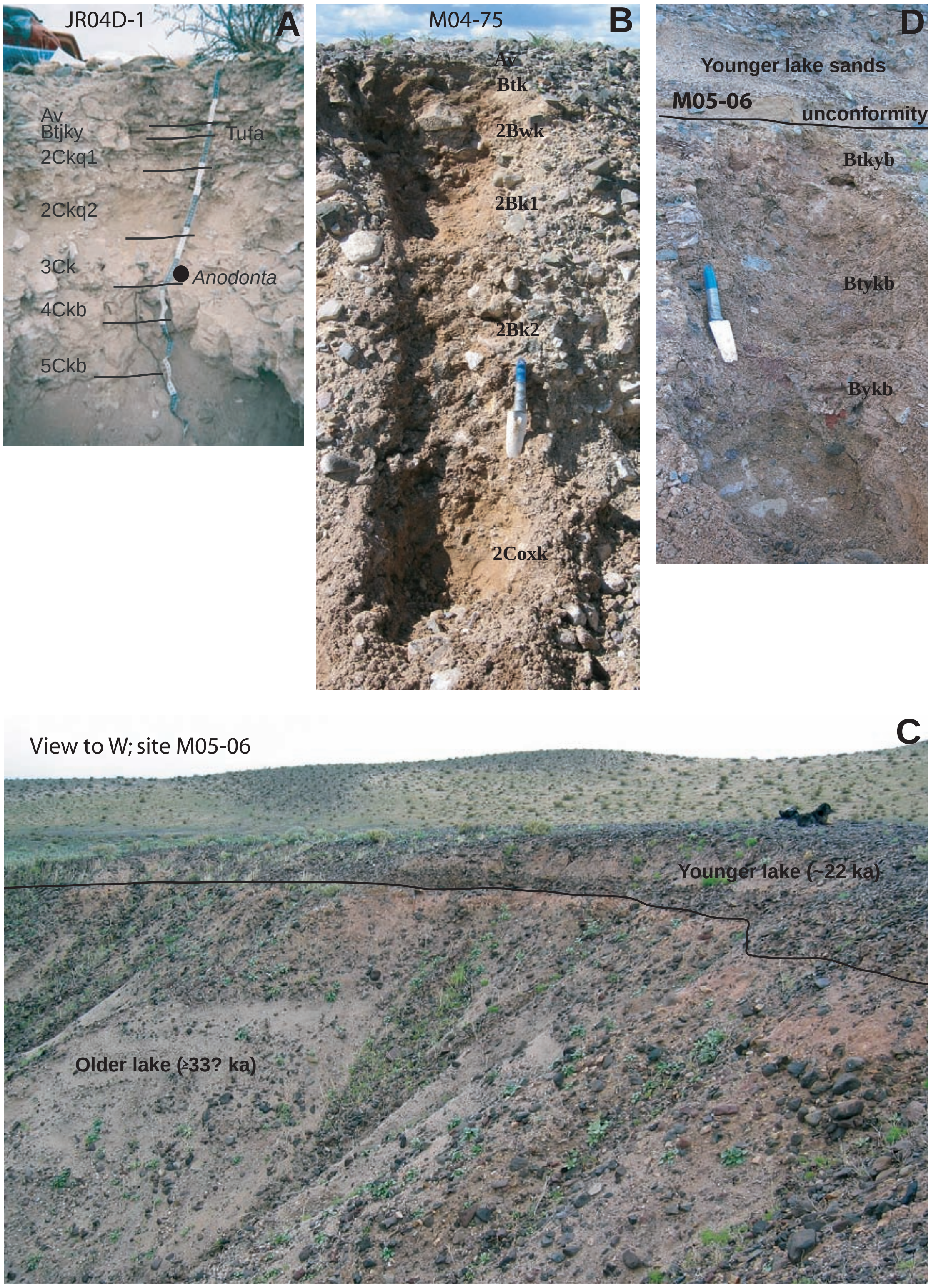

Figure 7. Photographs of soils and stratigraphy of beach deposits (Tables 2 and 3; locations and stratigraphy are shown in Figs. 2, 4, and 5). (A) Soil with weak horizonation on shoreface of 543 m beach barrier adjacent to Dunn wash; note position of *Anodonta* shells dated 25,420 ± 120 ^{14}C yr B.P. (Table 1). (B) Soil on beach platform at 542 m on Buwalda Ridge has more distinct horizons than soil in A but a younger age of 22,470 ± 70 ^{14}C yr B.P. Reddish color and scattered disintegrated clasts are probably caused by presence of pedogenic gypsum. (C) Buried soil formed on lake deposits unconformably overlain by younger unit (dog for scale). Note characteristic red color and white mottles of buried soil. (D) Buried soil profile. White mottles are dominantly pedogenic $CaCO_3$ near top; lower horizons contain common masses of gypsum as soft rosettes in sand matrix and as stone pendants. Note intense red color (5YR hues) and abundant shattered and rotted clasts cut through by shovel, likely due to gypsum accumulation.

well-sorted sands that contained shells (sites M04-32, M04-50) or bedrock scarps higher than ~543 m (M04-49, M04-50) around Shoreline Hill (Figs. 2A and 3; Table DR1 [see footnote 1]). However, the samples from these sites contained relatively low abundances of lacustrine ostracodes, which were poorly preserved as a result of abrasion or polish. One sample (M04-32) of *Anodonta* fragments ~0.2–0.5 cm in size at an altitude of 557.8 m yielded a ^{14}C age of 20,810 ± 60 yr B.P. (Table 1). This altitude is far too high to be reached by storm waves from a lake at 543 m, and all other comparable ^{14}C ages from the Manix Basin (Meek, 1990, 2000; Dudash, 2006) are from samples at or below 543 masl. Thus, these deposits are interpreted as eolian sand reworked from late Pleistocene nearshore sands. Site M04-51 exhibits well-bedded and sorted sand extending as high as 547.5 masl. The sand beds are interbedded with alluvial-fan gravel in two units separated by a buried soil, and they exhibit small-scale cross-bedding, heavy-mineral laminations, and locally dip against the local slope rather than parallel to it. These features, combined with closely associated bedrock scarps at sites M04-49 and M04-50, are interpreted to indicate two highstands that reached altitudes of ~547 m in the Afton subbasin.

In the Cady and Troy Lake subbasins, several sites exhibit an assemblage of lacustrine features at altitudes significantly higher than 543 m (Fig. 5; Table DR1 [see footnote 1]). These sites include (1) preserved beach barriers with associated scarps that are underlain by nearshore sediment (M04-76, M05-46, and M06-57), locally containing lacustrine fossils, and (2) lags of rounded, exotic clasts in locations sheltered from alluvial deposition or reworking from older gravels (M04-13 to M04-15, M04-21, M05-30, and M05-48). The higher beach barriers generally can be distinguished from those around 543 masl by their greater dissection, lack of fine-grained sediment in back-barrier settings, and well-developed desert pavement and darkly varnished surface clasts, all of which indicate an age older than ca. 30–20 ka.

On the west end of Buwalda Ridge, two nested beach ridges (Figs. 5, 6A, and 6B) lie north of the Manix fault. Our survey (Table DR1 [see footnote 1]) confirmed Meek's (1990, p. 60–63) result that the upper, moderately dissected beach ridge (M04-76) lies ~2 m higher than the lower beach ridge. This upper barrier once formed a pendant bar attached to the hill to the east, but it was eroded to form two separate arms. We measured an altitude of 550 m (site M04-76B) where the upper beach ridge merges with the adjacent slope underlain by indurated Tertiary gravel; a degraded, sand-blanketed scarp lies upslope, and an even higher scarp exists at ~564 m (M04-76A). A low, more sharply defined scarp trending perpendicular to the Manix fault strands is incised into the upper beach ridge at 543 m, and this scarp grades downslope into a gravel-covered platform associated with the lower beach ridge (site M04-77, 537 m; Fig. 6A). The upper beach ridge has densely 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 (discussed later). 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 and fish bones (R. Forester, U.S. Geological Survey, 2005, oral commun.). Shell fragments from lacustrine sand beneath a moderate buried soil at a nearby site to the east (Fig. 5), also north of the Manix fault, yielded an age of 32,690 ± 210 ^{14}C yr B.P. (M05-07, Table 1). Meek (1990) interpreted the anomalous altitude to indicate that the older ridge was deposited at a lower level and was displaced by vertical uplift on the north side of the adjacent Manix fault. Our observations at nearby sites at altitudes higher than 543 m south of the fault and near Troy Lake, discussed next, indicate that these higher shorelines were deposited by higher lake levels, not by fault displacement. However, we do not rule out fault-related deformation of the higher shoreline at Buwalda Ridge.

Across the Mojave River in an embayment south of Buwalda Ridge, three sites (M04-21 and M05-30 and M05-31; Fig. 5) bear patches of desert pavement with abundant varnished, subrounded rhyolite and other volcanic clasts mixed with more angular clasts (Figs. 6C and 6D). Alluvial-fan deposits that lie upslope and downslope from these patches consist entirely of angular rhyolite clasts derived from the adjacent hillslopes. Lagged carbonate fragments are also present, but they are probably reworked from pedogenic clast coats and are not lacustrine tufa. Rounded clasts at sites M04-21 (Fig. 6D) and M05-30 terminate upward at a break in slope at altitudes of 557.8 and 558.0 m, respectively (Table DR1 [see footnote 1]). The sites are protected from alluvial deposition other than sheetwash, and wave action is the most likely means of rounding the clasts.

South of the river, on the north side of Soldier Mountain (Fig. 5), there are numerous outcrops of interbedded lacustrine, alluvial-fan, and sand-ramp deposits. The largest exposure is a gravel pit on the northwest corner, which contains multiple sequences, ranging in age from ca. 23 to 7 ka (luminescence dating with numerous stratigraphic reversals), of interbedded sand-ramp and talus deposits separated by weak to moderate buried soils (Rendell and Sheffer, 1996); some of the presumably eolian sands contain reworked ostracodes. Farther east, natural outcrops formed by deeply incised, steep arroyos draining to the nearby Mojave River expose at least two and possibly three cycles of lacustrine deposits. At site M04-27, a low-relief beach barrier with a packed desert pavement and varnished clasts lies on a fan surface at an altitude of 552.5 masl. To the south, an outcrop exposes a buried soil (Bwk horizon) that formed in gravelly sand atop a thin, steeply lakeward-dipping beach gravel; this gravel lies at 549 masl. The beach gravel in turn overlies another buried soil with a Btk horizon, which caps 1–4-m-thick alluvial-fan deposits, which are in turn underlain by ~4 m of well-bedded lacustrine sand and gravel and finally by massive eolian sand. Assuming the surface beach ridge is the same age as the thin lakeward-dipping unit, and assuming no tectonic displacement, these exposures suggest that at least one lake phase reached an altitude of ~552 masl.

At least three sites in the Troy Lake subbasin also record highstands above 543 masl (Fig. 5; Table DR1 [see footnote 1]). A geomorphically distinct beach ridge at site M05-46 extends as high as 549.0 masl and bears a packed desert pavement with varnished clasts (inset, Fig. 5; surface soil described later); dissected fine-grained deposits behind the ridge were likely deposited in a small back-barrier lagoon. The barrier is attached to a conical, basalt-capped hill and consists mostly of angular to subrounded basalt clasts that have undergone little transport. Farther south in a similar setting, a long, well-preserved late Pleistocene barrier was built southward from a hill at a near-constant altitude of 544.4 m (site M05-48E, Fig. 5). A remnant of a barrier extends east from the same hill; the lower, more distinct part of this barrier lies at 544.5 m, and a higher area of degraded pavement (M05-48B) slopes up to a scarp at 548.0 m (M05-48D). At site M06-57, a well-preserved tombolo composed of beach gravel extends as high as 555 masl (inset, Fig. 5) and projects north from a basalt hill that must have been an island when Lake Manix stood at levels higher than 543 m.

Sites M04-13, M04-14, and M04-15 lie on the east side of Harvard Hill (Fig. 5), west of Manix Wash and adjacent to the Manix fault (Fig. 2A). Subrounded volcanic clasts locally derived from Harvard Hill form a colluvial blanket on this slope. M04-13 consists of GPS surveys of a north-south float contact along the slope; rounded granitic pebbles that are identical to those carried by the modern Mojave River lie downslope of this float contact, and are not found above the contact. Over a horizontal distance of 1 km, the altitudes of these measured points are constant at ~558 ± 1 m, which is well above the top of the fill terrace deposited by the Mojave River on the south side of Harvard Hill. The points also coincide with a subtle east-facing scarp visible on low-altitude aerial photography. Two exploratory pits dug at site M04-14, on a very subdued ridge crest slightly lower in altitude, and at M04-15, in a depression north of the ridge, did not reveal definitive evidence of lacustrine origin. As an alternative origin, fluvial aggradation to the same altitude along the east side of Harvard Hill would be required to account for the consistent altitudes of the float contact. If these sites do represent fluvial deposits of the Mojave River, either the river was graded to a higher local base level (i.e., a higher lake level) than the 543 m highstand, or the area of Harvard Hill has experienced significant fault-related uplift as suggested by D.M. Miller in Reheis et al. (2007).

