WILLIAM LETTIS & ASSOCIATES, INC.

Final Technical Report

Evaluating the Repeatabilty of Lateral Spreading

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FINAL TECHNICAL REPORT

EVALUATING THE REPEATABILITY OF LATERAL SPREADING

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ABSTRACT

This first-year feasibility study, designed to evaluate whether lateral spreads occur repeatedly in the same location, established an example of recurring sand injection and lateral spreading along a stratigraphic unconformity within the Pajaro River floodplain near Watsonville. We excavated two trenches across a lateral spread formed by the 1989 Loma Prieta earthquake on the Pajaro River floodplain near Watsonville, within the Miller Farms site identified and studied by U.S. Geological Survey geologists and geotechnical engineers (Holtzer et al., 1994; Bennett and Tinsley, 1995). In addition to liquefaction-related features produced in 1989, the trench walls revealed evidence for at least 2 to 3 prior lateral spread failures and associated liquefied sand bodies. The site likely records evidence for failure from the 1906 M 7.8 San Francisco earthquake and earlier events on the San Andreas fault. The spreading repeatedly occurred along a ~1-m-wide zone that coincides with a buttress unconformity between middle to late Holocene floodplain deposits (south of the unconformity) and late Holocene to historic fluvial deposits of an aggraded inset river terrace (north of the unconformity) of the Pajaro River (Dupré and Tinsley, 1980). Trench walls exposed a secondary zone of discontinuous normal faults with small (< 1 cm) vertical displacements, located several meters north of the primary lateral spread zone. The minor faults generally coincide with ground cracks caused by the 1989 earthquake, although it is permissible that an earlier lateral spread produced some of the these normal fault displacements. The small magnitude of the secondary zone relative to the massive failure along the primary lateral spread zone indicates that the primary mode of deformation at the Miller Farms site has been repeated, localized failure. Detrital charcoal collected from within, and above, a structurally tilted sand layer suggests that the ante-penultimate event happened after A.D. 1400. Efforts to place limiting ages on younger floodplain sediments using the presence or absence of non-native pollen species (Mensing and Byrne, 1998) were not successful, based on poor preservation of pollen within the oxidized silt and sand stratigraphy.

A single trench excavated across the distal alluvial fan of Coyote Creek near Milpitas, California, did not provide evidence of lateral spread failures, despite reports of widespread lateral spreading in the vicinity during the 1906 San Francisco earthquake and the 1868 Hayward earthquake (Lawson et al., 1908; Youd and Hoose, 1978). Two narrow sand dikes exposed in the trench walls indicate that the natural levee deposits have liquefied during past events, supporting prior site-specific (Egan et al., 1992) and regional (Knudsen et al., 2000) interpretations that the deposits that underlie the site have a high susceptibility for liquefaction.

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1.0 INTRODUCTION

Lateral spreads commonly occur during large earthquakes and are a primary cause of damage to the built environment (e.g., lifelines and buildings). The occurrence of lateral spreads is not an indiscriminate process, but is confined to areas or zones with specific geologic, hydrologic and geotechnical properties. Although lateral spreads will occur within specific zones, we do not know whether or not the specific locations of lateral spreads within these zones are predictable or random, and, if predictable, what geologic and/or geotechnical properties control the location of lateral spreading.

Numerous geotechnical studies currently are in progress to investigate the geotechnical parameters that may control the location, orientation, and amount of lateral spreading during liquefaction. These studies are focused on identifying specific locations of lateral spreads within areas of high susceptibility to liquefaction. The underlying premise or assumption to these studies is that the location and magnitude of lateral spreading is a predictable geotechnical phenomenon subject to epistemic uncertainties and does not occur randomly within an area of high liquefaction susceptibility. Absent from these geotechnical investigations is a careful evaluation of the possible geologic constraints on the location of liquefaction (e.g., depositional environment, facies changes, stratigraphic and/or structural unconformities, etc.).

This final technical report presents the results of year one of a multi-year study of the repeatability and, therefore, predictability of lateral spreading associated with liquefaction during strong ground shaking. This study tested whether lateral spreading is a predictable phenomenon by evaluating geologic evidence for repeated lateral spreading across known historical lateral spreads. This research examines whether or not we can treat lateral spreads similar to fault rupture such that specific locations, magnitudes, and orientations can be predicted, or whether areas within high susceptibility units should be treated as a "zone within which lateral spreads may occur" for evaluation of impact to the built environment. The results from this and future studies are critically important for reducing losses from future earthquakes by improving our understanding of the phenomenon of lateral spreading. The goal of our research is to provide input such that next-generation maps can better depict the location and magnitude of displacement of future occurrences of lateral spreading. A more accurate depiction of the hazard allows planners and policy-makers to revise building codes, public policy, emergency preparedness, and insurance guidelines, which ultimately are designed to minimize loss.

