Environments of nearshore lacustrine deposition in the Pleistocene Lake Manix basin, south-central California

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ABSTRACT

Lake Manix, in the central Mojave Desert of southern California, was the terminus of the Mojave River from about 500 to 25 ka. Deposits of this lake provide excellent examples of depositional environments of a low-desert, clastic-dominated lake sustained by a mostly perennial river, a setting atypical for most Great Basin pluvial lakes. We characterize and provide examples of the nearshore environments of deposition of Lake Manix, which include extensive low-gradient fluvial-deltaic and mudflat deposits and ephemeral alluvial-fan—lake-marginal deposits, to aid in their recognition in other settings and in the geologic record. The sedimentary character and stratigraphic architecture of these nearshore deposits depend on proximity to the mouth of the Mojave River, to position on fringing alluvial fans, to steepness of fan slope, and to presence of active channels. Recognition of these nearshore deposits, some of which are enigmatic or difficult to recognize, in the geologic record may provide valuable information on response of desert lakes to past climate change.

INTRODUCTION

Deposits of paleolakes have been studied for well over a century (e.g., Russell, 1885; Gilbert, 1890; Morrison, 1991; Adams, 2007). Characterization of lake sediments and stratigraphy provides information on age, hydrologic environments (water temperature and chemistry), water depth, relations to feeder streams, and basin evolution. Sedimentary and chemical facies of lakes also provide analogues for interpretation of ancient sediments in the rock record (e.g., Smith and others, 1983; Lowenstein and others, 1999; Adams, 2007; Waldmann and others, 2009). The large pluvial lakes in the Great Basin, such as Lakes Bonneville, Lahontan, Russell, and Owens, have been magnets for geological investigations of both outcrops and cores. These lakes lie in the higher, less arid part of the Great Basin, received direct runoff from extensive mountain glaciers, and were fed by sizable rivers. Nearshore deposits of these lakes, such as beach barrier and deltaic complexes along steep range fronts, have been thoroughly studied (Russell, 1885; Gilbert, 1890; Komar, 1997; Adams and Wesnousky, 1998).

In contrast, only a few sedimentologic studies have targeted lake basins in the southern low deserts of the Great Basin, and none have focused on nearshore deposits other than beach complexes. Southern lake records include Lake Estancia, in central New Mexico (outcrop studies summarized in Allen and Anderson, 2000) and Lake Babicora of Chihuahua state in Mexico (coring studies by Metcalfe and others, 2002). Neither was sustained by substantial rivers, and Babicora lay at relatively high altitude (~2140 m). In the low Mojave Desert, well-characterized pluvial lakes include Lake Mojave (Enzel and others, 1992; Wells and others, 2003), the present terminus of the Mojave River (Fig. 1), and Lakes Searles, Panamint, and Manly (Smith, 1976; Smith and others, 1983; Forester and others, 2005; Jayko and others, 2008; Knott and others, 2008; Phillips, 2008), along the episodic overflow route of the Owens River and, for Lake Manly, the Amargosa River. Most sedimentologic interpretations of the latter three lakes focus on the features in their deep-water settings and especially chemical precipitates as seen in cores.

Lake Manix, the terminal basin of the Mojave River from about 500,000 to 25,000 years ago (Jefferson, 2003) (Figs. 1 and 2), was sustained by the Mojave River, which sources in the Transverse Ranges. During historic time, and likely during much of the Holocene, the Mojave River was not a perennial stream in its lower reaches (below Victorville; (Enzel and Wells, 1997). Short-duration Holocene lakes that formed in the Silver Lake basin are interpreted to have been sustained by extreme winter storms in the headwaters that were sustained over years to decades (Enzel and others, 1992; Enzel and Wells, 1997). Enzel and others (2003) inferred that sustaining a lake during the late Pleistocene, when evaporation rates were reduced and transmission losses to groundwater may have been lower, would have required an average annual discharge at least an order of magnitude larger than today. Although Lake Manix was farther upstream in the fluvial system than the younger Lake Mojave, and likely had lower transmission losses as a result, river inputs that sustained Lake Manix were almost certainly highly variable. Preliminary results from outcrop study and from analysis of sedimentology and stable isotopes in the Manix core suggest large variability in lake level on timescales ranging from possibly seasonal to millennial (Reheis et al., 2009a, b). Variable river input, combined with relatively high evaporation rates in this low-desert setting, would have caused lake level to fluctuate continually and would have created dynamic and generally unstable nearshore environments.

The general history of Lake Manix was established by Jefferson and Meek (Ellsworth, 1932; Meek, 1990, 2000; Jefferson, 2003; Meek, 2004), and our recent mapping, stratigraphic studies, and dating (Miller and McGeehin, 2007; Reheis and others, 2007b; Reheis and Redwine, 2008; Reheis and others, 2009a, 2009b) have added much new information. The Manix basin contains a spectacularly well-exposed record of lake fluctuations in settings that are somewhat atypical for Great Basin pluvial lakes, in that they include extensive low-gradient fluvial-deltaic and mudflat deposits, as well as ephemeral alluvial-fan—lake-marginal deposits. The exposures are unusual because the lake drained by threshold failure, with stream flow eventually cutting into the floor of the lake, incising lake deposits in a wide variety of geomorphic settings. The purpose of this short paper is to characterize and provide examples of the nearshore environments of deposition of Lake Manix, to aid in their recognition in other settings and in the geologic record. We make no attempt to provide detailed sedimentologic or stratigraphic characteristics or to adopt formal basin-analysis procedure, as these are abundantly well documented in textbooks (e.g., Reading and Collinson, 1996; Talbot and Allen, 1996; Komar, 1997) and research papers. Rather, our intent is to point out some unique depositional features of this low-desert, fluvially controlled lake.

NEARSHORE ENVIRONMENTS OF LAKE MANIX

Throughout the geologic history of Lake Manix, the lake interacted with a variety of depositional settings influenced by proximity to the Mojave River, the amount of alluvial activity, surface slope, and basin configuration. There was an abrupt contrast in sedimentary environments near the migrating mouth of the Mojave River and the rest of the basin's margins, which are alluvial fans modified in places by eolian deposits. The Manix basin consists of four interlinked subbasins (Fig. 2). Although all of these subbasins are traversed by faults, some of them active as recently as the Holocene, their margins are not fault-bounded; hence, most of the nearshore environments are characterized by fluvial and alluvial-fan and locally, eolian sediments. Three exceptions of steep topography adjacent to the lake are (1) the south face of Buwalda Ridge, which is underlain by Pliocene fanglomerate that is bounded by the Manix fault, (2) the north face of Soldier Mountain, and (3) the eastern end of the Afton subbasin, where the lake abutted the bedrock of Shoreline Hill and slopes to the south. The Cady and Troy Lake subbasins are the ones that lay nearest the entry point of the Mojave River, and thus their sediments record interaction of the lake with the encroaching fluvial fan of the Mojave River, as well as with alluvial fans of local drainages. The Coyote Lake subbasin, surrounded by alluvial fans, is separated by a shallow bedrock sill from the Cady subbasin (Meek, 1990), and hence served as a release valve for high lake levels in the rest of the Manix basin. As such, Coyote Lake was shallow or even dry during part of the history of Lake Manix. The Afton subbasin is most distant from the Mojave River inlet, and is bounded on the north and south by alluvial fans. On the east end, this subbasin is characterized by steep margins with relatively high-gradient fans and bedrock. The Afton subbasin was abruptly integrated into Lake Manix shortly before the deposition of the Manix tephra (Reheis and others, 2007b; Reheis and others, 2009a) at about 185 ka (Jefferson, 2003).

The depositional environments of Lake Manix are subdivided on the basis of adjacent deposits and their gradients as follows: (1) deltaic, interacting with fluvial inputs of the Mojave River, either proximal or distal to the river mouth; (2) interacting with active alluvial fan channels of either gentle or steep gradients; (3) interacting with alluvial-fan deposits with no active channels, with gentle or steep gradients; and (4) interacting with talus and very steep fans along mountain fronts. These interactions resulted in characteristic suites of sediments and stratigraphic architectures, many of which of course overlap among these groups.