Soil Properties on Lake Deposits

In the Lake Manix Basin, properties of soil profiles formed on deposits associated with the 543 m shoreline and on higher shorelines show that the higher deposits are significantly older than the lower (Fig. 7). Soils were described and sampled on deposits of the 543 m shoreline at four sites (Table 2; Dunn wash—JR04D-1, Afton exit—JR04D-105, and Buwalda Ridge—M04-77, M04-75), and on deposits higher than 543 m at two surface sites and one buried site (Buwalda Ridge—M04-76, M05-06; Troy Lake—M05-46). Soil profiles associated with the 543 m shoreline typically had horizon sequences of Av/Bwk/Ck or Av/Btk/Bty/Cyk, were weakly oxidized (generally 10YR hues), had maximum pedogenic developments of stage I to I + $CaCO_3$ and stage I gypsum and silica, and had normalized profile development index (PDI) values that ranged from 0.01 to 0.05 (Tables 2 and 3). In contrast, soils associated with higher or buried shorelines had horizon sequences of Av/Btk/Btk(y)/Ck(y), were more strongly oxidized, with hues generally 7.5YR and as red as 5YR, and had maximum development of stage II $CaCO_3$ and (or) stage II gypsum. The surface soil at M04-76 had a normalized PDI value of 0.11, and that at M05-46 had a value of 0.07. The buried soil at M05-06, in a deposit on the south side of the Manix fault, had a PDI value of ~0.13. Addition of this value to that of nearby 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.

Afton Canyon Fluvial Deposits

Afton Canyon is the deeply incised canyon of the Mojave River and has very steep and locally nearly vertical walls cut into older Tertiary deposits (Figs. 2 and 3; Danehy and Collier, 1958; J.L. Redwine, 2007, unpublished geological mapping). East of the canyon mouth, the river has constructed a large fluvial fan that extends to and fills the south end of Soda Lake (Fig. 1; Wells et al., 2003). West of the canyon, the river has incised into Quaternary and Tertiary alluvial-fan deposits that underlie the Lake Manix beds (Fig. 8A; Ellsworth, 1932; Danehy and Collier, 1958). Locally, incised meanders are preserved; the largest of these in this area form a double bend at the head of the canyon at the eastward limit of preserved lake deposits. Meek (2005, oral commun.) suggested that the position of this meander might have been controlled in part by the adjacent North Afton beach ridge (Fig. 3); the eastern section of the meander pair also coincides with the easternmost preserved lake deposits.

Within and west of Afton Canyon, there are numerous fluvial deposits, most of which are inset below the level of the lowest lake deposits in the Afton subbasin (Figs. 3 and 8B; Table DR1 [see footnote 1]). Many studies (e.g., Ellsworth, 1932; Meek, 1990; Wells and Enzel, 1994) have identified strath terraces with preserved depositional surfaces that lie within Afton Canyon and are especially common at the upper end. For this study, fluvial terrace remnants were mapped at a scale of 1:12,000 (J.L. Redwine, 2007, unpublished geological mapping), and surface soils were examined from several kilometers west of Afton Canyon to the canyon mouth (Fig. 3; Table 2; Table DR1 [see footnote 1]). In addition to the well-known straths, we mapped eroded gravels that lack preserved surfaces within Afton Canyon and that occur at slightly higher levels than the straths. Three groups of fluvial deposits are discussed here. (1) West and upstream of the Lake Manix threshold, there are inset terraces. By virtue of their being inset below the lake deposits above the canyon (Fig. 8A), all of these terraces must postdate the last highstand of Lake Manix. (2) East and downstream of the Lake Manix threshold, terraces and eroded fluvial deposits lie along the north side of Afton Canyon. (3) There are fluvial deposits high above the north rim

TABLE 2. SOIL PROFILE DESCRIPTIONS

Profile no., altitude*, parent materials, geomorphic feature	Depth (cm)	Horizon[†]	Moist color	Dry color	Structure	Gravel (visual %)	Wet con.	Moist con.	Dry con.	Texture	Lower boun-dary	Clay films	Efferve-scence	$CaCO_3$ stage[§]	Gypsum stage**	Notes
Soils on fluvial and alluvial deposits west of Lake Manix threshold																
JR05CM-198	0–2	Av	10YR 5/4	2.5 YR 7/3	2msbk	trace	ss, ps	fr	h	SL	cw	nil	EV	nil	nil	
469 m	2–7	Bw (Av2)	10YR 5/4	10YR 7/3	2fsbk	15	so, po	fr	sh	SL	cw	nil	EV	nil	nil	
eolian/alluvial fan	7–44	2Ck1	2.5YR 5/3	2.5YR 6/4	sg	10	so, po	lo	lo	LS	cs	nil	ES to nil	I	nil	Interbedded sand and gravel; $CaCO_3$ and effervescence stratigraphically dependent
overlies strath terrace	44–48	2Ck2	2.5YR 5/3	2.5YR 7/2	sg	5	so, po	lo	lo	LS	as	nil	EV	nil	nil	
	48–65	2Ck3	2.5YR 6/2.5	2.5YR 7/2	sg	40–50	so, po	lo	lo	S	as	nil	EV to nil	I	nil	Effervescence dependent upon stratigraphy; mostly local lithologies; some volcanics
	65–67	2Ck4	10YR 5/4	10YR 7/3	m	10	so, po	vfr	sh	S	cs	nil	EV	nil	nil	Cemented sand; slakes in water
	67–97+	2Ck5	2.5YR 5/3	2.5YR 7/3	sg	10	so, po	lo	lo	SL	cs	nil	nil	I–	nil	
JR04D-95	0–3	Av	10YR 5/4	2.5Y 7/3	2 m-c sbk	<10	ss, ps	fr	sh	L	as	nil	EV	nil	nil	
>463 m	3–13	Bwk	2.5Y 5/4	2.5Y 7/3	2 m-c sbk	10–25	ss, po	fr	h	SL	cw	nil	EV	nil	nil	
eolian/fluvial gravel	13–20	2Bwk1	2.5Y-10YR 5/4	2.5Y 7/3	2msbk	10–25	so, po	fr	sh	SL	cw	nil	EV	I	nil	
strath terrace	20–31	2Bwk2	2.5Y 5/4	2.5Y 7/4	1msbk	50	so, po	fr	sh	SL	cw	nil	EV	I	nil	More carbonate than below
	31–44	2Bwk	2.5Y 5/4-5/6	2.5Y 7/4	1fsbk	50–75	so, po	vfr	sh	SL	cw	nil	EV	I+	nil	
	44–90+	2Ck	2.5Y 5/4	2.5Y 7/3	sg	>75	so, po	lo	lo	LS	NA	nil	EV	I+	nil	
JR04CM-77	0–2	Av	10YR 4/2	10YR 7/3	1vfpl	10	s, ps	vfr	sh	L	as	nil	EV	nil	nil	
451 m	2–8	?Btk1	10YR 5/4	10YR 7/3	2fsbk	50	ss, ps	fr	h	SCL	cw	nil	EV	nil	nil	
eolian/fluvial gravel	8–15	?Btk2	10YR 4/4	10YR 7/3	2fsbk	50	ss, po	fr	h	SL	cw	1fcobr	ES	nil	nil	
strath terrace	15–37	2Coxk1	2.5Y 5/3	10YR 6/4	sg	75	so, po	lo	lo	LS	cw	nil	ES	I	nil	
	37–177	2Coxk2	2.5Y 5/3	2.5Y 6/3	sg	50	so, po	lo	lo	S	ab	nil	ES to nil	I	nil	
	177–184	3Coxk	5Y 5/3	5Y 6/3	2vfabk	0	ss, ps	fr	sh	SL	ab	3fpf	EV	I	nil	Slack-water deposit or reworked lake clays. Clay films look depositional
	184–204	4Coxk	2.5Y 5/3	2.5Y 6/4	sg	>75	so, po	lo	lo	S	gs	nil	ES to EV	I	nil	Clasts of lake sediment and of brown conglomerate
	204–365	4Coxk	2.5Y 6/3	2.5Y 7/3	sg	>75	so, po	lo	lo	S	aw	nil	ES to EV	I–	nil	
	365+	R	5Y 6/3	5Y 4/2												Sheared bedrock
JR04CM-78	0–4	Av	10YR 6/4	10YR 7/3	2csbk	<10	ss, p	fr	sh	L	cw	nil	EV	nil	nil	
<439 m	4–15	Bwk/Av2?	10YR 5/4	10YR 6/3-6/4	2m-csbk	35	ss, ps	fr	h	L	cw	nil	EV	nil	nil	
eolian/fluvial gravel	15–20	2Btjk	10YR 4/4	10YR 6/4	1msbk	75	ss, ps	fr	h	L	aw	1fpfpo	EV	nil	nil	
strath terrace	18–46	2Coxk1	2.5Y-10YR 5/4	2.5Y-10YR 7/4	sg	50	so, po	lo	lo	LS	cs	nil	EV	I+	nil	
	46–109	2Coxk2	10YR 5/6	10YR 7/4	sg	75	so, po	lo	lo	LS	as	nil	EV	I	nil	
	109–149	2Coxk2	10YR 5/6	10YR 7/4	sg	75	so, po	lo	lo	LS	as	nil	ES	I–	nil	
	149–219	2Coxk2	10YR 4/3	10YR 5/3	sg	75	so, po	lo	lo	LS	as	nil	nil	nil	nil	
	219+	R														Brown conglomerate

(*continued*)

TABLE 2. SOIL PROFILE DESCRIPTIONS (*continued*)