The scope of work during this first-year study included the following:

(1) Identification of target sites through literature review of historical areas of lateral spreading, compilation of previous geological and geotechnical studies, and ground reconnaissance;

(2) Selection of two sites in northern California for investigation: The Miller Farms site near Watsonville and the Cilker Orchards site near Milpitas;

(3) Excavation, logging, and interpretation of exploratory trenches at both sites;

(4) Collection of samples for grain-size analysis, micro-textural analysis, pollen analysis, and radiocarbon dating;

(5) Meetings with stakeholders within the scientific community, including members of the U.S. Geological Survey, California Geological Survey, and local city and county geologists; and

(6) The preparation of this final technical report.

Through trench exposures and standard paleoseismic techniques we have evaluated the repeatability of lateral spreads at two sites. From late August through early October, 2003, we excavated trenches across the floodplains of Pajaro River, near Watsonville, and Coyote Creek, near Milpitas, at sites that have experienced historic lateral spread failures (Figure 1). The Pajaro River (Miller Farms) site contains a record of at least three to four lateral spreads and paleoliquefaction events that recurred in a narrow (about one-meter-wide) zone. This site motivated our formulation of a hypothesis that the depositional environment and local geologic and geomorphic site history create conditions that can localize lateral spreading over a range of earthquake magnitudes. The Coyote Creek (Cilker Orchards) site revealed evidence against lateral spreading within sediments highly susceptible to liquefaction located 45 to 145 meters from the current river channel free-face. Most historical reports of lateral spreading along the Coyote Creek floodplain from the 1906 earthquake were confined to a narrow corridor close to the levee and banks of Coyote Creek, in areas now within a floodwater control corridor that we were unable to access.

In this final technical report, we present the results of the Miller Farms study site in Section 2, the results of the Cilker Orchards study site in Section 3, and provide a discussion of the study implications and suggestions for future research in Section 4.

2.0 MILLER FARMS SITE, PAJARO RIVER

Extensive lateral spreading occurred in the Monterey Bay lowlands during both the 1906 San Francisco and 1989 Loma Prieta earthquakes (Youd and Hoose, 1978; Tinsley et al., 1998). A prominent lateral spread 1.7 km long in 1989 crossed the Miller Farms site on the Pajaro River floodplain. Extensive study of the Miller Farms site after the 1989 earthquake characterized the geotechnical properties of the deposits and sources of liquefiable sands (Holzer et al., 1994; Bennett and Tinsley, 1995; Charlie et al., 1998).

2.1 Geologic Setting

The Miller Farms study site lies in the lowlands adjacent to Monterey Bay, between the southern Santa Cruz Mountains and the Pacific Ocean (Figure 1). The lowland alluvial plain of the Pajaro River is presently aggrading, with Holocene deposits in the Monterey Bay basin tens to hundreds of meters thick (Dupré and Tinsley, 1980). The lower Pajaro River collects runoff from the southern Santa Cruz Mountains, and deposits: (1) channel and point-bar sand, (2) proximal overbank and levee silt, and (3) distal floodplain fine silt and clay. These three facies are laterally and vertically accreted across the broad meandering floodplain formed by the river, forming lens-shaped to laterally continuous deposits of sand, sandy silt, and silty clay. Unconsolidated channel, point bar, and levee deposits are highly susceptible to liquefaction where saturated (Dupré and Tinsley, 1980).

The Miller Farms site is located on the south side of the Pajaro River, across the river from the community of Watsonville (Figure 2). Near and upstream of Watsonville, younger Holocene floodplain deposits (Qyf) are inset in older Holocene floodplain deposits (Qof) (Dupré and Tinsley, 1980). Although modern agriculture has resulted in extensive grading of the floodplain, the terrace riser separating older and younger floodplain deposits is preserved locally, and gradually increases in height to the east. A possible remnant of the terrace riser is located at the east end of the study area, within the Kiwi fruit arbor (Figure 2). Within the study area and west of Watsonville, late Holocene aggradation has buried the older floodplain deposits with a veneer of younger floodplain deposits (Qyf(a)) (Dupré and Tinsley, 1980).