Fluvial-deltaic (?) deposits

Fluvial-deltaic(?) deposits at the junction of the perennial Mojave River and Lake Manix are abundantly exposed along the northern bluffs of the modern Mojave River near and west of the core site (Fig. 2). They form the uppermost ~8-10 m of outcrop, were described as “Member D” of the Manix Formation by Jefferson (2003), and accumulated between about 50 and 25 ka

(Miller and McGeehin, 2007; Reheis and others, 2007b). These deposits form nearly parallel-bedded exposures on faces parallel to the modern Mojave River (Fig. 3A), that is, oriented parallel to past streamflow, and form notably lenticular deposits in faces perpendicular to stream flow. Lenses fill channels cut into adjacent deposits and into the top of older Lake Manix deposits, and generally channels are draped mud and sand interpreted as overbank deposits. The overbank deposits fine upward from pebble gravel to mud beds with rip-up mud balls common near the base and mudcracks common at the top. The sand beds in places contain calcium-carbonate nodules and plates (Fig. 3B) that we interpret as forming from groundwater discharge. Most beds are composed of grussy sand and fine gravel, with less common mud beds and laminae (Figs. 3C and D); the clast composition indicates deposition by the Mojave River. Sedimentary facies and structures are largely fluvial and include “cross-bedded channel-fill deposits, crevasse-splay deposits, marsh, and floodplain deposits” (D. Miller, p. 23-24 in Reheis et al., 2007). The rare beds that least ambiguously indicate lacustrine deposition are planar-bedded very thin beds of well sorted fine sand (Fig. 3B), some of which are diatomaceous. Intervals of poorly sorted sand and silt, including armored mud balls, are locally observed in the Manix core (Fig. 4A). Poorly sorted sands and those with curving crossbeds are interpreted as fluvial, whereas well sorted, ripple-bedded sands are interpreted as lacustrine (Fig. 3B). Thin intervals (10-20 cm) of very well sorted, sometimes gently dipping, sand and silt are also interpreted as lacustrine deposits (Fig. 4B), and small intervals of steeply dipping deltaic foreset beds are present (Reheis et al., 2007). Moderately sorted, planar-bedded sands (basal sand, Fig. 3D) may represent either lacustrine or fluvial deposition. Beds with abundant *Anodonta* shells are locally observed in these deposits and have provided radiocarbon ages. However, *Anodonta* occupy both fluvial and lacustrine habitats, and were historically present in the Mojave River (reported in Meek, 1990); thus, their presence is not diagnostic of depositional setting. Fish fossils (*Gila bicolor mojavensis*; Jefferson, 2003) and lacustrine ostracodes (Steinmetz, 1987; Bright and others, 2006), have been identified in older, finer-grained sediments of Lake Manix and also in younger lacustrine sands in the Afton subbasin (J. Bright, Northern Arizona Univ., written commun., 2007), but have not been reported in the fluvial-deltaic deposits. Rare beds contain lacustrine diatoms (*Stephanodiscus* sp.), which are common in large freshwater, eutrophic lakes (S. Starratt, U.S. Geological Survey, written commun., 2007).

The limited presence of clearly lacustrine sediment and classic Gilbert-type delta foreset and bottomset beds and the dominance of fluvial sedimentary features suggest that these deposits represent mainly fluvial aggradation, with temporary transitions to a fluvial-dominated delta on a gently sloping lake margin with shallow lake depths. In addition, the frequent 5-15-m fluctuations in lake level during the period of deposition of these deltaic sediments (Reheis and others, 2009b) would have resulted in significant fluvial reworking, during lower lake levels, of any lacustrine sediment deposited at higher lake levels. The dominant westerly wind regime in this region also would have limited reworking by wave action at this western edge of the lake with minimal fetch. Similar deposits in the rock record, with limited occurrence of clearly nearshore or deltaic features, would likely not be recognized as being proximal to a lake.

Distal fluvial-deltaic and mudflat deposits are well exposed in the upper part of Jefferson's (2003) "Member C" along the bluffs of the Mojave River and Manix Wash (Fig. 2). Although Jefferson interpreted most of these sediments to represent relatively high lake levels, detailed study of equivalent intervals in the Manix core and in outcrop suggests instead that they represent shallow lacustrine to mudflat environments, with short intervals of deeper water, and reflect proximity to sediment inputs from the Mojave River (Oviatt and others, 2007; Reheis and others, 2007a). The primary reason for the change from relatively deep-water sedimentation recorded in older deposits to shallow water and mudflats in “upper C” is the shift of the lake depocenter to the newly incorporated Afton subbasin just prior to 185 ka (Reheis and others, 2007a; Reheis and others, 2009a). Because much of the accommodation space in the older part of the lake basin had been filled with Mojave river sediment, the area of the lake bottom at the Mojave River-Manix Wash confluence was frequently exposed as a mudflat or playa after the depocenter shift, and was only submerged to moderate depths when Lake Manix approached highstand levels. In addition, proximity to the encroaching front of the Mojave fluvial fan increased the frequency of incursion of fluvial sediment during low to moderate lake levels.

The distal deltaic and mudflat deposits typically consist of normally graded sequences of sand, silt, and clay (Figure 5A). The basal arkosic, coarse to medium sands are commonly oxidized and locally cross-bedded. In some intervals they grade up through thinly bedded and sorted, pale gray, very fine sand and silt to laminated clay and silt, suggesting delta-front sedimentation. In other intervals interpreted as fluvial sedimentation on a mudflat surface, possibly from a single flooding event, the sands grade up through brown muddy sand and sandy mud to blocky clay with burrows and sand-filled cracks. Some fine-grained beds appear contorted and brecciated, and some sand beds are mixed with rip-up mud clasts. Muds that are cracked and oxidized to a dark red (7.5 to 5 YR colors) are interpreted to represent episodes of soil formation on an exposed mudflat. These sequences differ from sandflats and mudflats previously described for the margins of arid closed basins (e.g., Talbot and Allen, 1996) because of the influence of the Mojave River.

Other mudflat deposits in the Manix basin, such as in the Coyote subbasin (Fig. 5C) share some characteristics with the distal deltaic deposits in that they are characterized by rapidly changing, interbedded, fining-upward sand, silt, and clay beds, with the clays cracked and oxidized. However, they lack evidence for fluvial sediment transport, and instead are similar to the sandflat and mudflat environments of other closed-basin lakes (Allen and Anderson, 2000; Wells and others, 2003). In addition, intervals of bedded to massive silt and clay in the older, deeper-water sediments of Lake Manix (unit “lower C” of Jefferson, 2003) are commonly capped by prominent red soils (Fig. 5B), similar to those in the mudflat deposits. These soils resemble vertisols and represent lengthy subaerial weathering on desiccated lake sediments.

Active fan-lake interface deposits

Active alluvial fans are characterized by ephemeral drainages that episodically transport water and sediment. Due to the dynamic nature of the fan channels, which may shift laterally across the fan, the episodic nature of runoff, and the rapid lake-level fluctuations, the fan-lake margin is a very dynamic environment. The sedimentary structures and stratigraphic architecture of these environments around the Manix basin depend primarily on slope. Previous studies have not well characterized such deposits formed in low-gradient settings.

Gently sloping active fan-lake margins are characterized by sediments that strongly resemble clast-supported alluvial-fan sediments. However, close examination reveals that in some beds, the sediments have been modified by lacustrine processes and (or) contain lacustrine fossils such as *Anodonta* shells and lacustrine ostracodes. Such sequences are well exposed in the upper reaches of Dunn wash, in northeastern Afton subbasin (Figs. 2 and 6; Reheis and Redwine, 2008). Here, the upper several meters consist of gravel and sand atop an erosional unconformity channeled into older, fine-grained lacustrine sediment (Fig. 6A). The gravelly deposits exhibit rapid lateral and vertical changes in bedding and sorting characteristics, but individual beds are laterally continuous and can be traced 25 m or more along outcrop unlike typical lenticular-bedded fan deposits. The dominantly fluvial units consist of planar-bedded coarse sand to cobble gravel and in places, exhibit alluvial clast imbrication indicating downslope flow (Fig. 6C). Due to shifting fan channels and lake levels, fluvial channel fills may be inset within dominantly lacustrine sequences. Fluvial units that have been modified by nearshore processes have similar grain-size distribution, but are better sorted and somewhat better bedded (Fig. 6B). As a result, they are commonly looser and less indurated than the purely alluvial units because they have fewer fines mixed with the coarser sediment. Lake-reworked fluvial deposits are typified by thin lacustrine tufa coats on clasts, especially at the base of each unit, locally contain *Anodonta* shells, and may fine upward into muddy sand. In addition, they may exhibit gently dipping foreset and backset beds of a barrier beach (Fig. 6B).