Profile no., altitude*, parent materials, geomorphic feature	Depth (cm)	Horizon[†]	Moist color	Dry color	Structure	Gravel (visual %)	Wet con.	Moist con.	Dry con.	Texture	Lower boun-dary	Clay films	Efferve-scence	$CaCO_3$ stage	Gyp-sum stage	Notes
Soils on fluvial and alluvial deposits west of Lake Manix threshold (*continued*)																
JR04D-157, 478 m	Av	0–5	2.5Y 5/3-matrix	2.5Y 7/2-matrix	2csbk	<10	vsp	fi	h	CL	cw	nil	EV	nil	nil	
eolian/fan gravel/slack-water deposits	2Bwk1	5–17	2.5Y 5/3 and 7.5Y 5/8	2.5Y 6/3 and 7.5Y 5/6	2m-csbk	25	sopo	vfr	sh	SL	cs	v1fco,br	EV	nil	nil	Mixed red and green fan material from nearby red conglomerate and from Manix formation or slack-water deposits
alluvial fan	2Bwk2	17–30	2.5Y 5/4	2.5Y 7/3	2m-csbk	25	sopo	vfr	sh	SL	gs	v1fco,br	EV	nil	nil	$CaCO_3$ increasing downward
	2Ck	30–37	5Y 6/2	5Y 7/2	2msbk	50	sopo	vfr	sh	LS	ci	nil	EV	I–I+	nil	Slakes in water
	3Ck	37–120+	5Y 5.5/3	5Y 7/2	2mpl to 1fsbk	0 and 50	sspo	vfr	sh	SL	NA	nil	EV	nil	nil	Laminated sand with lenses of gravel
Soils on fluvial terraces and alluvial deposits east of Lake Manix threshold																
JR04CM-87	0–3	Av	10YR 5/4	10YR 7/2	2msbk	<10	sopo	vfr	h	L	aw	nil	EV	nil	nil	Eolian mixed with local fan
538 m	3–10	2Bwjk	2.5Y 5/4	2.5Y 6/3	v1vfgr	50	sopo	vfr	so	LS	cw	nil	EV	nil	nil	Local fan
eolian/fluvial gravel	10–50	2Coxky	2.5Y 5/3	2.5Y 6/3	sg	65	sopo	lo	lo	LS	aw	nil	EV	nil	I+	Local fan; more subrounded stones
river terrace remnant	50–58	2aBtkyb1	10YR 5/4	10YR 5.5/4	2fsbk	20	ssps	vfr	so	SCL	gs	2fco,br	EV	II	I–	Local fan; clasts more weathered than above
	58–106	2aBkyb1	10YR 4.5/4[††]	10YR 5/4[††]	2msbk	30	sopo	vfr	sh	SL	cw	nil	EV	I	I	Local fan; groundwater stained
	106–112	2bBwkyb2	10YR 4/4	10YR 5/4	1fgr	10	sopo	vfr	so	SL	cw	2fpf,co,br	EV	I–	I–	Local fan
	112–117	2bBwykb2	10YR 5/3-6/3	2.5Y7/4-10YR5/4	v1vfgr	10	sopo	vfr	so	LS	aw	nil	EV	nil	I	Local fan; rotted clasts present
	117–122	2cBtjkb3	ND	ND	1vfgr	10	sp	vfr	sh	SCL	ci	nil	EV	nil	nil	Local fan; clay increase, probably depositional
	122–157	2cCykb3	2.5Y 6/4	2.5Y 7/4	sg	50	sopo	lo	lo	S	aw	nil	EV to ES	nil	I	Local fan; shattered clasts
	157–169	2dBtkyb4	10YR 5/4	7.5YR 5/4	2msbk	25	sp	vfr	sh	SCL	gs	3dpf,co,br	EV to nil	II	I–	Local red fan; shattered clasts
	169–226	2dBkyb4	10YR 5/4	7.5YR 5/6	2f to m sbk	15	sspo	vfr	sh	SL	cs	nil	EV to nil	I+	I–	Local red fan; shattered clasts
	226–253	3Bwkb4	2.5Y 5/3	2.5Y 5/4	2fsbk	<5	sp	vfr	sh	SL	ai	nil	EV	I+	nil	Local fan/fluvial; some green sandy clay
	253–310	4Coxkb4	10YR 4.5/4[††]	10YR 5/4[††]	sg	20	sopo	lo	lo	S	gs	nil	EV to nil	I+	nil	Colluviated fluvial; groundwater stained
	310–358	5aCkb5	2.5Y 5/4, 6/2	2.5Y7/4, 7/2	sg	95	sopo	lo	lo	S	as	nil	ES to nil	nil	nil	Mojave River fluvial; cross-bedded sand and gravel
	358–378	5bCoxkb6	10YR 4/3[††]	10YR 5/4[††]	sg	95	sopo	lo	lo	LS	as	v1fgr	ES to EV	I–	nil	Mojave River fluvial gravel, Mn staining
	378–388	5cCb7	2.5Y 4/3	2.5Y 5/6	sg	<5	sopo	lo	lo	LS	cs	nil	nil	nil	nil	Mojave River fluvial; well-sorted quartzose sand
	388–398	5dBwb8	2.5Y 5/3	2.5Y 5/4	1vfgr	95	sopo	vfr	so	LS	cs	v1fgr	nil	nil	nil	Mojave River fluvial; sand and gravel, some local clasts
	398–418	5dCoxb8	7.5YR 4. 5/3[††]	7.5YR 5/3[††]	sg	95	sopo	lo	lo	SL?	as	2fgr	nil	nil	nil	Mojave River fluvial; well-rounded gravel; groundwater stained
	418–424	6aCkb9	ND	ND	sg	10	sopo	lo	lo	S	ai	nil	ES to nil	nil	nil	Local fan gravel mixed with well-sorted sand; clasts rotted
	424–444	6bBtk1b10	5Y 5/3	2.5Y 5/3	2csbk	40	ssps	fr	sh	SCL	gs	2dpf	EV	II	nil	Local fan gravel as above
	444–458	6bBtk2b10	10YR 5/3	10YR 5/4	2msbk	35	sp	vfr	so	SCL	cs	1fpf, v1dpf	EV to ES	I	nil	Local fan gravel; clasts mostly rotted
	458–466	6bBtk3b10	2.5Y 5/3.5	2.5Y 5/3	2fsbk	20	sp	vfr	so	SCL	cw	2fpf	EV	nil	nil	Local fan gravel; clasts mostly rotted

(*continued*)

TABLE 2. SOIL PROFILE DESCRIPTIONS (*continued*)

Profile no., altitude*, parent materials, geomorphic feature	Depth (cm)	Horizon[†]	Moist color	Dry color	Structure	Gravel (visual %)	Wet con.	Moist con.	Dry con.	Tex-ture	Lower boun-dary	Clay films	Efferve-scence	$CaCO_3$ stage	Gyp-sum stage	Notes
Soils on fluvial terraces and alluvial deposits east of Lake Manix threshold (*continued*)																
	466–501	6bCoxkb10	2.5Y 5/3	2.5Y 6/3	sg	75	sopo	lo	lo	LS	as	nil	EV	nil	nil	Local fan gravel; rotted clasts in sand matrix
	501–511	6cBwk1b11	10YR 5/4	10YR 6/4	2fsbk	40	sopo	vfr	so	LS	cs	nil	ES to nil	nil	nil	Local fan gravel; rotted clasts and red clay in sand matrix
	511–525	6dBwk2b11	2.5Y 6/3	2.5Y6/4	1fsbk	25	sopo	vfr	so	LS	cs	nil	EV	nil	nil	Local fan gravel; clasts in sand matrix
	525–549	6eBwkb12	2.5Y 6/4	2.5Y 6/3	2msbk	<10	sopo	vfr	sh	LS	as	nil	EV	nil	nil	Local fan, gravelly sand
	549–559	6eBtkb12	2.5Y–10YR 6/4	10YR 7/6	2msbk	<10	sspo	vfr	h	SL	as	3fco,br	EV	nil	nil	Local fan, gravelly sand
	559–569	6eBwkb12	10YR 5/4	10YR 7/4	2msbk	<10	sopo	vfr	h	LS	as	nil	nil	nil	nil	Local fan, gravelly sand, groundwater stained
JR05CM-197	0–2	Av	10YR 5/4	10YR 7/4	2m-c sbk	trace	s, p	fr	h	SCL	ci	nil	nil	nil	nil	
~415 m	2–7	Btk	10YR 4/4	10YR 7/3	2m-c sbk	10–15	ss, ps	fr	h-vh	SL	ci	v1fpocobr	EV	nil	nil	Discontinuous horizon, goes to zero locally
Eolian/fan gravel?/	7–14	Ck	10YR 5/4	10YR 8/4	sg	5–10	so, po	lo	lo	L-SL	ai	nil	EV	nil	nil	
tributary and Mojave River	14–25	Btkb	10YR 6/4	10YR 5/4	1msbk	20	ss, ps	fr	sh	SL	cs	nil	ES to nil	nil	nil	buried?
fluvial deposits	25–200+	2Ckb	10YR 4/5	10YR 5/4	sg	70	so, po	lo	lo	LS		nil	nil	I+	nil	Isolated patches of $CaCO_3$; stratigraphically dependent areas of stage II $CaCO_3$
Strath terrace	25–200+	carbonate coatings		10YR 8/1												
	25–200+	silica coatings		10YR 6/6												
JR04D-124	0–4	Av	2.5Y 4/4	2.5Y 7/4	2csbk	tr	sps	fr	h	SCL	aw	nil	EV	nil	nil	Patchy EV
>402 m	4–13	Btk	10YR 5/6	2.5Y 7/4	2m-csbk	<10	ssps	fr		SL	cw	v1fpf 2fpo,co,br	EV	I–	nil	
eolian/fan	13–24	Bwk	2.5Y 5/4	2.5Y 7/3	v1fgr	10	sopo	vfr	so	SL	cw	nil	EV	I	nil	Veinlets of $CaCO_3$
gravel?/fluvial deposits	24–41	Btkb	2.5Y 5/4	2.5Y 7/4	2fsbk	15	spo	vfr	so	SCL	cw	nil	EV	I+	nil	Filaments, almost nodules, but few veinlets, 0%–15% no fizz
fluvial terrace	41–53	Ckb	2.5Y 5/4	2.5Y 6/4	sg	25	sopo	lo	lo	SL	aw	nil	EV	I+	nil	
	53–83	2Ck1b	2.5Y 5/3	2.5Y 7/3	sg	50–75	sopo	lo	lo	S	as	nil	EV	I+	nil	Rounded-subrounded clasts 2–5 cm; sand and smaller clasts in bottom 20 cm
	83–148	2Ck2b	2.5Y 5/3	2.5Y 7/3	sg								EV		nil	Effervescence is stratigraphically dependent
	148–230	2Ck2b	2.5Y 5/3	2.5Y 7/3	sg	50	sopo	lo	lo	S		nil	ES	I–	nil	Rounded to subangular clasts 2–5 cm; interbedded sand and gravel

(*continued*)

TABLE 2. SOIL PROFILE DESCRIPTIONS (*continued*)

Profile no., altitude*, parent materials, geomorphic feature	Depth (cm)	Horizon[†]	Moist color	Dry color	Structure	Gravel (visual %)	Wet con.	Moist con.	Dry con.	Tex-ture	Lower boun-dary	Clay films	Efferve-scence	$CaCO_3$ stage	Gyp-sum stage	Notes
Soils on beach barriers																
JR04D-105	0–1	Av	10YR 5/4	10YR 7/3	2msbk	trace	ss, ps	fr to fi	sh	L	as	nil	ES	nil	nil	
543 m	1–5	Bwk1-Av2	10YR 5/4	10YR 7/3	2msbk	<10	ss, ps	fr to fi	sh	L	cw	nil	EV	nil	nil	
eolian/beach gravel	5–11	Bwk2	10YR 5/4	10YR 7/2.5	2msbk, sg	10–25	so, po	vfr	h	SL	cs	nil	EV	nil	nil	Possibly a buried Av
beach barrier	11–21	Bwjk	10YR 4/4	10YR 6/4	v1fsbk	10–25	so, po	lo	lo	LS	cw to ci	nil	ES–EV	nil	nil	More silt than below
	21–30	2Coxk	10YR 4.5/4	10YR 5/4	sg	25–50	so, po	lo	lo	S	cw	nil	ES–EV	I–	nil	Mostly beach gravel
	30–45	2Coxk	10YR 4.5/4	10YR 6/4	sg	50–75	so, po	lo	lo	S	as	nil	ES–EV	I– to 1+	nil	Well-sorted, well-rounded clasts
	45–	3Ck														Partly cemented sand; not described
JR04D-1	0–2	Av1	10YR 5/4	10YR 7/3	2msbk	tr	ss, ps	fr	sh	SL	cs	nil	ES	nil	nil	
<543 m	2–6	Btjky	10YR 4/4	10YR 7/3	2fsbk	25	ss, ps	vfr	sh	SL	cs	nil	EV	nil	nil	Originally was called Av2
eolian/beach gravel	6–17	2Ck1	10YR 5/4	10YR 7/3	sg	>75	so, po	lo	lo	SL		nil	EV	I+	nil	Tufa-coated cobbles at top
beach barrier	17–38	2Ck2	10YR 5/4	10YR 7/3	sg	>85	so, po	lo	lo	SL	cs	nil	EV	I+ to II	nil	
	38–52	3Ck	10YR 6/4	10YR 7/4	sg	<10	so, po	lo	lo	S	as	nil	EV		nil	*Anodonta* shells at base; see Table 1. Sand locally cemented; slakes in water
	52–66	4Ckb	10YR 4.5/4	10YR 6/4	sg	>75	so, po	lo	lo	S	as	nil	EV	II+ to I+	nil	
	66–80	5Ckb	10YR 5/4	10YR 6/4	m	<10	so, po	fr	vh	S	cs	nil	EV	I+ to II	nil	Cemented sand; slakes in water
	80–105+	5C				>75										Beach gravel; not described
M04-77	0–5	Avt			2vcpr,sbk	<10	vs, p	fr	h	CL	as	2dpo,pf	EV	nil	nil	
537 m	5–16	Btk			2msbk	<10	s, ps	fr	sh	SL	gs	nil	E–EV	I+	nil	Gypsum not visible but may be present
eolian/beach gravel	16–30	2Btky			2fsbk	75	ss, ps	fr	vh	SL	gs	nil	EV	II	I	Gypsum-shattered stones
beach platform	30–60+	2Cky			sg	65	so, po	lo	lo	SL		nil	E–	I	I	Effervescence in pockets
M04-75	0–3	Av	7.5YR 7/4	10YR 8/3	2msbk	20	s,p	fi	N.D.	SiL	cs	nil	ES	nil	nil	Soil was very wet when described
542 m	3–15	Btk	7.5 YR 6/4	7.5YR 6/3	2f-msbk	20	ss,ps	vfr	N.D.	SL+	cs	nil	ES	II	nil	
eolian/beach gravel	15–22	2Bwk	7.5YR 6/4	7.5YR 7/4	1f-msbk	40	so,po	vfr	N.D.	LS	cs	1nco	0 to E–	I–	nil	
beach platform	22–34	2Bk1	7.5YR 6/6	7.5YR 7/4	sg	60	so,po	lo	N.D.	S	as	nil	0	I	nil	
	34–105	2Bk2	7.5YR 7/6	10YR 7/4	m	60	so,po	fr	N.D.	S	as	nil	E–ES	II	nil	
	105–135	2Coxk	10YR 7/4	10YR 8/3	sg	30	so,po	lo	N.D.	S	gs	nil	0	I–	nil	
	135+	2Cox														*Anodonta* shells at ~2 m depth; see Table 1

(*continued*)

TABLE 2. SOIL PROFILE DESCRIPTIONS (*continued*)