Land use in the Monterey Bay lowlands has changed since the arrival of the Spanish explorers and missionaries in the late 18th century, and has impacted the hydrology of the Pajaro River. At the time of Portola’s 1789 expedition, the Monterey Bay lowland was covered with mixed forest and grassland, and the southern Santa Cruz Mountains were forested (Gordon, 1977). Spanish, and later Mexican, settlers cleared portions of the lowlands for fuel and to open up range land for livestock. Later development by U.S. settlers, starting in the middle 19th century, cleared trees from the forested slopes of the Santa Cruz Mountains, the headwaters for the Pajaro River. Extensive aggradation in the lowlands resulting from historic land-use change is suggested by wood and charcoal samples dated at less than 300 ^{14}C-yr-old from the upper 5 meters of sediment along the Salinas and Pajaro rivers (Bennett and Tinsley, 1995). Numerous floods during the early 20th century, combined with extensive development onto the Pajaro River floodplain, prompted construction of flood-control levees in 1929 and 1949 (Swanson et al., 1991).

2.2 Earthquake Sources and History of Lateral Spread Failures

The Miller Farms site is located about six kilometers southwest of the San Andreas fault, and within 40 kilometers of the San Gregorio and Calaveras faults (Figure 1). Although large earthquakes have occurred on the Calaveras and San Gregorio faults in late Holocene time, the major seismic source for the Monterey Bay region is the San Andreas fault, including the nearby Santa Cruz Mountains segment. At least nine large earthquakes in the last 1000 years capable of causing liquefaction likely occurred on the San Andreas fault zone (Fumal et al., 2003), including the historic 1989 Loma Prieta and 1906 San Francisco events. The penultimate 1906-type event, which may have ruptured the entire northern San Andreas fault, occurred around A.D. 1600 (Knudsen et al., 2002). Other pre-20th century events likely were restricted to single-segment ruptures on the Santa Cruz Mountains segment, with magnitudes similar to the 1989 event. Thus, the study area has experienced strong ground motions capable of generating lateral spreading from at least two types of seismic sources with contrasting shaking duration and intensity. Our first-year results from the Miller Farms site along the Pajaro River show that both moderate 1989-type and large 1906-type events produced lateral spreading along the same failure zone that coincided with a sub-vertical stratigraphic unconformity.

Extensive liquefaction and lateral spreading occurred historically in the Monterey Bay region during the 1989 Loma Prieta Earthquake (Tinsley et al., 1998) and 1906 San Francisco Earthquake (Lawson, 1908, Youd and Hoose, 1978). Liquefaction and lateral spreading were particularly widespread in fluvial channel, levee, point bar, estuarine, and aeolian deposits, particularly those less than a few hundred years old (Tinsley et al., 1998). Observed lateral spread failures from the 1989 earthquake generally occurred within 50 to 150 m of a free-face; however, the geologic and/or geotechnical control on the location of lateral spreading, or whether lateral spreading occurred repeatedly in the same location or within the same general zone, is not known.

2.2.1 1906 San Francisco Earthquake

Lateral spreading along the lower Pajaro River floodplain was widespread during the M7.8 1906 earthquake (Lawson et al., 1908, Youd and Hoose, 1978). Near the Miller Farms study site, liquefaction-induced failure included settling and lateral spreading at the southern abutments at the broad-gage railway and highway bridges in Watsonville (Lawson et al., 1908), and affected Chinatown, located near the present town of Pajaro on the south side of the river (Figure 2). As reported in the *Salinas Daily Index* (from Youd and Hoose, 1978):

> *…the damage done to the Monterey side of the Pajaro River bridge was…caused by a sink which extends along the bank of the river on this side and allows Chinatown to drop about four feet. This sink, or fissure, followed the bank of the river and enters under the approach from this side, throwing the whole bridge out of line…another fissure followed the Watsonville side of the river, but was not so bad as on this side.*

2.2.2 1989 Loma Prieta Earthquake

The 1989 earthquake also produced extensive liquefaction and lateral spreading along the lower Pajaro River floodplain (Tinsley et al., 1998). Although lateral spreads and sand boils were widespread along both river banks, the most continuous lateral spread extended along the southern margin of the Pajaro River for 1.6 km from the broad-gage train trestle near Watsonville to just east of the Miller Farms site (Holzer et al., 1994). Aerial photographs taken three days after the earthquake show a prominent, laterally continuous crack and several discontinuous branching cracks across the cultivated floodplain (Figure 2). There was no vented sand apparent at the surface along the prominent lateral-spread crack, which appeared on the air photos as a dark line, likely due to water seepage (J. Tinsley, personal communication, 2003). Shorter *en echelon* cracks, sand boils, and cracks at the base of and within the Pajaro River levee occurred north (towards the river) of the primary crack. The prominent lateral spread crack coincided closely with the geologic contact separating floodplain deposits of older (Qyf(a)) and younger (Qyf) age (Dupré and Tinsley, 1980).