Steeply sloping active fan-lake margins are similar to the gently sloping margins in that they are characterized by lake-modified alluvial deposits. Although such deposits locally exhibit tufa coats on clasts, they rarely contain fossils due to the higher-energy environment, and must be recognized on the basis of bedding, sorting, and stratigraphy. Such deposits are abundantly exposed in the deeply dissected drainages around and north of Shoreline Hill, in the eastern end of the Afton subbasin (Fig. 2). Here, an alluvial-fan complex was built on the steep eastern flank of Cave Mountain. After the integration of the Afton subbasin into Lake Manix, the style of deposition shifted abruptly from that of coarse, angular clast-supported and debris-flow beds, with common buried soils formed during periods of stability, to shoreline-modified fluvial beds (Fig. 7; Reheis et al., 2007b). Site M06-135 is unique in this area in exposing the architecture of a Gilbert-type fan-delta and sub-lacustrine bar. The basal unit consists of interbedded moderately sorted, well-bedded medium to coarse sand and pebble to cobble gravel; the clasts have thin scattered tufa coats, but the gravelly beds form channel fills (Fig. 7B). To the left and right, however, the channel gravel appears to grade into backset and foreset beds, respectively. Stratigraphically above this unit are sets of fining-upward, well bedded sand and locally, pebble gravel arranged in alternating sequences of bar structures with backset and foreset beds and delta foreset and bottomset beds (Fig. 7A).

Other exposures of the steeply sloping fan-lake environment are more like that at site M06-141, where deposits of two lake cycles overlie dipping, indurated older fan deposits capped by a strong calcic buried soil (“old fan,” Fig. 7C). The basal unit consists of two parts: the lower part is 2 m of stratified, interbedded moderately to poorly sorted sand and lesser angular pebble-cobble gravel, with local thin lenses of sandy mud, interpreted as alluvial-fan deposits at the photograph site; downstream (to the right), however, these beds become sandier and better sorted, suggesting this lower unit was deposited in a lake-marginal setting. This lower part is capped by about 30 cm of coarse gravel with abundant tufa coats, and this in turn is overlain by the upper part, about 2 m of interbedded, fining-upward packets of angular to subangular cobble gravel and coarse to medium sand capped by a buried soil. Beds in this upper part dip 10o and fine in a downslope direction, and are interpreted as delta foresets. The upper unit above the buried soil is overall sandier and better sorted and bedded, but still contains channel-fill gravels.

In summary, active alluvial fan-lake hybrid deposits are expected to vary laterally on scales of tens to hundreds of meters. Indicators of lake interactions can be very subtle, but generally are increased lateral persistence of beds and greater size sorting. Gently sloping fan-lake marginal deposits may preserve lacustrine fossils.

Stable fan-lake interface deposits

Away from active alluvial-fan channels, fan surfaces are relatively stable with little aggradation. On distal fan slopes, intermittent sheetwash flow may cause slow sedimentation such that sediments are generally somewhat oxidized throughout, but soil horizonation is weak to absent. On medial to proximal parts of fans, surfaces are generally stable enough that soils form, with typical desert pavement. These different substrates influence the depositional environment of the fan-lake interface.

Distal fan-lake margins generally exhibit sharp transitions in color, induration, and sorting of sediments from the fan to the lake environment, but little change in overall particle-size distribution (Fig. 8). Distal fan deposits consist mainly of planar-bedded, moderately to poorly sorted silt, sand, and fine-pebble gravel with occasional larger clasts, generally arranged in fining-upward sets and parallel to the fan slope, with little or no channeling apparent. They are generally slightly to moderately indurated. Lake trangression across this surface may or may not produce a single-clast-thick lag deposit (Fig. 8B) that rarely has very thin tufa coats. The transgressive surface is overlain by a generally fining-upward sequence of non-indurated, moderately to well-bedded and sorted pebble gravel, sand, and silt that is planar bedded and may be ripple-laminated (Fig. 8A). The finer sands commonly contain lacustrine ostracodes.

Medial to proximal fan-lake margins are easily recognized by abrupt contacts between oxidized, poorly to moderately sorted, coarse gravelly fan deposits, typically with preserved soils, and overlying reduced, well-bedded, fine-grained lacustrine deposits (Fig. 9). In such cases, the sediment is likely supplied by longshore drift along with minimal reworking of the local fan surface, such that the lacustrine sequence is constructed on top of an inactive fan. The trangressive surface typically has a concentration of clasts with prominent tufa coats (Figs. 9A and B); coats tend to be thicker on larger clasts and where underlain by buried calcic soils. Overlying lacustrine deposits are typically well bedded and sorted, fining-upward pebble gravel, sand, silt, laminated where finer-grained. Some locations (e.g., M05-71, Fig. 9C) exhibit dipping interbedded sand and gravel representing a transgressive beach setting, locally overlain by finer-grained green or brown muddy sand and mud that are interpreted as lagoonal deposits on the landward side of a beach berm.

Mountain-front deposits

Steep bedrock slopes are erosional environments, and lakes that abut such slopes have limited detritus to rework and deposit as well as reduced longshore transport. In addition, sediments that are deposited have low potential for preservation and are probably largely absent from the rock record. At the eastern end of the Afton subbasin (Fig. 2), where wave energy was high due to the long fetch, a few lacustrine deposits that interfinger with talus and very steep small fans are preserved (Fig. 10). These deposits consist of interbedded, moderately bedded and sorted gravel and sand, commonly overlying a wave-eroded shoreline platform cut on rock (Fig. 10A) or fan deposits and locally with tufa-coated clasts at the base (Fig. 10B). The angular clasts show little or no sign of rounding. Fossils are rare or absent due to the high-energy environment, and typically no beach-barrier bedding is preserved.

CONCLUSIONS

Nearshore settings of Lake Manix vary in sedimentary character and stratigraphic architecture, depending on proximity to the mouth of the Mojave River, to position on fringing alluvial fans, or to bedrock. Depositional features are also related to steepness of slope on the fan, presence of active channels, and length of fetch. These lake-marginal features are by no means unique to Lake Manix, but they have not been well characterized for lakes in low-desert settings, where the principal focus has been on interpreting lake fluctuations from cores taken in the deeper parts of the basins. Although some of the settings we have described are enigmatic (i.e., the fluvial-mudflat setting), are initially difficult to recognize (the active fan-lake margin), or have low preservation potential (the mountain-front deposits), valuable information on response of desert lakes to past climate change can be obtained by using such features for reconstruction of lake altitude.

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Figure Captions

Figure 1. Location map of the Mojave River watershed and paleolakes sustained by the river. Modified from Wells et al. (2003).

Figure 2. A, geographic features of the Manix basin, showing subbasins, playas (dotted), the Mojave River fluvial fan, and major faults (modified from Reheis and Redwine, 2005). Medium-weight line is the 543-m highstand level that depicts the minimum extent of Lake Manix during the late Pleistocene; western margin is not known due to progradation during highstands and later burial by Mojave River alluvium. Stars and numbers (eg., 06-135; prefix "M" omitted for convenience) show locations of sites described in text and figures 3-9.

Figure 3. Upper ~8 m of section ("member D" of Jefferson (2003) exposed along bluffs north of river at intersection of Mojave River and Manix Wash. A, weathered outcrop appearance of parallel-bedded sand and intercalated finer sediment consisting of stacked fluvial and minor lacustrine deposits. Most clearly fluvial sand is oxidized (darker bands). Pack for scale at top. B, ripple-bedded laminated fine sand (lacustrine) overlain by wavy white bands of ground-water carbonate, in turn overlain by poorly sorted coarse sand (fluvial). C, crossbedded sands with thin mud drapes. In lower part, beds fine upward; in upper part, beds coarsen upward from a basal mud. D, basal coarse, planar-bedded sand is overlain by mud rip-ups, then by pale cross-bedded well-sorted sand, in turn capped by more mud rip-ups. Photos by D. Miller.

Figure 4. Fluvial-deltaic (?) and nearshore sediments photographed in the Manix core. Depths below surface shown in headers; scale in cm. A, core segment MX-3; note 10-15° dips in bottom half. B, core segment MX-7; note laminated sand in middle of core and brown laminated silty clay at base. Photos by J. Honke (U.S. Geological Survey).

Figure 5. Distal fluvial-deltaic and mudflat deposits. A, segment MX-11 of the Manix core shows fluvial fining-upward sequences with clay rip-ups and mudcracks. Photo by J. Honke, U.S. Geological Survey. B, oscillating shallow-water and mudflat deposits exposed on the southeastern margin of the Coyote Lake subbasin. Numbers mark 10-cm increments on scale. Photo by D. Miller. C, vertisols formed on desiccated lake sediments. Shovel and meter stick for scale. Photo by J. Oviatt (Kansas State University).