Profile no., altitude*, parent materials, geomorphic feature	Depth (cm)	Horizon†	Moist color	Dry color	Structure	Gravel (visual %)	Wet con.	Moist con.	Dry con.	Texture	Lower boundary	Clay films	Efferve-scence	$CaCO_3$ stage	Gypsum stage	Notes
Soils on beach barriers (*continued*)																
M04-76	0–4	Av	7.5YR 6/3	10YR 7/3	2vcsbk,pr	<5	vs,p	fi	h	CL	cs	nil	EV	nil	0	
546 m	4–11	Avy	7.5YR 5/4	7.5YR 7/4	2msbk	20	s,ps	vfr	sh	SL	cw	nil	EV	nil	I–	
eolian/beach gravel/sand	11–19	2Btky1	7.5YR 5/4, 5/6	10YR 7/4	2fsbk	40	s,ps	fr	h	SCL	cs	3fpf,po	EV	I+	II	Gypsum-shattered stones
beach barrier	19–35	2Btky2	7.5YR 5/4	7.5YR 5/4	1fsbk	70	ss,ps	vfr	h	SL+	cw	3dpf	EV	I+	II	Gypsum-shattered stones
	35–62	2Cky	7.5YR 6/4	10YR 6/4	sg, 2fsbk	80	so,po	lo	lo	LS	as	nil	EV	I+	I	Gypsum in cracked clasts
	62–78+	3C	10YR 6/3	10YR 6/4	2msbk	0	so,po	vfr	sh	S		nil	EV	I–	I	
M05-06	0–25	Btkyb	2.5YR 6/4	5YR 5/4	2f-csbk	25	s,ps	fr-fi	N.D.	SCL	cs	2nco,pf,po and 1mkpf	E–ES	II	I	Description begins ~125 cm below surface; soil very wet when described. Most clasts completely rotted
543 m	25–60	Btykb	5YR 6/4	5YR 6/4	2f-msbk	50	ss,po	vfr	N.D.	SL–	cs	1nco	E–	I	II	Rotted and shattered clasts abundant
lake deposits	60–110	Bykb	5YR 6/4	7.5YR 6/6	sg, 1fsbk	60	so,po	lo-vfr	N.D.	S+	cs	nil	0 to E–	I–	II+	Shattered and rotted clasts common
buried beach platform	110–130+	Cyb	10YR 7/4	N.D.	sg	75	so,po	lo-vfr	N.D.	S		nil	0	nil	I	Few rotted clasts
M05-46	0–7	Av	7.5YR 6/4	5YR 7/3	2f-msbk, 1cpr	5	vs,p	n.d.	sh-h	SiL	cw	nil	n.d.	I	nil	
549 m	7–12	Btk	5YR 6/4	7.5YR 6/4	2msbk, 2cr	20	s,ps	n.d.	sh	SCL	cw	2fbr,co	n.d.	II	nil	
eolian/beach gravel	12–23	2Btk	7.5YR 5/4	7.5 YR 7/4	2fsbk, 1cr	70	ss,ps	n.d.	so-sh	SCL	gw	nil	n.d.	II	nil	
beach barrier	23–42	2Coxk1	5YR 4/4	5YR 6/4	sg	90	so,po	n.d.	lo	S	gw	nil	n.d.	I	nil	Moderate sorting and rounding despite dominance by angular coarse basalt clasts from adjacent hill
	42–65	2Coxk2	7.5YR 4/4	7.5YR 6/3	sg	90	so,po	n.d.	lo	S		nil	n.d.	I	nil	

*Altitude from topographic map except bold font indicates differentially corrected global positioning system (GPS) data.
†U.S. Department of Agriculture Soil Survey nomenclature (1993) as modified by Birkeland (1999).
§$CaCO_3$ stage after Machette (1985).
**Gypsum stage after Reheis (1987).
††Colors in these horizons are affected by groundwater alteration; not used in calculations of profile development indices (PDI) in Table 3.

TABLE 3. PROFILE DEVELOPMENT INDICES (PDI) FOR SOILS

Site	Figure location	Altitude (m)*	Surface	PDI values (total)	PDI values (normalized to 150 cm)
JR04D-95	3, 11	>463	Inset fluvial terrace	4.4	0.03
JR04CM-77	3	451	Inset fluvial terrace	9.4	0.06
JR04CM-78	3, 11	<439	Inset fluvial terrace	9.9	0.07
JR04CM-124	3	>402	Fluvial terrace	7.3	0.05
JR05CM-197	3	415	Fluvial terrace	3.0	0.02
JR05CM-198	3, 11	469	Fluvial terrace	3.1	0.02
JR04D-157	3	<u>*478*</u>	Alluvial fan	2.5	0.02
JR04CM-87	3, 14	**538**	Entire section	57.0	0.41
Upper part			Above fluvial beds	26.8	0.24
Middle part			Within fluvial beds	5.3	0.04
Lower part			Below fluvial beds	19.1	0.13
JR04D-105	2B	**543**	Beach barrier	2.1	0.01
JR04D-1	2B, 7A	<543	Shoreface of beach barrier	2.5	0.02
M04-75	4, 5, 7	**542**	Beach platform	13.5	0.05
M04-76	5, 6	**546**	Beach barrier	14.4	0.11
M04-77	5, 6	**537**	Beach platform	5.4	0.04
M05-06	5, 7	543	Buried beach gravel	17.0	0.13
M05-46	5	**549**	Beach barrier	9.1	0.07

*Bold font indicates differentially corrected global positioning system (GPS) data; altitudes not in bold font were estimated from topographic map using handheld GPS location device. Underlined italic font indicates altitudes from National Aeronautics and Space Administration (NASA) ATM-III LIDAR data acquired September 2003, funded by the U.S. Army Corps of Engineers, WRAP program (R. Lichvar and D. Finnegan).

Key: ATM—Airborne Topographic Mapper; LIDAR—Light Detection and Ranging; WRAP—Wetlands Regulatory Assistance Program.

just downstream of the Lake Manix threshold; these sites were previously unreported (Figs. 3 and 8B).

Inset Strath Terraces West of the Lake Manix Threshold

Fluvial deposits inset below Lake Manix deposits west of the lake threshold are mostly well-preserved fluvial terraces, including strath terraces both with a veneer of gravel and with much thicker alluvial fills that are variably reincised, and associated terrace risers. Terrace surfaces lie between 12 and 36 m above the modern channel (Fig. 8B) and commonly exhibit meander scars. The terraces (Fig. 9) are almost entirely cut into a Tertiary(?) fanglomerate that Ellsworth (1932) termed the "brown fanglomerate." This fanglomerate is mostly well-indurated and matrix-supported and is composed primarily of angular to subangular, locally subrounded, coarse pebble- to boulder-size clasts of mafic and felsic plutonic rocks sourced from nearby Cave Mountain. 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 clay and silt. The gravels are interbedded with moderately well-sorted, rounded to well-rounded, 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. The fluvial deposits are interpreted as the result of the Mojave River reworking and rounding clasts of the older fanglomerate, winnowing out the finer-grained and cemented material, and mixing it with sediment eroded from Lake Manix beds upstream.

Soils that developed into deposits upstream of the lake threshold typically have Av/Bwk/Ck or Av/Btk/Coxk horizon sequences (Table 2; Figs. 9B and 9C). Normalized PDI values for these terrace soils range from 0.02 to 0.07, similar to values for soils on the 543 m beach ridges in the eastern Afton subbasin (Table 3). Although there are some differences among soils from the set of three inset terraces examined, soil differences are not consistent relative to elevation above the river, and they likely reflect a range of natural soil variation for soils that are similar in age.

"Slack-Water" Deposits

An interesting set of fine-grained deposits is associated with valleys incised into the prelake fanglomerate on the north side of Afton Canyon west of the lake threshold (JR04D-68 and JR04D-70, Fig. 3). Ellsworth (1932) described these deposits as green clay overlying interpreted beach gravel and inferred them 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

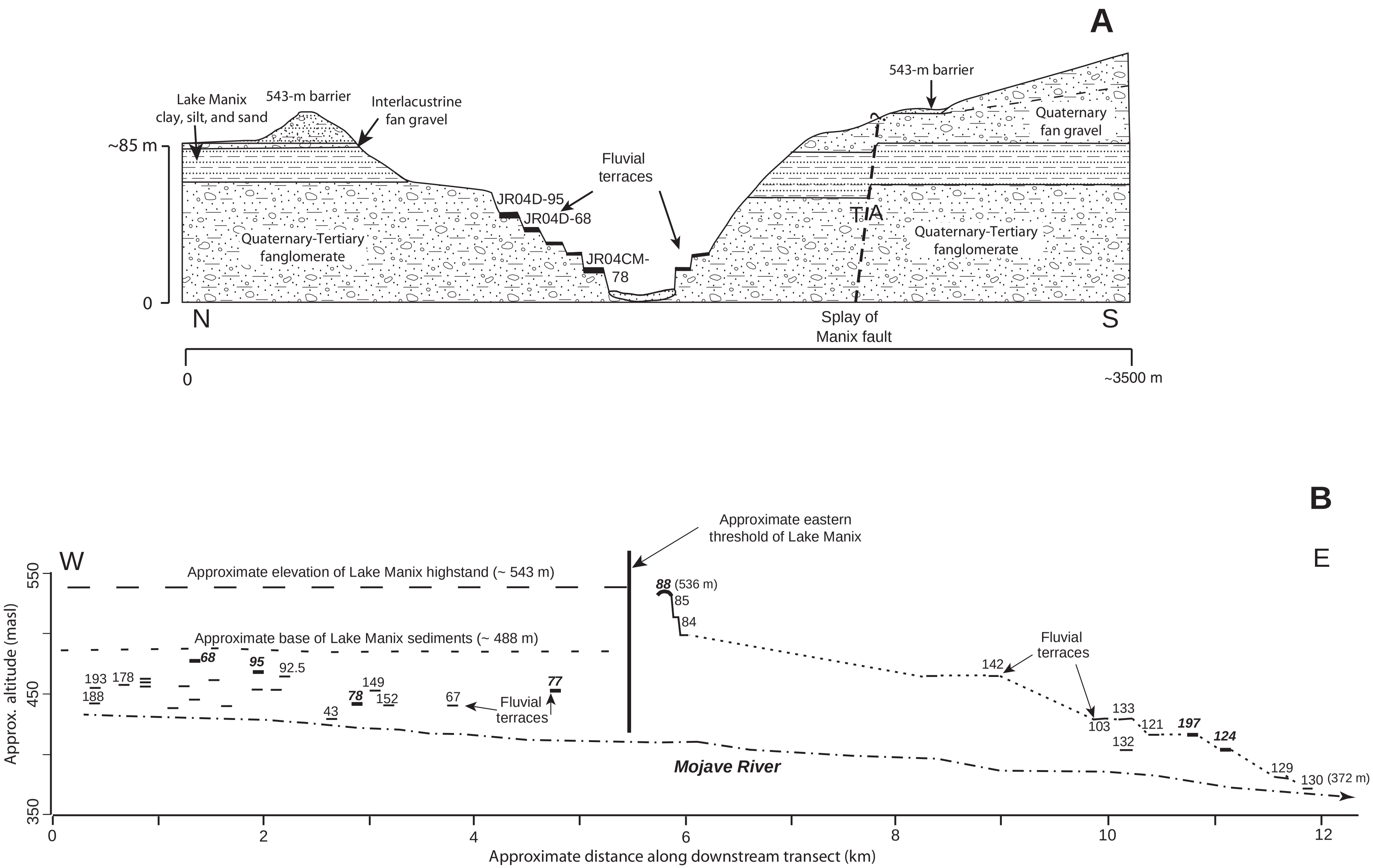

Figure 8. Schematic profiles of strath terraces and fluvial deposits in Afton Canyon area (see Table DR1 [see text footnote 1] and Fig. 3 for site locations and descriptions). (A) Cross section upstream of proposed Lake Manix threshold. (B) Longitudinal profile of Mojave River and fluvial terraces; view to north. Line of profile (dash-dot) follows modern channel (Fig. 3). Sites 88, 85, and 84 are old fluvial deposits and straths above north canyon rim. Numbers are sites from Table DR1 with characters preceding dash omitted for convenience. Bold numbers with heavy lines are soil description locations (Table 2). Lines with no numbers are observed terraces lacking site numbers. Dotted line connects terrace remnants but does not imply definitive correlations.