Post-1989 earthquake investigations focused on several sites of lateral spreading, including the Miller Farms site (Holzer et al., 1994; Bennett and Tinsley, 1995; Charlie et al., 1998) (Figure 2). These investigations focused on geotechnical properties of the deposits that did and did not show surface manifestations of liquefaction. CPT, SPT, and Piezovane data show that the area north of the prominent lateral spread, where sand blows and secondary cracking were evident, is underlain by sands and silts susceptible to liquefaction. The area south of the primary lateral spread crack, where no sand boils or cracks were observed, is underlain by deposits that area not susceptible to liquefaction.

2.3 Results of the Trench Investigation

A rubber-tire backhoe with a 36-inch bucket excavated two trenches to a maximum depth of 3.5 meters across the geologic contact of Dupré and Tinsley (1980) and the primary lateral spread crack documented on the 1989 aerial photographs at the Miller Farms site (Figure 2). Trench T-1 extended 30 meters across the primary crack and secondary branching cracks; trench T-2 was 17.5 meters long and was designed to provide an additional exposure of the primary lateral spread and the mapped geologic contact. We cleaned all trench walls to expose fresh surfaces, and logged the trench walls at a scale of 1 inch = 0.5 meters (about 1:20). The northern six meters of trench T-1 were benched to stabilize the trench walls. Groundwater was encountered about 4 meters below the ground surface in boreholes dug with a hand auger in both trench floors.

The trench walls exposed a buttress unconformity that forms the contact between younger (late Holocene to historic) point-bar and proximal floodplain deposits to the north and older (middle to late Holocene) overbank deposits to the south (Plates 1-3 and Appendix A). The unconformity coincides with extensive normal faulting and sub-vertical, injected sand bodies that reveal evidence for lateral spreading failure. Although stratigraphic units are correlative between trenches T-1 and T-2, the trenches expose different structural relationships related to past lateral spreading failure. Additionally, the northern end of trench T-1 revealed a two- to four-meter-wide zone of minor normal faulting that coincides with the secondary ground cracks observed in the aerial photographs following the 1989 Loma Prieta earthquake.

Limited dating control was provided by radiocarbon analysis of detrital and in situ charcoal samples (Table 1). Sediment samples collected for pollen analysis throughout the trench stratigraphy had poor pollen preservation, and were not useful for determining the presence or absence of a non-native grass species introduced in the late 18th century (Appendix B). Samples were also collected for grain-size analysis, in order to help evaluate materials susceptible to liquefaction and to correlate sand blow samples from the 1989 earthquake to shallow source areas (Appendix C).

2.3.1 Trench Stratigraphy

Both trenches expose a buttress unconformity that separates younger, latest Holocene floodplain deposits to the north and older, mid-to-late Holocene overbank deposits to the south (Plates 1-3; Figures 3 and 4). South of the unconformity are sub-horizontal layers of overbank sands, silts, and clays. A buried soil, 1.3 to 1.4 m below the ground surface, shows horizons of organic accumulation, filamentous and nodular carbonate accumulation, and translocated clays developed in clayey silt deposits (unit 20; Plates 1-3 and Appendix A). The buried soil represents a period of landscape stability within the vertically accreted sequence (J. Sowers, personal communication, 2003). Disseminated charcoal and organic material collected from a reddish clayey silt burn layer within the C horizon of the buried soil sequence (unit 20c; Plate 3), interpreted to be produced in-situ from a local fire, has a calibrated radiocarbon age of 3380 to 3630 Cal yr B.P. (Sample RC-204, Table 1 and Plate 3). Overlying the buried soil are fine silty sands with little organic content (units 30 and 40), with the exception of discontinuous, two- to five-cm-thick organic accumulation at the top of unit 30b. These sediments represent the veneer of younger floodplain deposits overlying older floodplain deposits mapped regionally by Dupré and Tinsley (1980). The upper 40 to 60 cm is the modern plow zone.