Figure 6. Deposits of gently sloping active fan-lake margins. A, measured section M05-19 in upper Dunn wash at the pipeline crossing (modified from Reheis and Redwine, 2008). Black circles are lines of tufa-coated clasts; size of circle proportional to tufa thickness. Ticks on horizontal lines represent buried soils. M05-19I is a radiocarbon age obtained from *Anodonta* shell. B and C, photographs keyed to measured section; note barrier-bar structure with backset and foreset beds in second unit from base. Dashed lines are unit boundaries commonly marked by tufa-coated clasts; only the lowest unit is alluvial. 50-cm trenching shovel for scale in both photos. Photos by M. Reheis.

Figure 7. Deposits of steeply sloping active fan-lake margins. A, fan-delta and offshore-bar features exposed at site M06-135, east of the North Afton beach ridge. This section, oriented nearly N-S, lies at an oblique angle to SW-trending depositional slope, thus apparent bedding dip is low; where parallel to depositional slope, basal fan deposits slope ~7° basinward. Modified from Reheis et al. (2007b). B, closeup of bedding in part of upper photograph. 50-cm trenching

shovel for scale. C, fan-delta deposits exposed at site M06-141 just north of Shoreline Hill; note rightward dip of gravel beds in middle unit. Photos by M. Reheis.

Figure 8. Deposits of distal fan-lake margins. A, distal-fan and overlying nearshore sediments at site M06-81 near Midway wash. Nearshore sediments are capped by a thin distal-fan unit and another transgressive sequence with laminated, deeper-water muds at top. Geologist, dog, and daypack for scale. B, distal-fan and overlying nearshore sediments at site M08-131 on the east side of Manix Wash. Note transgressive lag of tufa-coated pebbles and cobbles at base. 50-cm trenching shovel for scale. Photos by M. Reheis.

Figure 9. Deposits of medial to proximal fan-lake margins. A, photograph of basal part of section M05-19 (see measured section in Fig. 5A). 50-cm trenching shovel for scale. B, beach sand and gravel overlie tufa-coated clasts at top of a prominent, red calcic soil formed on alluvial-fan gravel; many clasts are rotted. 20-cm trowel for scale. C, measured section M05-71 on east side of North Afton beach ridge. Beach gravel was deposited during initial transgression over calcic soils formed in massive eolian (?) sand. Photos by M. Reheis.

Figure 10. Deposits of mountain-front—lake margins. A, view to north showing two buried wave-cut platforms separated by a wave-cut scarp on bedrock at site M06-50. Platforms are overlain by interbedded lacustrine sand and gravel (very thin on the upper platform). Mid-ground field of view about 75 m across. B, tufa-coated angular clasts reworked from talus slope up to a wave-cut scarp on bedrock at site M06-51, just south of the previous site. 2-m white antenna for scale. Photos by M. Reheis.

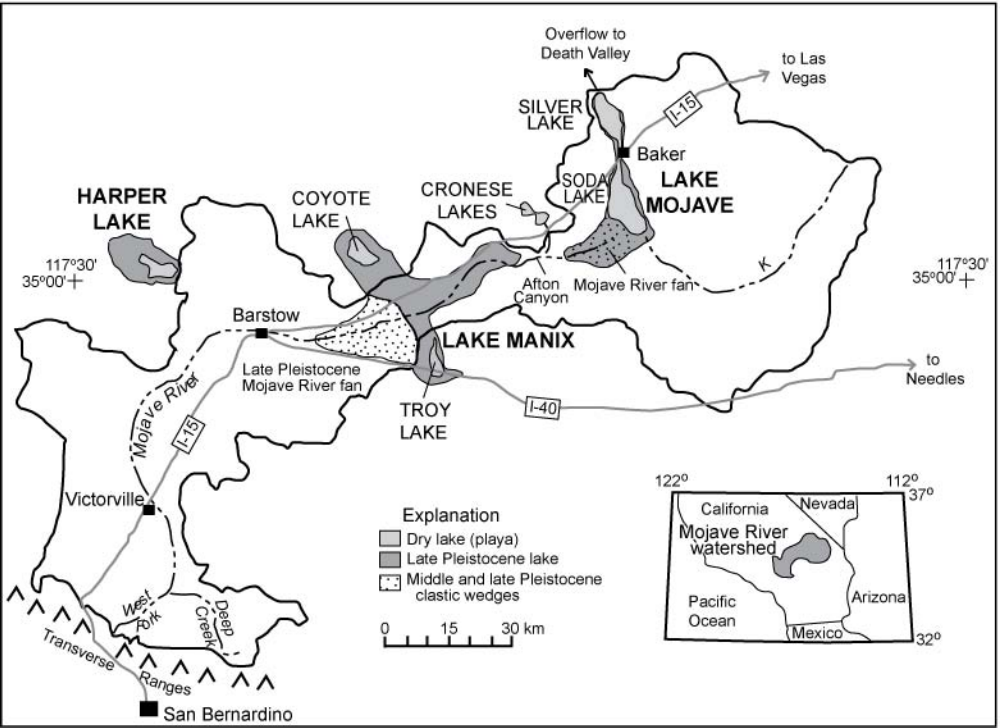

Overflow to Death Valley
to Las Vegas
I-15
SILVER LAKE
Baker
SODA LAKE
LAKE MOJAVE
HARPER LAKE
COYOTE LAKE
CRONESE LAKES
117°30'
35°00'
Afton Canyon
Mojave River fan
K
117°30'
35°00'
Barstow
LAKE MANIX
Late Pleistocene Mojave River fan
Mojave River
I-15
TROY LAKE
I-40
to Needles
Victorville
Explanation
Dry lake (playa)
Late Pleistocene lake
Middle and late Pleistocene clastic wedges
0 15 30 km
122°
112°
37°
California
Nevada
Mojave River watershed
Pacific Ocean
Arizona
Mexico
32°
West Fork
Deep Creek
Transverse Ranges
San Bernardino