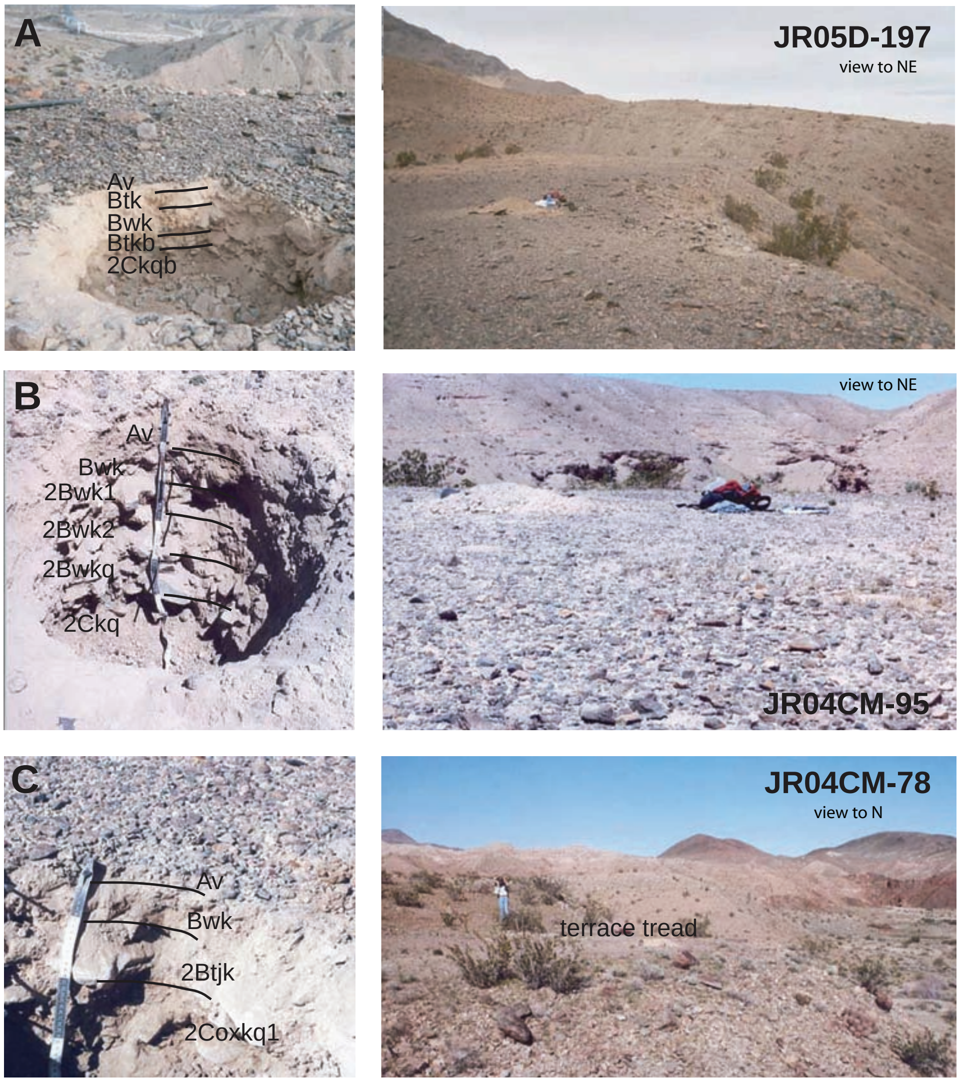

Figure 9. Surfaces and soils of Mojave River fluvial terraces (Figs. 3 and 8B). (A) Site JR05D-197 (~415 m) is east of the Lake Manix threshold. Sites (B) JR04CM-95 (>463 m) and (C) JR04CM-78 (<439 m) are inset below the basal Lake Manix sediments within Afton Canyon, west of the Lake Manix threshold. Soil descriptions are in Table 2.

Ellsworth (1936) were confounded by the absence of evidence for damming of the canyon to the east by fan aggradation, fault movement, or landslides 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, Figs. 3 and 10), has yielded more data, yet the interpretation of their origin and age remains inconclusive. More than 5 m of deposits rest unconformably on prelake fanglomerate at site JR04D-68, at and below ~478 masl. These deposits include the following, from bottom to top (Fig. 10): (1) sandy alluvium overlain by well-sorted sand; (2) blocky green mud that is locally burrowed and contains 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, which coarsens upward and intertongues toward the adjacent hillslope with coarse fan sand and gravel; and (4) locally derived fan gravel. Many beds in unit 1 contain abundant to rare lacustrine ostracodes that are winnowed and abraded and appear to have undergone either or both fluvial transport and postdepositional dissolution (note presence of secondary soluble minerals, Fig. 10). However, unit 2 contains abundant to common, well-preserved lacustrine ostracodes, including a coquina-like "death bed" at the top of unit 2, the assemblages and stratigraphic changes of which are interpreted to represent life assemblages in a perennial lake; the species represented are identical to those found throughout the Manix lakebeds (R. Forester, U.S. Geological Survey, 2005, written commun.; Steinmetz, 1987). Analyses of ostracodes from four strata in units 1 and 2 (two ages in Table 1

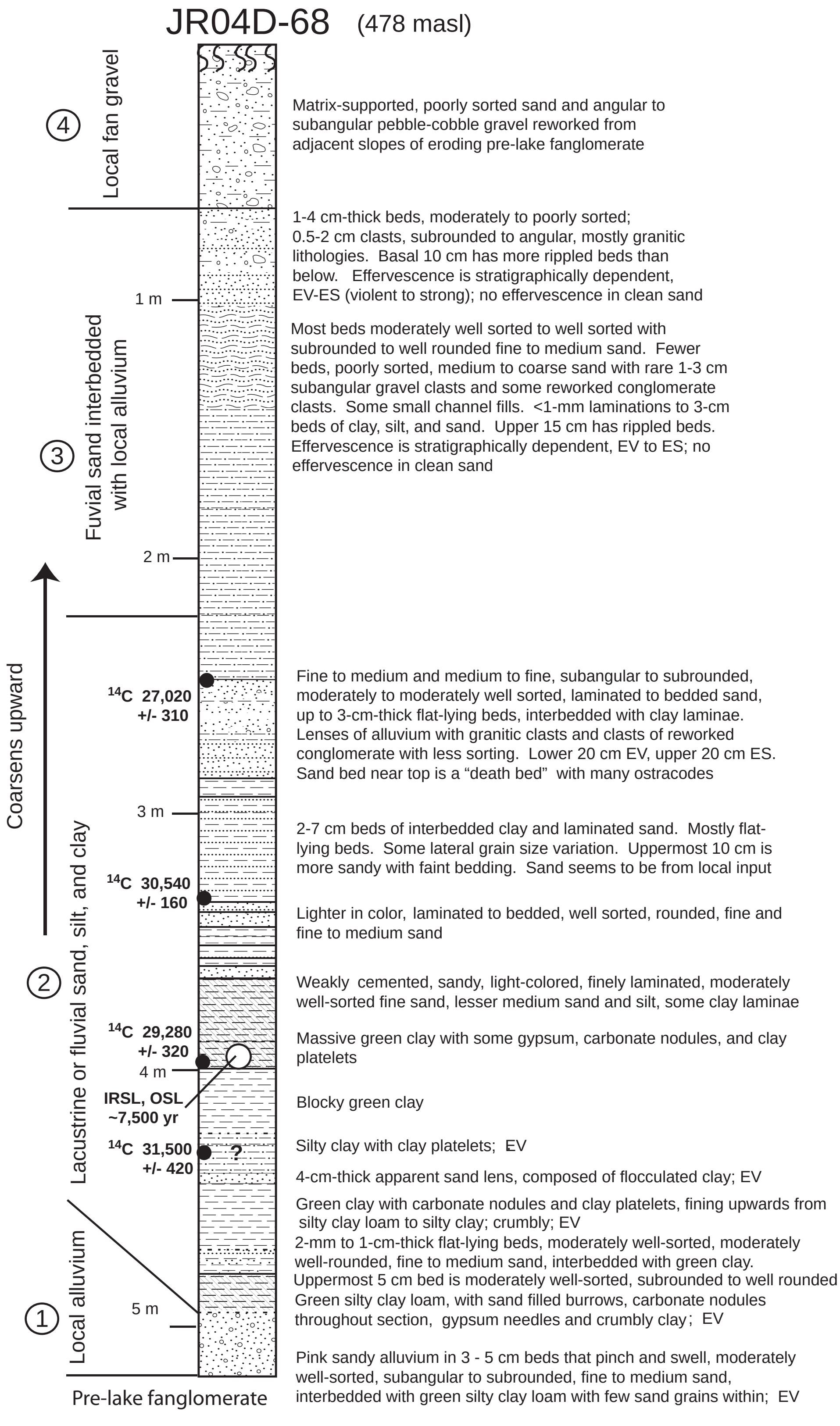

Figure 10. Composite stratigraphic section of “slack-water” deposits at site JR04D-68 (see Table DR1 [see text footnote 1] and Fig. 3 for site location and Table 2 for surface soil description). Filled circles show sample depths from which ostracodes were obtained for 14C ages (Table 1); open circle is location of luminescence sample discussed in text. E—effervesces; ES—effervesces strongly; EV—effervesces violently.

are repeat measurements on ostracodes obtained using no chemical dispersants) yielded ages in approximate stratigraphic order from 31,500 ± 420 to 27,020 ± 310 ^{14}C yr B.P. (Table 1; Fig. 10), with the exception of the age from the sample at 390–395 cm, which was from a unit with abraded or dissolved shells. The luminescence ages of ca. 7500 yr measured using both infrared stimulated luminescence (IRSL) and optically stimulated luminescence (OSL) techniques (S. Mahan, U.S. Geological Survey, 2006, written commun.; methods described in Mahan and Brown, 2006) are in direct conflict with these consistent ^{14}C ages and with the apparent life assemblages of lacustrine ostracodes.

Interbedded colluvial deposits and incipient soil development in a part of this "slack-water" deposit exposed on side slopes at site JR04D-70 (Fig. 3) show a history of incremental incision. In this exposure, the fanglomerate bedrock was incised by either the Mojave River or a tributary and is overlain by colluvium containing carbonate filaments and probable weak pedogenic structure near the top of the deposit. The slack-water or lacustrine deposits, similar to those of unit 2 in Figure 10, are cut into and overlie this colluvium. These fine-grained deposits may have an incipient soil (carbonate filaments only); however, in this location, the deposit is shallow, and the carbonate could be associated with the modern surface. An overlying colluvial deposit has a soil profile (Av/Bwk/Coxk) that is similar to the soil developed into a nearby fan deposit (JR04D-157; Fig. 3; Table 2), which also overlies the "slack-water" deposits.

Strath terraces inset below basal Lake Manix sediments at site JR05CM-198 (Figs. 3 and 11) are also relevant to the incision of Afton Canyon. The straths at this site, along an abandoned paleochannel of the Mojave River, track incision to within ~12 m of the modern channel. Overlying these strath terraces and filling one end of the paleochannel, there are 20–25 m of fluvial deposits, mudflows, and tributary alluvium that have been reworked from lake sediment and Cave Mountain–derived fanglomerate from higher slopes to the north. In the upper ~2 m, there are well-rounded volcanic lithologies—mainly rhyolite and basalt—which must have been emplaced by the Mojave River and likely originated from the Cady Mountain fans to the southwest. A tributary subsequently incised a 200-m-long exposure through this deposit. The surface characteristics and soil development of the uppermost deposit (JR05CM-198, Table 2) are similar to those of the inset fluvial terraces. Although the stratigraphy at site JR04D-70 (Fig. 3), including interbedded "slack-water" deposits, suggests pauses in incision that permitted colluviation and incipient soil development, stratigraphic relations at site JR05CM-198 suggest that this process occurred quickly enough that the events cannot be distinguished chronologically by soil properties.

In conclusion, the majority of our new evidence supports a fluvial origin for the "slack-water" deposits at site JR04D-68, as suggested by Meek (1989, 1990). The stratigraphy, ^{14}C ages, and lifelike 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 that existed significantly before the last highstand of the lake (ca. 22,000 ^{14}C yr B.P. in this study). However, no stratigraphic or geomorphic data support such a hypothesis and the ca. 7500 yr luminescence ages are in conflict. In addition, the calibrated ^{14}C ages do not show a consistent age progression with depth (Fig. 12). No plausible damming mechanism is known once Afton Canyon had been partially or completely incised. Some of the alluvial and fine-grained deposits, the intertonguing of some of the upper beds with coarse local sand and gravel, and the luminescence ages of ca. 7500 yr are consistent with slack-water deposition during Mojave River floods. If this was the case, then a lifelike assemblage of mostly unabraded, well-preserved ostracodes was fortuitously redeposited at this site. Soil development (JR04D-157, Table 2) and surface characteristics of the overlying alluvial fan are consistent with those of other inset terraces and suggest an age younger than the last highstand of Lake Manix.

Fluvial Deposits East of the Lake Manix Threshold

Fluvial deposits east of the Lake Manix threshold vary from well-preserved fluvial terraces to eroded gravel (~1–2 m thick) or lags of well-rounded quartzite and plutonic and volcanic rock types (Table DR1 [see footnote 1]; Fig. 8B). These deposits are associated with eroded fluvial scarps that are 1–3 m high. The clast lithologies differ from those contained in locally derived fan gravel and from those in a Tertiary fanglomerate that, along the north side of the canyon, almost entirely consists of mafic and felsic plutonic rocks of the Cave Mountain pluton to the north (Fig. 2). The fanglomerate is in fault contact with the Cave Mountain pluton (J.L. Redwine, 2007, unpublished geological mapping); this shear zone does not appear to have Quaternary displacement. The allochthonous quartzite and volcanic clasts that are interpreted as fluvial gravel of the Mojave River resemble the volcanic component of the Cady Mountain fanglomerate exposed west of the Lake Manix threshold south of the river.

Local tributaries have constructed alluvial fans, the beds of which grade into and intertongue with the main-stem fluvial deposits. Tributary fan deposits have angular to subangular mafic and felsic plutonic clasts. Tributary fluvial deposits are better sorted and slightly better rounded than tributary fan deposits, are clast supported, and are often interbedded with moderately well-sorted quartz-rich sand beds. Most of the fluvial deposits east of the Lake Manix threshold are composed of both tributary- and Mojave River–sourced deposits, with varying proportions of each depending on location. For example, site JR05CM-197 has a large tributary component that intertongues with Mojave River sand and gravel, whereas at site JR04CM-124 (Fig. 3), most clasts are volcanic, and the terrace and deposit are mostly of Mojave River origin.

High, eroded fluvial deposits of the same description exist all along the north rim as far as west as site JR05CM-143 (Fig. 3). Due to erosion in close proximity to the steep canyon walls, surface characteristics and soils cannot be used to estimate age. Some smaller terrace remnants, mostly consisting of a gravel lag of Mojave River origin deposited on a strath surface and associated with a fluvial scarp, are interpreted to be relatively young based on their low position and inset relation relative to preserved terraces with described soil profiles (sites JR04CM-124 and

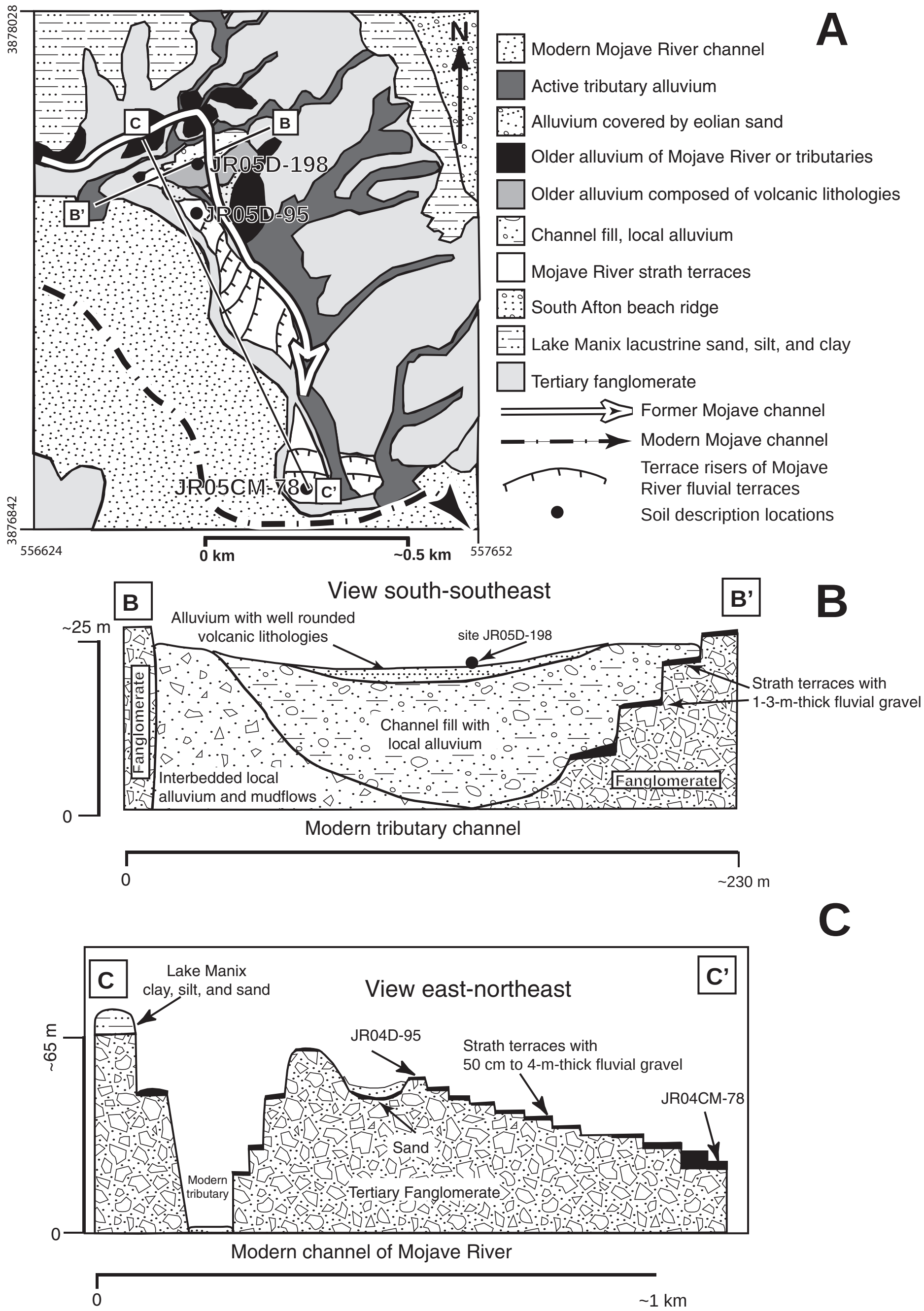

Figure 11. Map (A) and schematic cross sections (B and C) of surficial deposits at and near site JR04D-198. Mojave River has incised a now-abandoned series of straths and a channel east of its modern channel, cut into Tertiary fanglomerate as well as Lake Manix sediments. At its northern end, this paleochannel was then filled with 20–25 m of locally derived alluvium capped by Mojave River gravels, and this fill was reincised by a tributary to the present Mojave River. Coordinates are in UTM units, NAD 83, Zone 11.

JR05CM-198, Fig. 3; Table 1). Even those remnants only ~24 m above the modern Mojave River (site JR05CM-132; Figs. 3 and 8B) are sometimes extremely eroded.

Based on pavement development and varnished clasts on the best-preserved surfaces of two of the terraces in the eastern part of the canyon (JR05CM-124, JR05CM-197; Figs. 3, 8, and 9), these terraces may be slightly older than those terraces inset below lake sediments upstream of the sill (sites JR04D-95, JR04CM-78, JR04CM-77; Fig. 3). In addition, the two eastern terrace sites possess thin buried soils within the eolian sediments incorporated into their profiles (Table 2). Although these soils have PDI values similar to those of the inset terraces upstream (Table 3), the buried soils suggest that the soils at the east end may be slightly more developed. This subtle difference could reflect either a slightly older age or local variations in soil development and influx of eolian sediment.

Fluvial Deposits above the North Rim

In addition to the fluvial straths and deposits inset below lake beds and well below the canyon rim, we here describe previously unrecognized fluvial deposits at much higher elevations that are located atop the north rim of Afton Canyon

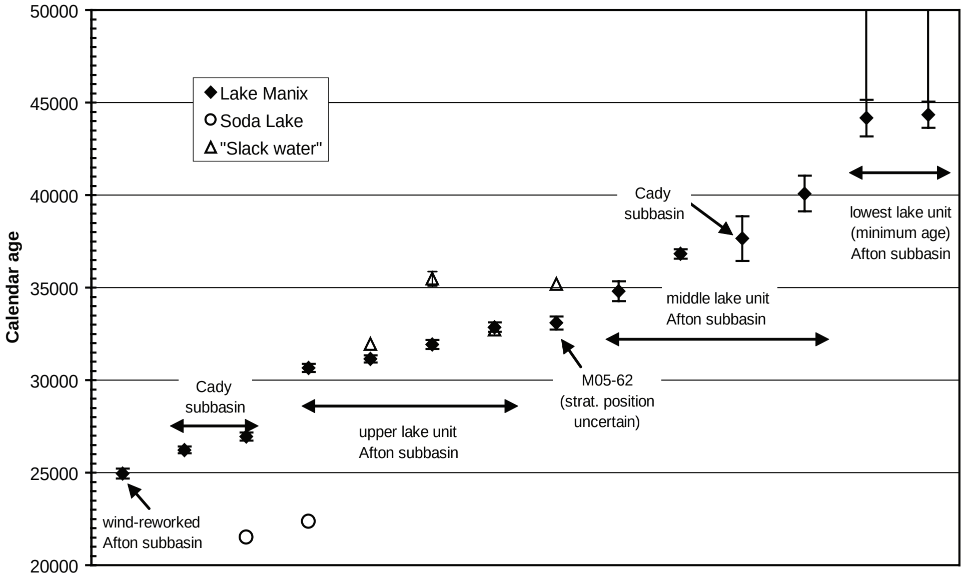

Figure 12. Plot showing calibrated ages (curve of Fairbanks et al., 2005) of lacustrine units in Manix and Afton subbasins, "slack-water" site JR04D-68, and lake clays from ca. 25 and 26 m depth in Soda Lake core. Ages are plotted from left to right with increasing stratigraphic age for Lake Manix deposits and with increasing depth at site JR04D-68 and the core. Bars are two standard deviations (not shown if smaller than symbol). Calibrated ages from ostracodes in "slack-water" deposits do not show a consistent age progression and overlap with age ranges of the upper and middle lake units in Afton subbasin. Note that ages from ostracodes in Soda Lake core are younger than any ages thus far obtained from deposits associated with 543 m highstands of Lake Manix.

just downstream of the easternmost extent of Lake Manix deposits (JR04CM-87, JR04CM-88, JR04CM-85, JR04CM-84, and JR04CM-82; Figs. 3, 8B, and 13). The highest of these fluvial deposits, sites 87 and 88, are exposed in two small dissected outcrops that have no preserved terrace surfaces and are thickly blanketed by colluvium. Site JR04CM-87, which has a surface altitude of 537.7 m and is ~130 m above the present river channel, exposes nearly 6 m of alluvial-fan deposits derived from adjacent metamorphic rocks and contains an interval of fluvial gravel, including well-rounded volcanic and igneous clasts, and quartz-rich sand (Fig. 14). The outcrop, overlying bedrock, is composed of 18 depositional layers divided into 13 units that are separated and defined by buried soils (b1, b2, etc.; Fig. 14; Table 2). The uppermost four units are poorly sorted and weakly bedded to massive, local alluvial-fan deposits with angular to subangular clasts. The fifth unit consists of fluvial sand and pebbles reworked as massive to weakly bedded colluvium mixed with angular clasts like those above. Units 6 through 9 consist of moderately sorted, bedded and cross-bedded, sand and pebble-cobble gravel with rounded clasts; and the basal units 10–13 are again unsorted, weakly bedded, local alluvial-fan deposits. Reworked fluvial deposits of unit 5 contain lacustrine ostracodes (R. Forester, U.S. Geological Survey, 2005, written commun.). Although abraded, the species present are 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 unit stratigraphy is preserved at site JR04CM-88.

We estimated the age of the fluvial deposits by summing the normalized PDI values of the overlying soils (surface soils and soils b1–b5, Tables 2 and 3). This yielded a value of 0.24, which is larger than PDI values of 0.11 (surface soil) and 0.19 (buried + surface soil) calculated for soils on older beach gravels at Buwalda Ridge. We stress that these soils and PDI values are difficult to compare due to the vastly different parent materials and deposit thicknesses. In addition, the PDI value of 0.04 summed for soils b6–b9, which formed on the four fluvial units (Table 3), implies a lengthy period of fluvial aggradation with short episodes of stability. Although most of the buried soils and the surface soil are weakly expressed, these soils and the complex sequence of deposits cumulatively 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. In particular, the presence of four fluvial units separated by weak buried soils implies a stable, slightly aggrading river—a sharp contrast to canyon incision and downstream construction of the Mojave fan triggered by failure of the lake threshold sometime later.

A luminescence sample of the buried fluvial deposits (Fig. 14) yielded ages of 19.9 ± 2.2 ka (IRSL) and 15.0 ± 1.5 ka (OSL on quartz; S. Mahan, U.S. Geological Survey, 2006, written commun.). The complex soil-stratigraphic sequence above the sampled unit, the large PDI values discussed previously, and the poor preservation of the entire deposit (far more eroded than beach-barrier deposits of the 543 m highstand of Lake Manix, which are no younger than ca. 22,000 ^{14}C yr B.P.; Table 1) suggest that these luminescence ages are much too young. Although the sand bed we sampled appeared unaltered, we suspect that disequilibrium in the dose rate caused by fluctuating groundwater may have affected the resulting OSL ages, based on the presence of bright oxidation colors and manganese bands in sands above and below the sampled unit (Fig. 14).