Figure 2

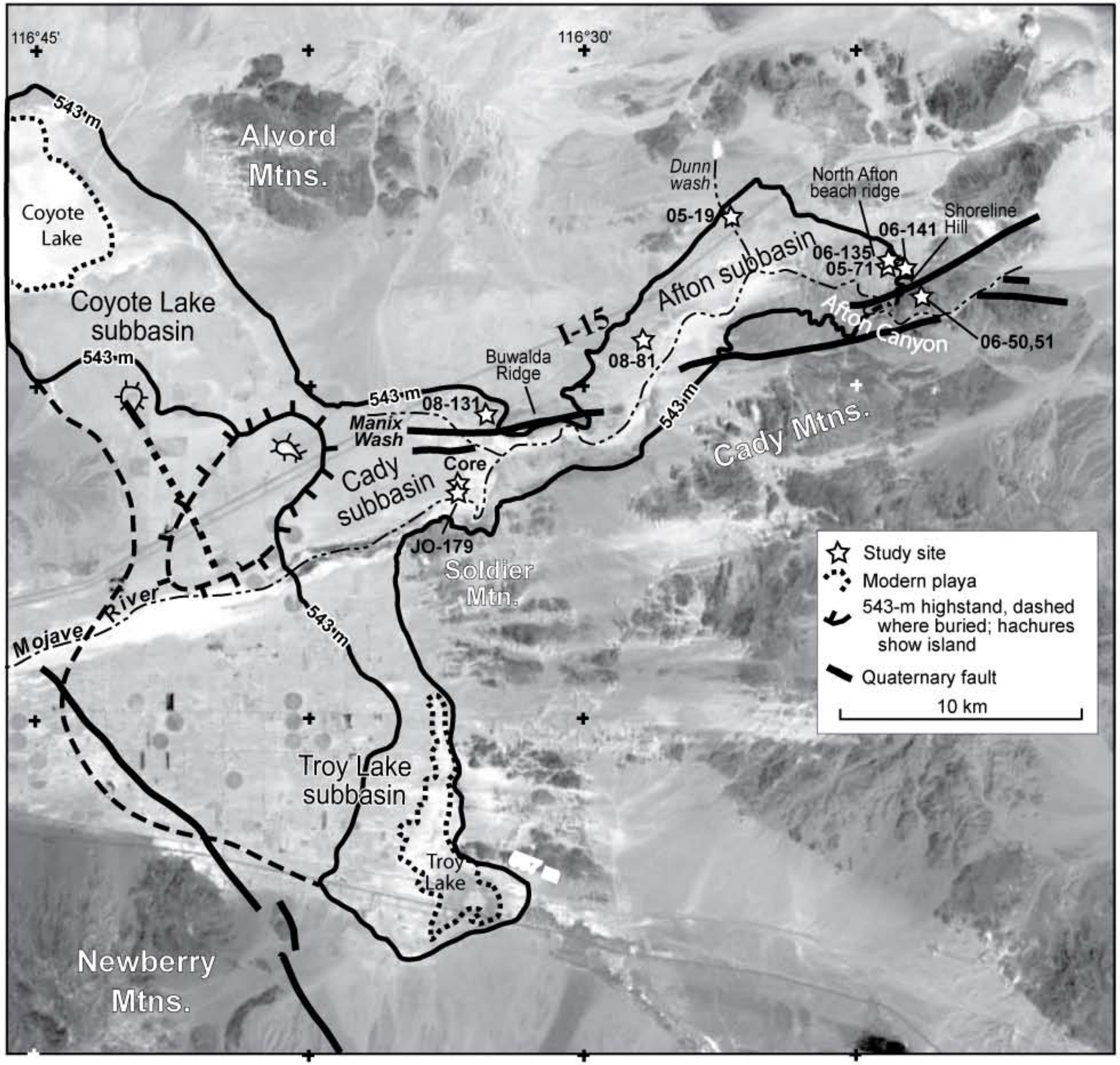

116°45'
116°30'
Alvord Mtns.
Coyote Lake
Coyote Lake subbasin
543 m
Dunn wash
05-19
North Afton beach ridge
Shoreline Hill
06-141
06-135
05-71
Afton subbasin
Afton Canyon
06-50,51
I-15
08-81
Buwalda Ridge
08-131
Manix Wash
Cady subbasin
Core
JO-179
Cady Mtns.
Soldier Mtn.
Mojave River
Troy Lake subbasin
Troy Lake
Newberry Mtns.
Study site
Modern playa
543-m highstand, dashed where buried; hachures show island
Quaternary fault
10 km

Figure 3

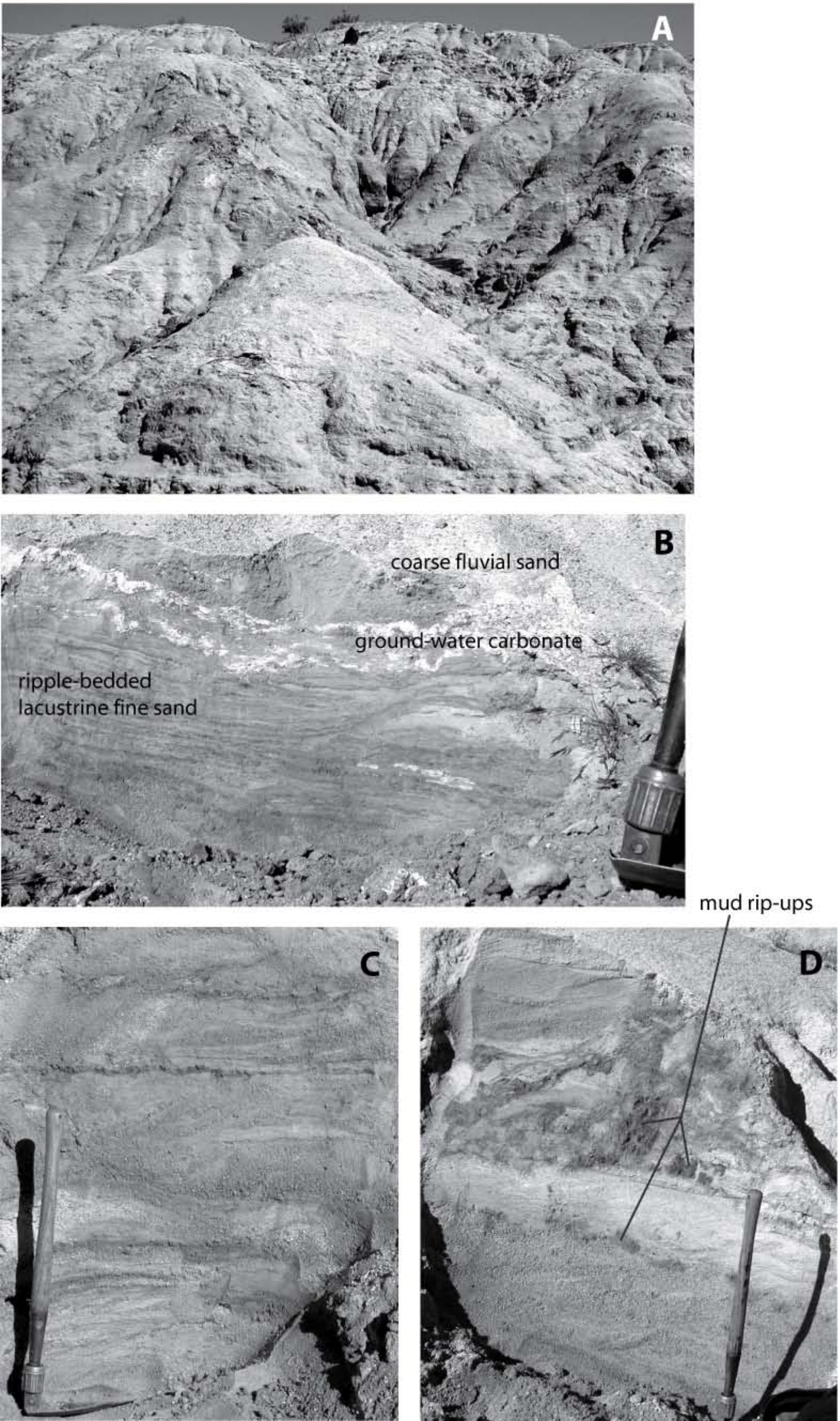

A
B
coarse fluvial sand
ground-water carbonate
ripple-bedded
lacustrine fine sand
mud rip-ups
C
D

Figure 4

A

MX-3 (152-247 cm)

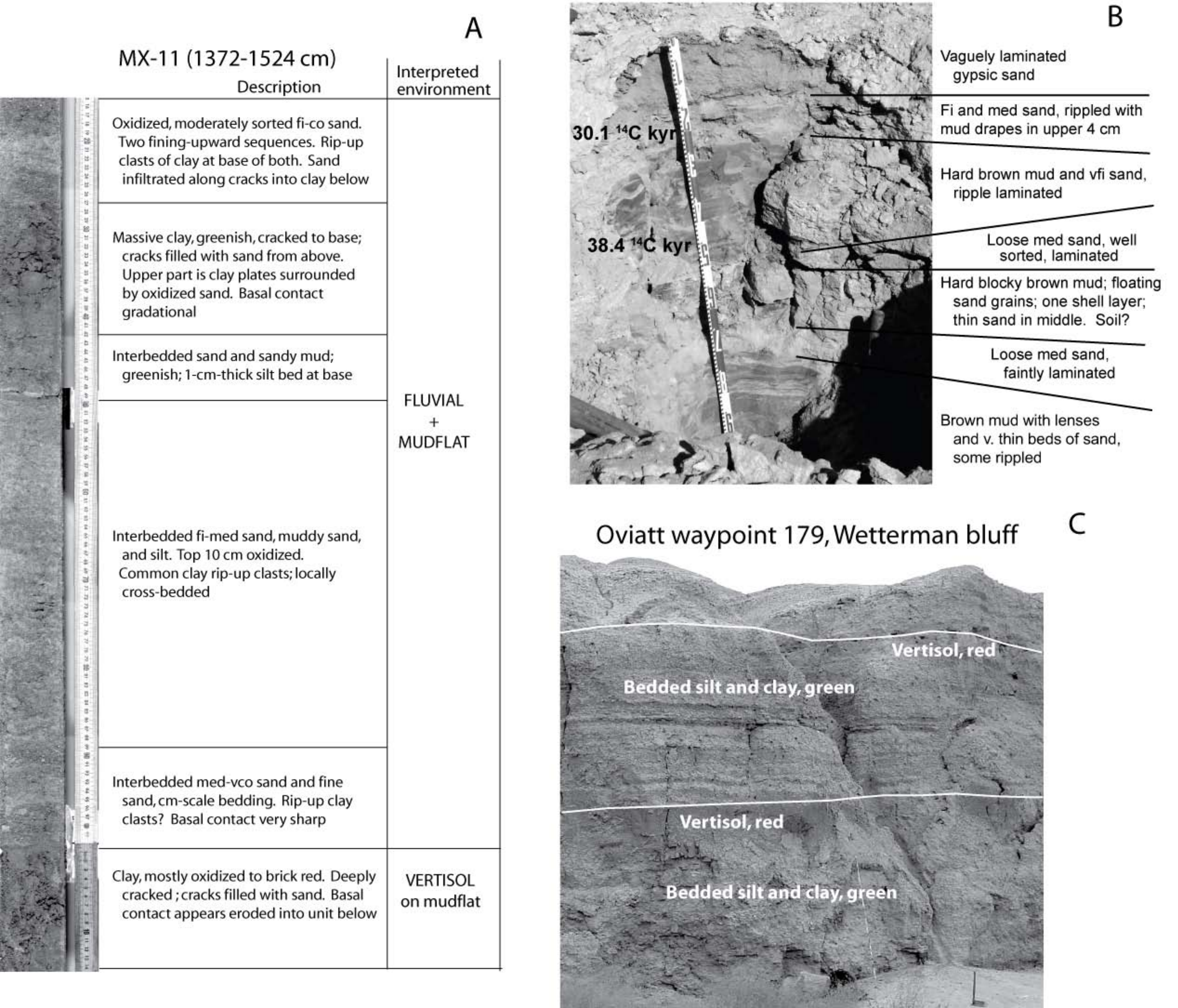
Description	Interpreted environment
Loose, coarse sand and granule gravel. Slop?	DELTAIC; fluvial
Poorly sorted fi-vco sand and armored mud balls	
Bedded, moderately sorted fi-co sand. Few clay laminae at 20-26 cm	
Poorly sorted fi-vco sand and armored mud balls	
Slightly indurated, moderately sorted, weakly bedded fi-med sand; grains moderately rounded	DELTAIC; foreshore
Loose to slightly indurated (at base), moderately sorted, massive, clean med-vco sand; well-rounded grains. Clean, well washed; faint, steeply dipping beds (foresets?)	

B

MX-7 (762 to 817 cm)

Description	Interpreted environment
Slop	DELTAIC; fluvial?
Moderately sorted vfi-med sand; faintly bedded; well rounded grains; <1-cm-thick co sand at base	
Very well sorted fine sand; bedding not visible	BEACH
Very well sorted fi-med sand; coarsens slightly downward; faint heavy-mineral laminae. Slightly dipping. Basal 2 cm more oxidized	
Thinly laminated (mm scale) brown silty clay. Vfi sand parting at 45.5-46 cm. Scattered sand grains increasing at base	SHALLOW LAKE; lagoon?

Figure 5



MX-11 (1372-1524 cm)

Description	Interpreted environment
Oxidized, moderately sorted fi-co sand. Two fining-upward sequences. Rip-up clasts of clay at base of both. Sand infiltrated along cracks into clay below	FLUVIAL + MUDFLAT
Massive clay, greenish, cracked to base; cracks filled with sand from above. Upper part is clay plates surrounded by oxidized sand. Basal contact gradational	
Interbedded sand and sandy mud; greenish; 1-cm-thick silt bed at base	
Interbedded fi-med sand, muddy sand, and silt. Top 10 cm oxidized. Common clay rip-up clasts; locally cross-bedded	
Interbedded med-vco sand and fine sand, cm-scale bedding. Rip-up clay clasts? Basal contact very sharp	
Clay, mostly oxidized to brick red. Deeply cracked ; cracks filled with sand. Basal contact appears eroded into unit below	VERTISOL on mudflat

Figure 6

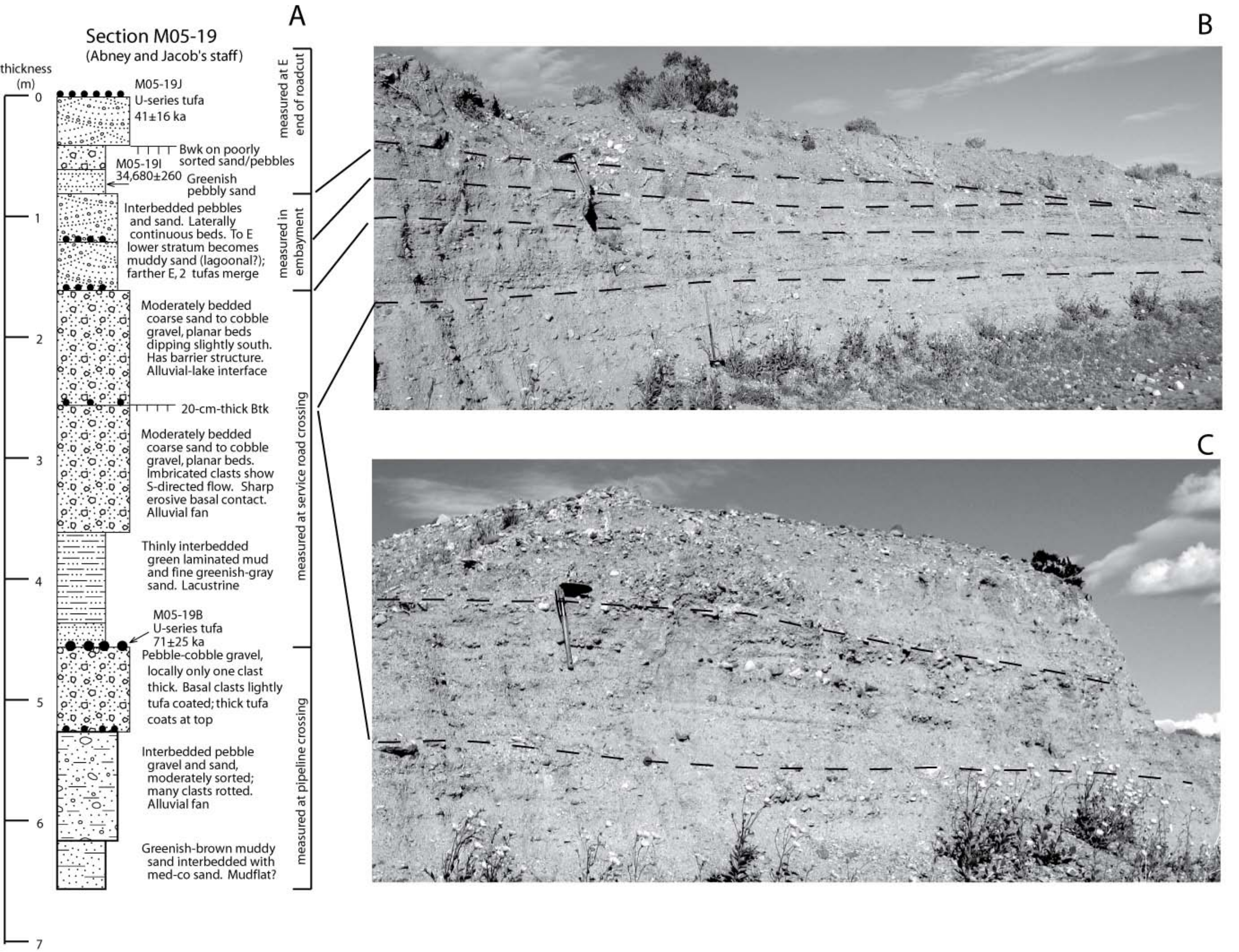

A
Section M05-19
(Abney and Jacob's staff)
thickness (m)
0
1
2
3
4
5
6
7
M05-19J
U-series tufa
41±16 ka
Bwk on poorly sorted sand/pebbles
M05-19I
34,680±260
Greenish pebbly sand
Interbedded pebbles and sand. Laterally continuous beds. To E lower stratum becomes muddy sand (lagoonal?); farther E, 2 tufas merge
Moderately bedded coarse sand to cobble gravel, planar beds dipping slightly south. Has barrier structure. Alluvial-lake interface
20-cm-thick Btk
Moderately bedded coarse sand to cobble gravel, planar beds. Imbricated clasts show S-directed flow. Sharp erosive basal contact. Alluvial fan
Thinly interbedded green laminated mud and fine greenish-gray sand. Lacustrine
M05-19B
U-series tufa
71±25 ka
Pebble-cobble gravel, locally only one clast thick. Basal clasts lightly tufa coated; thick tufa coats at top
Interbedded pebble gravel and sand, moderately sorted; many clasts rotted. Alluvial fan
Greenish-brown muddy sand interbedded with med-co sand. Mudflat?
measured at E end of roadcut
measured in embayment
measured at service road crossing
measured at pipeline crossing
B
C