Inset below the 538 m fluvial and alluvial-fan deposits, there are two nested strath terraces that slope gently and step down toward the canyon rim (Figs. 3, 8B, 13A, and 13B). These terraces

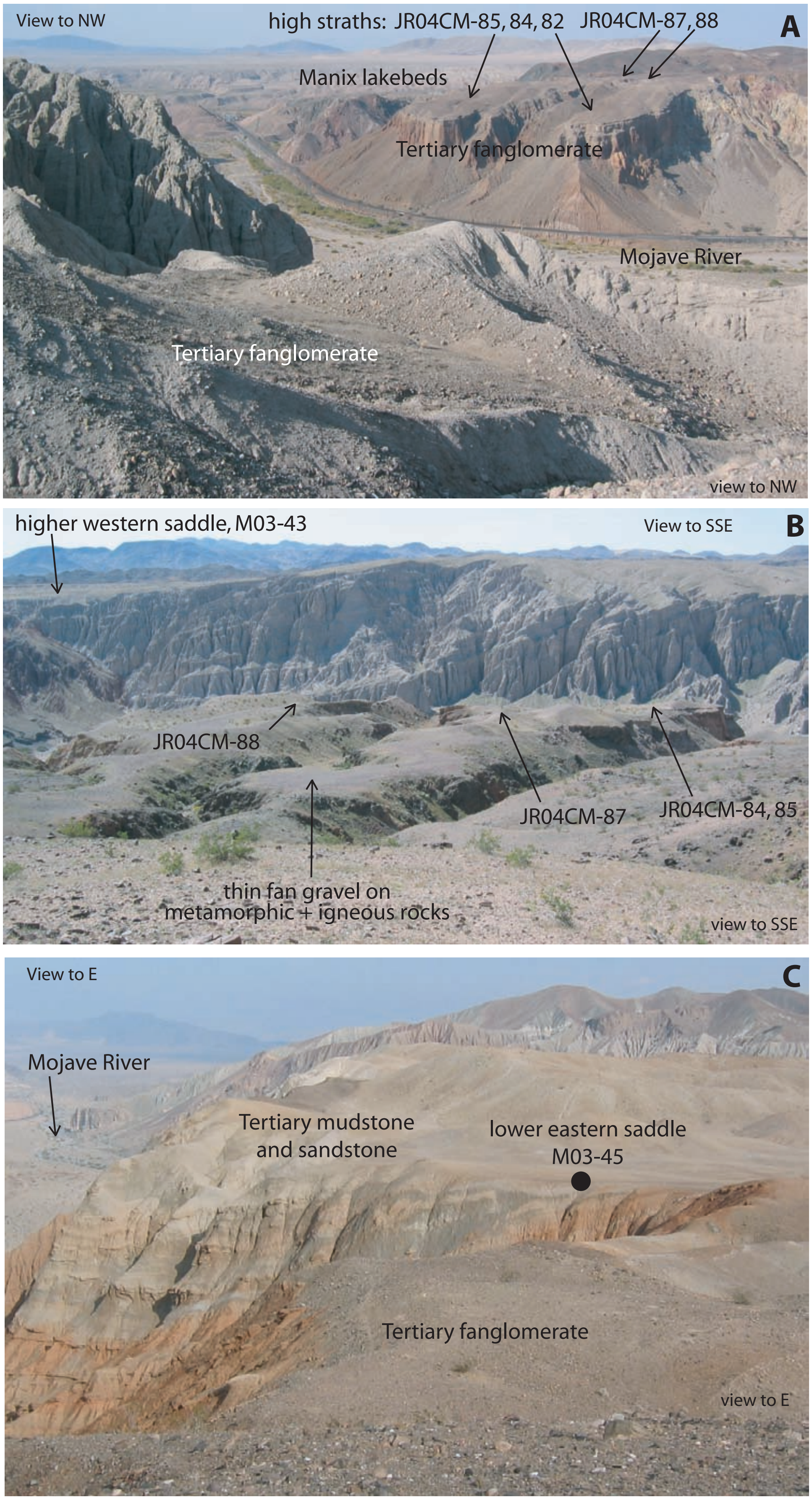

Figure 13. Photographs of high fluvial deposits and landscape above rim of Afton Canyon (sites are located on Fig. 3). (A) Location on north rim of high fluvial deposits (JR04CM-87, JR04CM-88) and strath terraces; straths overlie Tertiary fanglomerate comprising vertical canyon wall. Photo was taken from south canyon rim at approximate location of western saddle (M03-43). Note that slope of fluvial deposits extends below altitude of photo point. (B) Fluvial deposits overlain by thin alluvial fans (JR04CM-87, JR04CM-88) atop truncated metamorphic rocks, and inset strath terraces (JR04CM-84, JR04CM-85) above canyon rim. Higher (M03-43) of two saddles in south rim is visible on left. (C) Tertiary sedimentary rocks underlying lower eastern saddle (M03-45) on south rim and previously proposed drainageway leading southeast to Baxter Wash. Tilted sediments are truncated by a smooth erosion surface lacking any exotic clasts not found in adjacent Tertiary fanglomerate.

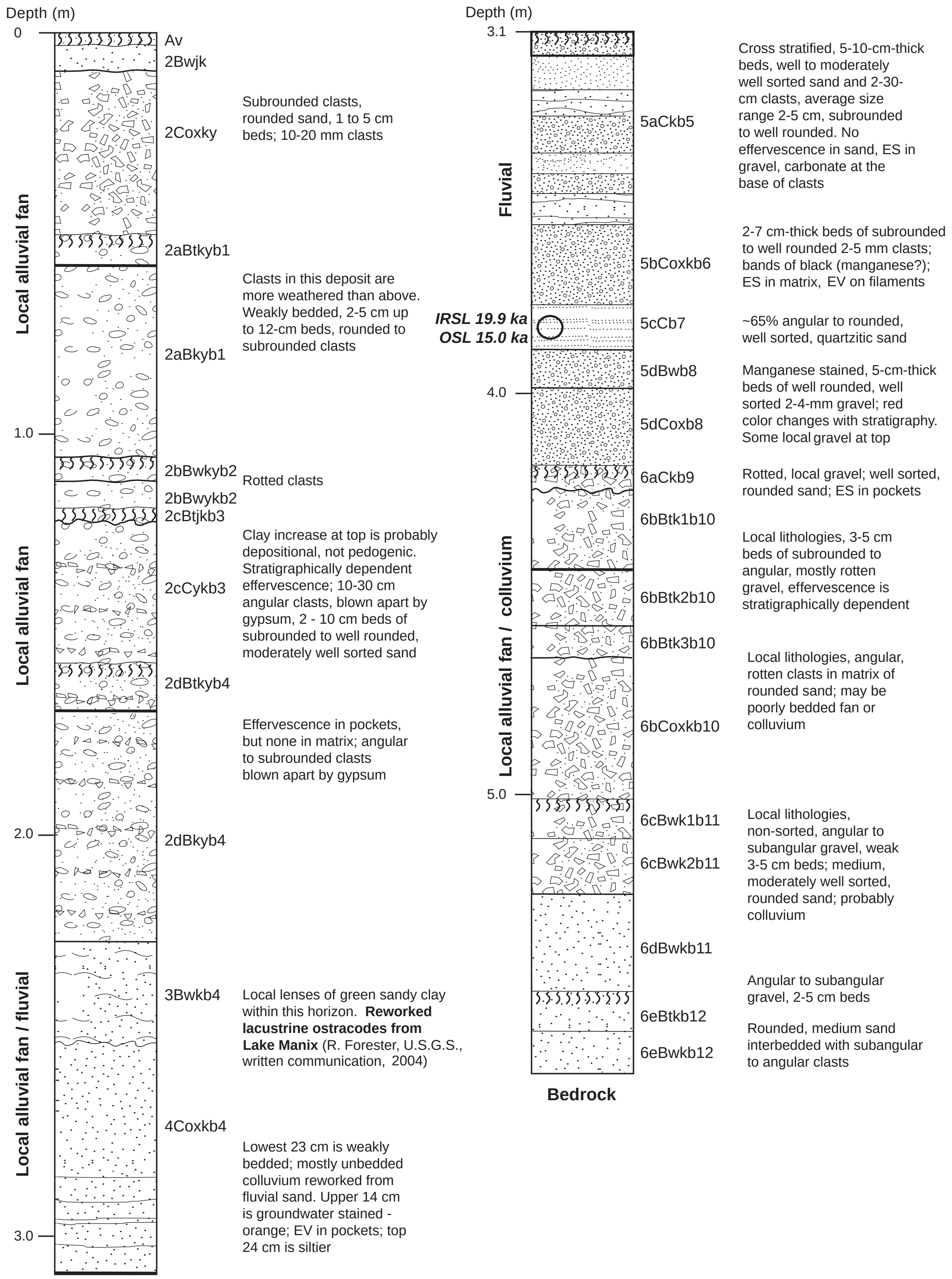

Figure 14. Stratigraphic column of site JR04CM-87. Section represents locally derived alluvium and colluvium overlain by Mojave River gravel and sand and capped by more locally derived alluvium. Reworked lacustrine ostracodes from Lake Manix are found in unit 3Bwkb4. Six soils overlie unit 5Cb7, the location of infrared stimulated luminescence (IRSL) and optically stimulated luminescence (OSL) samples with age estimates of ca. 14–12 ka, likely a large underestimate of age compared to soil development and normalized profile development indices (PDI) values (Tables 2 and 3); see text for discussion. Nomenclature follows U.S. Department of Agriculture soil description rules (Soil Survey Staff, 1975) except a lowercase letter is added after numeral for parent material in order to distinguish separate deposits within one type of parent material (e.g., 2dBtkyb4—second parent material, d—fourth deposit, B—B horizon, b4—fourth buried soil). E—effervesces; ES—effervesces strongly; EV—effervesces violently.

are similar in appearance and preservation to the straths below the canyon rim. The lower terrace slopes down from ~510 masl to ~490 masl at the rim (site JR04CM-84; Table DR1 [see footnote 1]). Clasts within the thin (<2 m) deposits that cap these straths include well-rounded quartzite, volcanic, and igneous pebbles mixed with angular to subangular clasts, which mostly were derived from the metamorphic rocks upslope. A shallow pit excavated on the best-preserved surface exhibited weak soil development and a horizon sequence of Av/Bwk/Coxk and stage I $CaCO_3$, similar to soils developed on the lower terraces.

Lake Mojave Deposits

The time of arrival of Mojave River water in the Soda Lake subbasin of Lake Mojave (Fig. 1) is an important piece of the puzzle regarding discharge from Lake Manix. All of the cores with detailed stratigraphy and ^{14}C ages studied previously are within the Silver Lake subbasin (Brown, 1989; Enzel, 1990). Wells et al. (2003) pointed out that this subbasin lies downstream of Soda Lake and a shallow bedrock sill that, prior to extensive sedimentation in the Soda Lake subbasin, could have prevented Mojave River water from entering Silver Lake subbasin. Based on core sedimentation rates, Wells et al. (2003) estimated that Lake Mojave waters first arrived in the Silver Lake subbasin at ca. 26 cal ka. Wells et al. (1989) and Brown (1989) used sediment borehole data to suggest that Soda Lake subbasin could have held ~7 km^3 of water prior to sedimentation from upstream, and Meek (1990) estimated that Lake Manix held ~3.2 km^3 of water at the 543 m highstand, so an incipient Lake Mojave could have been held in Soda Lake subbasin for a long time provided there was no failure of the Lake Manix threshold.

Several long cores were drilled in the Soda Lake subbasin in the 1950s (Muessig et al., 1957) to depths of 24–326 m. Parts of the core from Soda-1, located in the central part of the playa, are preserved in the original core boxes; the sediments are highly desiccated and fragmentary, having been stored in rough conditions and sampled repeatedly by several researchers during the past 50 yr. Brown (1989) and Brown and Rosen (1995) examined this core and the stratigraphic logs from other cores and drill holes (Burnham, 1955; Muessig et al., 1957; Wells et al., 2003); they found evidence of only a single sustained basinwide (including Silver Lake) lacustrine interval at depths between 3 and 36 m below the playa surface. However, logs of drill holes in the southernmost part of Soda Lake and west toward Afton Canyon describe deeper intervals of "blue clay" or "green clay" as well as evaporite minerals that Brown and Rosen (1995) suggested might represent a small moist playa or shallow lake confined to the southern part of the Soda Lake subbasin during the early(?) to middle Pleistocene.

We obtained sediment samples from Soda-1 core at depths between 6.1 and 62.5 m. Those samples that were deeper than 36 m were tan in color and contained no ostracodes; shallower, greenish-gray samples contained abundant ostracodes. Ostracodes concentrated from samples at depths of 25.3 and 26.2 m yielded ^{14}C ages of 18,040 ± 70 and 18,780 ± 80 yr B.P., respectively (Table 1). An extrapolation of these ages suggests that the base of definite lacustrine deposits in Soda-1 could be as old as 30 cal ka, but varying sedimentation rates could produce either older or younger ages for lake onset. These data provide some support for the suggestion (Enzel et al., 2003; Wells et al., 2003) that the late Pleistocene Lake Mojave could have been somewhat older in the Soda Lake subbasin than in Silver Lake.