Figure 7

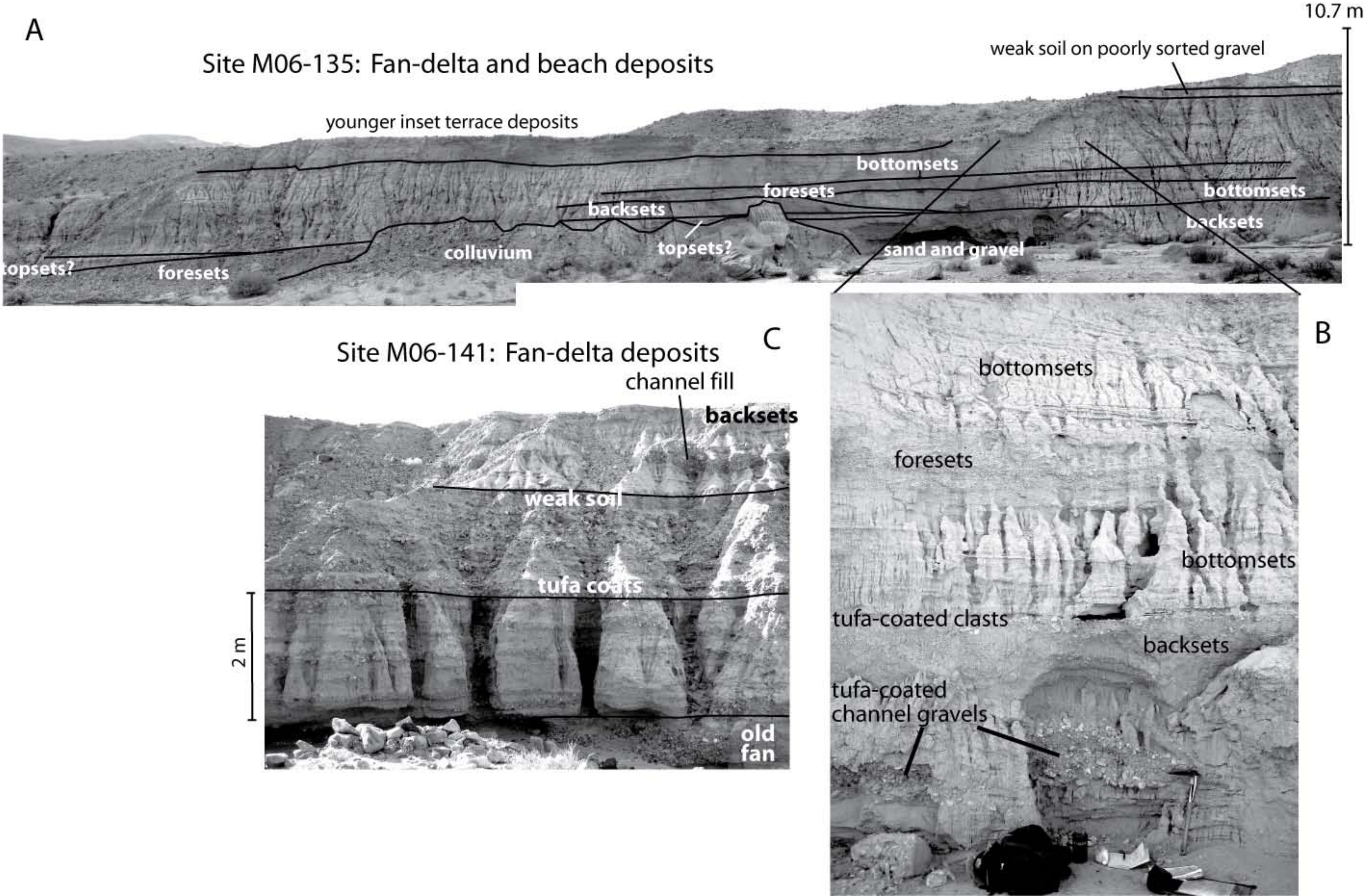
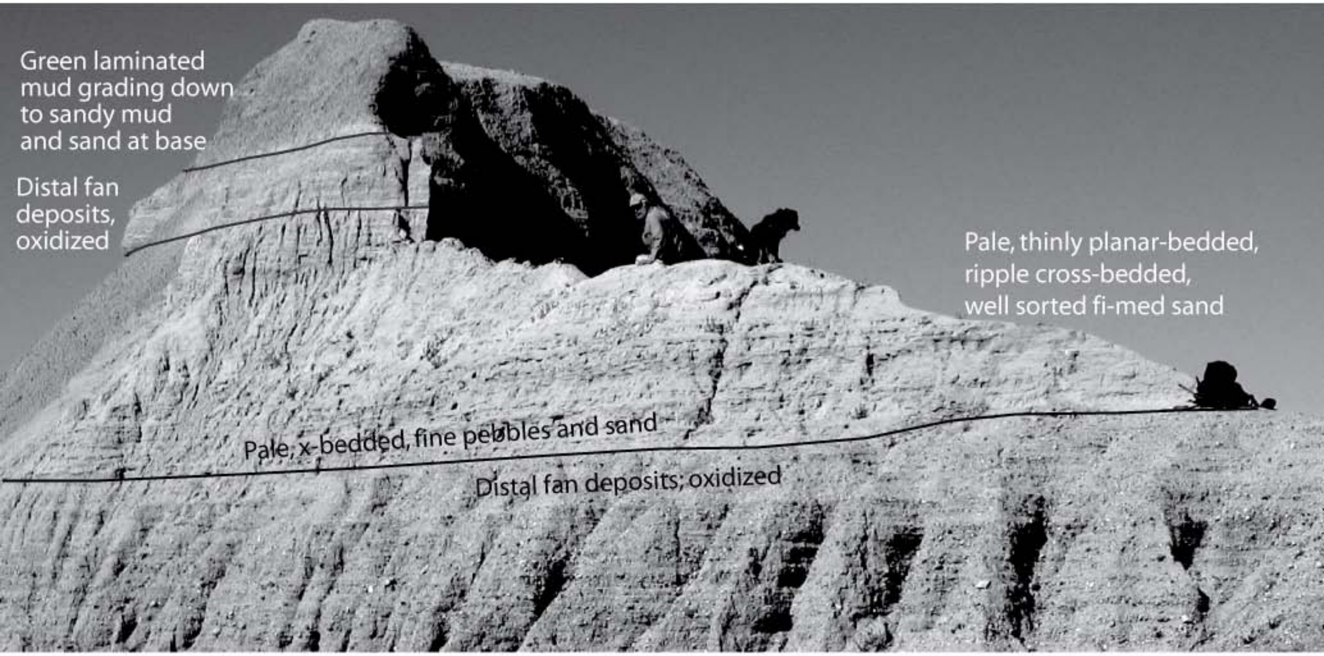

A
Site M06-135: Fan-delta and beach deposits
10.7 m
weak soil on poorly sorted gravel
younger inset terrace deposits
bottomsets
foresets
bottomsets
backsets
backsets
topsets?
colluvium
sand and gravel
opsets?
foresets
B
bottomsets
foresets
bottomsets
tufa-coated clasts
backsets
tufa-coated channel gravels
C
Site M06-141: Fan-delta deposits
channel fill
backsets
weak soil
tufa coats
2 m
old fan

Figure 8

M06-81, Midway Wash area, distal fan

A



M08-131, E side Manix Wash

B

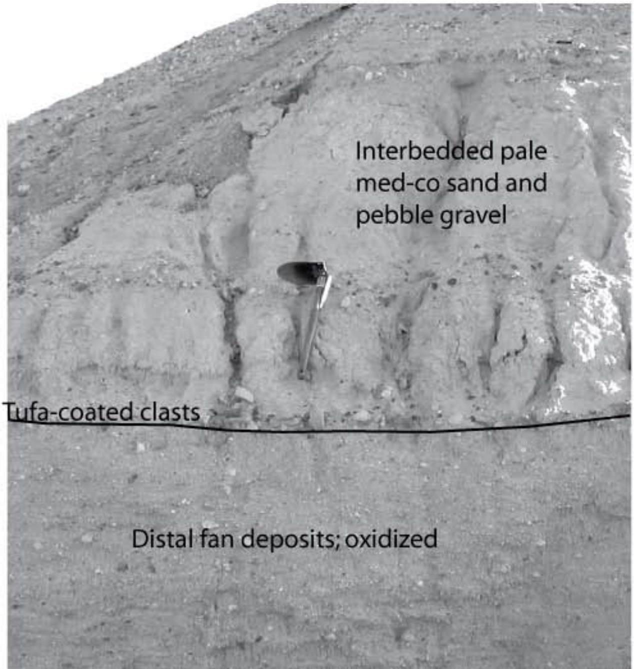


Figure 9

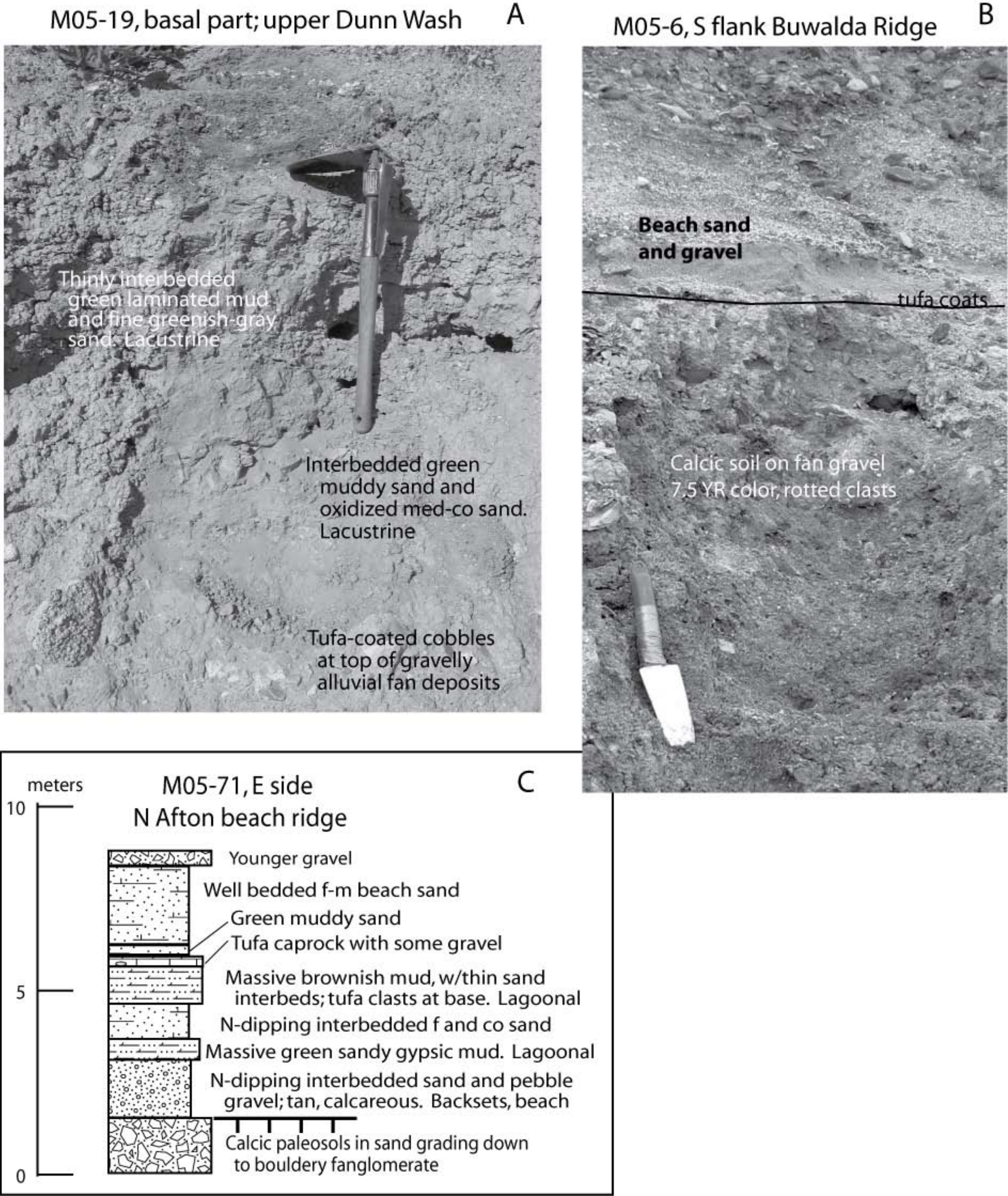
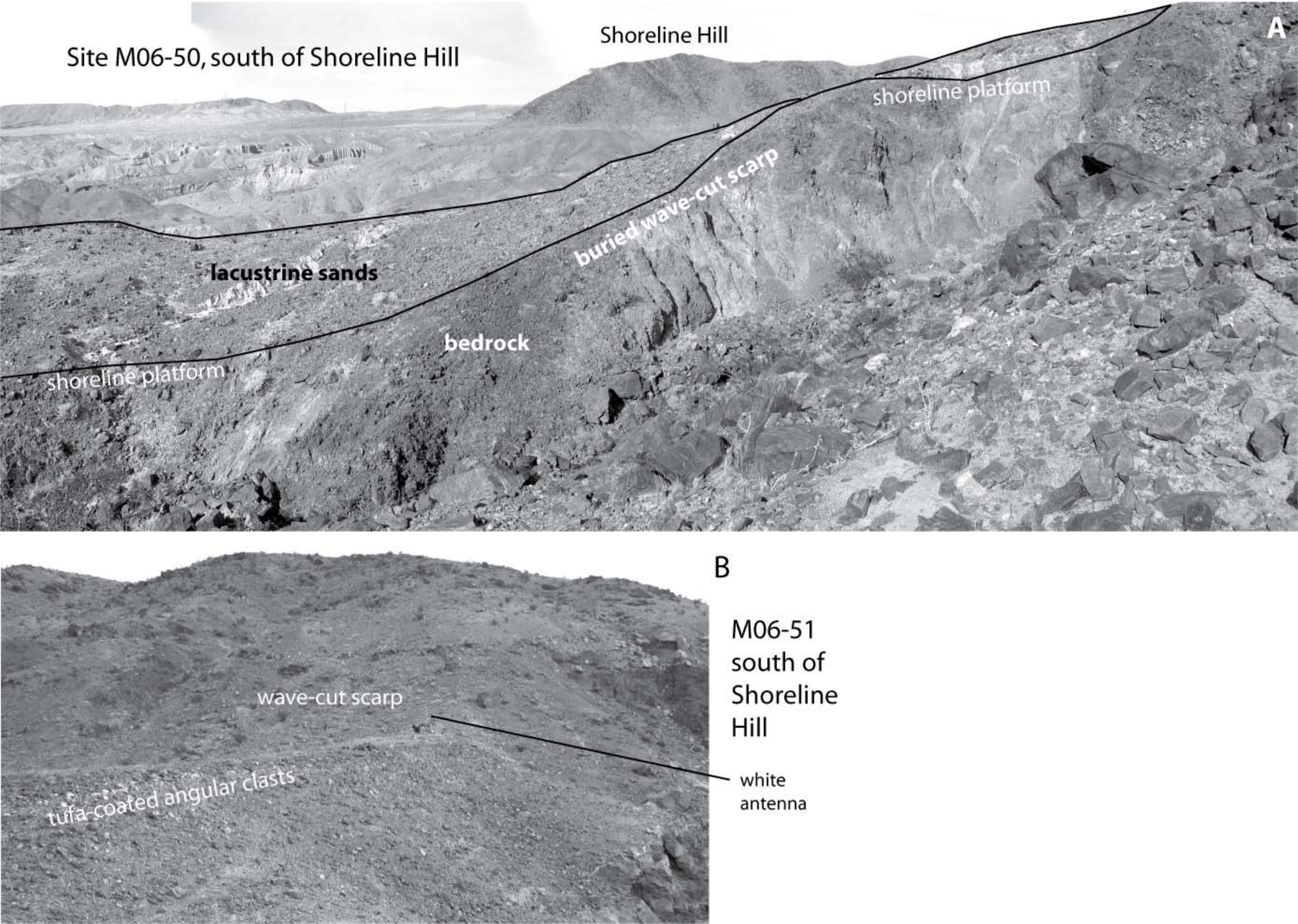

M05-19, basal part; upper Dunn Wash
A
Thinly interbedded green laminated mud and fine greenish-gray sand. Lacustrine
Interbedded green muddy sand and oxidized med-co sand. Lacustrine
Tufa-coated cobbles at top of gravelly alluvial fan deposits
M05-6, S flank Buwalda Ridge
B
Beach sand and gravel
tufa coats
Calcic soil on fan gravel 7.5 YR color, rotted clasts
M05-71, E side N Afton beach ridge
C
meters
10
5
0
Younger gravel
Well bedded f-m beach sand
Green muddy sand
Tufa caprock with some gravel
Massive brownish mud, w/thin sand interbeds; tufa clasts at base. Lagoonal
N-dipping interbedded f and co sand
Massive green sandy gypsic mud. Lagoonal
N-dipping interbedded sand and pebble gravel; tan, calcareous. Backsets, beach
Calcic paleosols in sand grading down to bouldery fanglomerate

Figure 10


A
Site M06-50, south of Shoreline Hill
Shoreline Hill
shoreline platform
buried wave-cut scarp
lacustrine sands
bedrock
shoreline platform
B
M06-51 south of Shoreline Hill
wave-cut scarp
tufa-coated angular clasts
white antenna