DISCUSSION

New ^{14}C ages, ranging from older than 50 to 25 cal ka, on samples from stratigraphic contexts in nearshore deposits allow refinement of the chronology of shoreline fluctuations of Lake Manix near 543 masl (Table 1; Fig. 12). The youngest age in the Afton subbasin is ca. 25 cal ka; although this sample represents reworked shell fragments in eolian sand well above the 543 m highstand, the fragments were likely derived locally and thus probably represent a nearby lake at an unknown altitude. At Dunn wash and the North Afton beach ridge, ages are ca. 33–30 cal ka on the uppermost lake unit and ca. 40–35 cal ka on the next lower unit, both of which can be traced to an altitude of ~543 masl in Dunn wash. The oldest unit beneath a moderately developed buried soil extends to at least 539 masl and has finite but minimum limiting ages of >50–44 ka. Farther west in the Cady subbasin, *Anodonta* shells at the base of the youngest lake unit at two sites yielded ages of ca. 27–26 cal ka (Fig. 12). At Buwalda Ridge (Figs. 2 and 5), a sandy unit on the north side of the fault yielded a ^{14}C age of ca. 38 cal ka; this unit may be the same as that which forms the higher beach ridge at 547 masl north of the Manix fault and that is buried on the south side of the fault. Meek (1990, 2000, 2004) interpreted clusters of ^{14}C ages on lacustrine tufa and *Anodonta* shells to indicate two highstands of Lake Manix at ca. 36–33 cal ka and 26.5–21.5 cal ka that reached ~543 masl; he also thought that an older highstand shortly after 80 ka (single U-series age on tufa) may have reached a similar altitude. A few of Meek's (1990, 2000) ages were obtained using accelerator mass spectrometry (AMS), but most were conventional ^{14}C ages. We suggest that our consistent and somewhat older AMS ages reflect a more accurate assessment of the timing of three lacustrine highstands at ca. 40–35, 33–30, and 27–25 cal ka.

Remnants of beach barriers and lag gravels with well-varnished desert pavements and moderately developed soils range in altitude from 547 to 558 masl and are found within the Afton, Cady, and Troy Lake subbasins on both sides of the Manix fault at locations separated by as much as 30 km (Figs. 2, 3, and 5; Table DR1 [see footnote 1]). These relations indicate that the high shoreline features cannot be attributed solely to displacement along the Manix fault, and they must represent one or more highstands that preceded the 543 m highstands in the Lake Manix Basin. The crests of subdued beach barriers found at the Soldier Mountain and Troy Lake sites, farthest from the Manix fault, are at identical altitudes of 549 masl; the similar barrier at Buwalda Ridge lies at 547 masl, suggesting either natural variation in beach crest height or some tectonic displacement if all these beach barriers represent the same highstand. Such down-to-the-north local displacement on the left-lateral Manix fault (McGill et al., 1988) is consistent with our observed drag of lacustrine sediments along the west end of Buwalda Ridge. Lake sediment is preserved at and below 547 m at Shoreline Hill in Afton subbasin. A higher and perhaps older lake highstand at ~555–558 m is suggested by a tombolo at the south end of Troy Lake subbasin and by a lag of rounded clasts in the embayment south of the Mojave River, as well as wave-cut scarps between 550 and 558 masl in the Manix and Afton subbasins.

Soil profiles developed on the 547 m beach barriers at Buwalda Ridge and Troy Lake sites in both surface and buried positions (Tables 2 and 3) indicate that these barriers are significantly older than the late Pleistocene 543 m barriers. Normalized PDI values for the higher barriers are 0.07–0.19, in contrast to PDI values of ~0.04–0.06 for the 543 m beach barrier at Buwalda Ridge and 0.01–0.02 for the barriers near Afton exit. These index values suggest that the 547 m shoreline may be at least twice as old as the latest 543 m highstand, assuming roughly linear rates of soil development, which are documented for many arid soil chronosequences (e.g., Reheis et al., 1989, 1995). Comparisons with soil data from the Silver Lake chronosequence (Reheis et al., 1989; McFadden et al., 1992) to the east also suggest that the 547 m barrier is at least twice as old as alluvial fans dated at ca. 13 ka and about the same or older than fans thought to be >35 ka. These relative ages, though not well constrained and subject to intrinsic soil variability, suggest that the 547 m shoreline could be equivalent to one of the older buried units in Afton subbasin, most likely that dated as >50 ka (Figs. 4 and 12).

The old, buried fluvial deposit and two lower strath terraces at sites JR04CM-87, JR04CM-88, JR04CM-85, JR04CM-84, and JR04CM-82 (Figs. 3, 13, and 14) downstream of preserved lake deposits represent discharges from Lake Manix that predate the major incision of Afton Canyon. On the basis of PDI values of the many buried soils (Table 3), we estimate that the uppermost fluvial unit (overlying summed PDIs = 0.24) was coeval with or older than the 547 m beach barrier at Buwalda Ridge, and that the period of fluvial aggradation (summed PDIs = 0.04) in the discharge channel could have lasted 20 k.y. or more. We suggest that lakes at the higher shorelines above 543 masl were producing threshold-controlled discharge at the level of the Afton Canyon rim for a long period of time, possibly during OIS 4 and (or) OIS 6 as previously speculated by Jefferson (1985). This discharge may have been sufficient to maintain a small perennial lake or marsh in the southern end of Soda Lake Basin, as suggested by the presence of green and blue clays at depths greater than the lacustrine clays to the north associated with the known Lake Mojave (Brown, 1989; Wells et al., 2003).

Threshold-controlled discharge from Lake Manix would probably have been limited in amount and might have been seasonal, given the high evaporation rates likely in this desert region even during pluvial periods. Local evaporation rates during the Last Glacial Maximum are estimated to have been reduced ~50% from modern rates (~3–4 m/yr) by comparing present pan evaporation data for nearby sites at different altitudes and mean annual temperatures (data from California State Department of Water Resources, 1979). Such discharge may have been maintained intermittently for a long period without drastic downcutting, as is suggested by the aggrading fluvial deposit at site JR04CM-87, despite the eastward gradient that was likely present (Fig. 8B). If we assume that this deposit was graded to the modern level of the blue-green clays in boreholes in southern Soda Lake Basin, and there was no subsequent vertical tectonic displacement, we calculate an average straight-line paleoslope of 1°. This value is not much higher than the present average slope of 0.5° of the Mojave River channel in this reach, and it is similar to the slopes of many distal portions of aggrading alluvial fans.

The stability of the discharge channel at site 87 would also have been favored by its location atop metamorphic rocks, which also underlie the nearest preserved lacustrine deposits just to the west (Fig. 13A). The highest preserved fluvial deposits lie just uphill from the shear zone of an east-striking fault that parallels the Manix fault, and the lower strath terraces lie on Tertiary fanglomerate south of the shear zone (Danehy and Collier, 1958; J.L. Redwine, 2007, unpublished geological mapping). A slight shift of the outlet to the south or headward erosion from the east along the Manix and nearby faults could easily have resulted in discharge and subsequent incision being concentrated along shear zones in weakly cemented fanglomerates.

Two saddles in the south rim of Afton Canyon (Figs. 13B and 13C) have been suggested as possible pathways for discharge from Lake Manix via Baxter Wash (Fig. 2), which drains to the Soda Lake subbasin (Weldon, 1982; Meek, 1990; Wells and Enzel, 1994). Presently, the lowest of these saddles (site M03-45; Fig. 3; Table DR1 [see footnote 1]) is at ~534 masl, and the buried fluvial deposits north of Afton Canyon are at 538 masl, which would permit drainage to the south through this saddle if present altitudes have not been affected by faulting. However, we have found no physical evidence of Mojave River deposits in or near the saddles or anywhere down Baxter Wash (J.L. Redwine, 2007, unpublished geological mapping). Previous inferences appear to be based solely on the size of the wash and the presence of saddles in the rim. Our observations indicate that Baxter Wash is just as wide above and west of the saddles as it is to the east; the saddles are erosional surfaces cut on relatively unresistant Tertiary conglomerate and mudstone (Figs. 13B and 13C), and no extralocal rounded clasts are present. The proximity of the strath terraces above the rim to the buried fluvial deposit and their descent toward the present canyon to an altitude as low as 490 m (Fig. 13A) suggest that the drainage must have been below the south rim and in approximately its present course when final downcutting began. These high nested straths also suggest that initial incision was not catastrophic, as proposed by Meek (1989, 2000).

Stratigraphic relations and soils in deposits associated with strath terraces, combined with similar soil profiles and surface characteristics among the strath terraces at many altitudes both above and below the canyon rim, suggest that incision of the canyon proceeded quickly but with hiatuses. Cosmogenic exposure dating techniques would be required to explore these relations more fully. We have found no unequivocal remnants of recessional shorelines, as suggested by Wells and Enzel (1994) and Enzel et al. (2003), to suggest lake stillstands during incision.

We suggest that the higher straths above the rim formed no later than ca. 25 cal ka, the age of eolian sand reworked from nearshore deposits in the Afton subbasin. We interpret the soils, stratigraphy, and fluvial landforms in the canyon to indicate relatively rapid incision of Afton Canyon to the depth of the bedrock floor, followed by intermittent, more gradual bedrock incision. An earlier discharge and, possibly, sediment delivery to Soda Lake are suggested by an estimated 30 cal ka age for the onset of lacustrine deposition in that subbasin based on extrapolation of ^{14}C ages from core Soda-1 (Fig. 12). If discharge did occur as early as 30 ka, it did not cause significant erosion of the Lake Manix threshold, because our youngest age in deposits associated with the 543 m shoreline is ca. 25 ka (Table 1; Fig. 2). However, deposits dated at 23.5 cal ka (Dudash and Miller, 2005; Dudash, 2006) are interpreted to record lake-level decrease in the Coyote Lake subbasin. This age adds definition to previous conclusions by Meek (1990) that headward erosion caused by incision of Afton Canyon had progressed far enough west that the Mojave River could still enter Coyote Lake by migration across its fluvial fan (Fig. 2) but otherwise flowed east to Lake Mojave.

CONCLUSIONS

A combination of detailed mapping, ^{14}C dating, and studies of stratigraphy and soils associated with lacustrine and fluvial deposits permits revision of the middle(?) to late Pleistocene history of Lake Manix and the record of downstream integration by the Mojave River in its lower reaches. The beginning of eastward discharge by the Mojave River in the Afton Canyon area was possibly as early as OIS 6, almost certainly by OIS 4 (ca. 80–60 ka); at this time, the river began to provide water, probably intermittently, to a proto–Lake Mojave in the southern Soda Lake subbasin. Such discharge may represent the first opportunity for aquatic species to migrate between these areas since the onset of extensional tectonics in the late Miocene. Our studies indicate the following conclusions and testable hypotheses:

1. Lake Manix reached a highstand of 547–558 masl at least twice prior to its previously known 543 m highstands. Properties of soils formed on beach barriers at 547–549 masl and ^{14}C ages of deposits possibly associated with these barriers suggest an age of 35–50 ka or older for this highstand. Scarps, one beach barrier, and lagged beach gravel extending to 558 m may represent an even older and higher shoreline.

2. Roughly at the time of the 547–549 m highstand, Lake Manix episodically overflowed down a spillway presently located on the north rim of Afton Canyon at 539 masl, downstream of the probable lake threshold. Fluvial aggradation in this drainageway may have persisted intermittently for 20 k.y. or longer, as indicated by weak buried soils formed on several beds of fluvial sediment exposed in two outcrops. The intermittent discharge may have sustained a small lake or marshy area in southern Soda Lake. This episode of discharge was followed by a period of relative stability without dramatic incision of Afton Canyon, during which the fluvial deposits were buried by a series of thin alluvial-fan deposits and paleosols.

3. Initial downcutting in Afton Canyon is marked by the formation of two strath terraces inset below the highest fluvial deposits but still above the present canyon rim. Surface properties and relatively weak soil development suggest that these terraces are not significantly older than the strath terraces that are inset well below the rim and below the basal lake sediments in the Afton subbasin. Thus, these higher straths probably formed no later than ca. 25 cal ka, the youngest age of eolian sediments derived from nearshore deposits in the Afton subbasin.

4. Soils and surface properties of the strath terraces within Afton Canyon and comparison to soils on dated deposits in the Manix and Silver Lake area indicate that all the terraces are latest Pleistocene to early Holocene in age, confirming Wells and Enzel's (1994) conclusion that most of the canyon incision was accomplished by mid-Holocene time. Interbedded colluvial and fluvial deposits with incipient soils suggest that this post–543-m-highstand incision did not occur at a constant rate. In addition, intermittent discharge during pre–543 m highstands could have contributed to erosion above the present canyon rim.

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