Table 1. Radiocarbon Ages and Calibration of Charcoal Samples, Miller Farms Site

Sample Code	Lab No.[a]	Age, 14C yr B.P. ± 1 σ	13C/12C Ratio	Calibrated Age[d] (95.4 % confidence)	Probability (%)[e]	Sample Location	Stratigraphic Unit
MF-RC24	187521[b]	290 ± 70	-22.2 ‰	Cal AD 1400 to 1850 Cal AD 1900 to 1950	93.1 2.3	T-1 West Wall, Meter 16	Unit 80b
MF-RC9	187520[c]	260 ± 40	-24.3 ‰	Cal AD 1490 to 1680 Cal AD 1760 to 1810 Cal AD 1930 to 1950	78.6 14.2 2.7	T-1 West Wall, Meter 14.5	Unit 60
MF-RC204	187522[c]	3260 ± 40	-27.2 ‰	Cal BP 3630 to 3600 Cal BP 3580 to 3380	2.0 93.4	T-2 West Wall, Meter 9.5	Unit 20e

[a] Sample pretreatment and analysis at Beta Analytic Laboratories, Miami, Florida
[b] Radiometric technique
[c] AMS technique
[d] Calibration with OxCal v.3.9 (Bronk Ramsey, 2001) using atmospheric data of Stuiver et al. (1998)
[e] Percent probability of age interval

North of the unconformity is a sub-horizontal to gently north-dipping sequence of silt and sand deposits (Plates 1-3). This sequence consists of ~10- to 30-cm-thick layers of clean sands to mixed silts and sands, and likely represents migrating point-bar and proximal overbank (levee) deposits. The lowest unit exposed on the north side of the trench, unit 60, is fine sand with silt with thin (< 1 cm) sub-horizontal laminations and elongate cross-beds. This unit is overlain by unit 70a, a layer of fine sandy silt with local fine laminations and cross beds, and local convolute bedding and flame structures. These point-bar facies are overlain by layers of predominantly silty material with massive structure, frequent rip-up clasts, and varying amounts of organic material that we interpret to be proximal overbank (levee) deposits, which are interlayered with a few sandy units with laminations and cross bedding (units 80a to 130). Northward-tapering deposits of more-organic-rich silts interfinger with the less-organic-rich silts and sands close to the unconformity (e.g., unit 70b). The more-organic-rich sediments likely are either scarp-derived or were deposited in organic-rich marshes present adjacent to the buttress unconformity. The modern plow zone north of the unconformity (unit 130b) has a slightly sandier texture than the plow zone south of the unconformity (unit 130a). The sandier texture likely is associated with the lighter soil color seen on the aerial photographs that provides a basis for mapping the contact between younger and older floodplain deposits (Dupré and Tinsley, 1980).

Limited radiocarbon dating suggests that these sediments are latest Holocene to historic. Single fragments of detrital charcoal collected from units 60 and 80a have radiocarbon ages of 260 ± 40 and 290 ± 70 ^{14}C yr B.P., respectively (Table 1 and Plate 2). Although the mean radiocarbon ages are in apparent reverse stratigraphic order, both the radiocarbon and calibrated age distributions have considerable overlap. The calibrated age distributions indicate that the deposits are likely within the age range of A.D. 1400 to A.D. 1850 (Table 1).

Within the unconformity zone are several sub-vertical to moderately north dipping, inorganic sandy silts and silty sands (units L-1 to L-11). These deposits are texturally massive to finely laminar, with laminations dipping gently to 70 degrees north. The laminations are frequently cut by normal faults. Often, but not always, the laminations dip sub-parallel to the upper and lower unit boundaries (Plates 1-3). These sand units extend to the modern plow (Ap) horizon in the east and west walls of trench T-1 (Plates 1-2), but are only present below 2.8 meters depth in trench T-2 (Plate 3). Several of these sand units, particularly those in trench T-1, we interpret as liquefaction deposits—likely injected or remobilized sands. Other sand units, particularly those in trench T-2 and those which tend to show pervasive mm-scale laminations, we interpret as either injected, liquefied sands similar to those in trench T-1 or as structurally tilted fluvial sands. Although laminations parallel to dike walls commonly are observed in earthquake-induced liquefaction-related dikes (e.g., Tuttle, 2001), and penetrative, sub-vertical laminations were documented within the conduit of a flood-induced sand boil (Li et al., 1996), most earthquake-induced liquefaction dikes contain poorly sorted, massive material from the liquefied layer, mixed with clasts torn from the dike walls (Li et al., 1996). The preservation of fine laminations within earthquake-induced clastic dikes may represent a lower energy, less explosive environment than that associated with poorly sorted, massive dike material (Li et al., 1996). Grain-size distributions for several of the liquefaction-related units, plus grain-size distributions for the surface samples collected from nearby sand blows following the Loma Prieta earthquake (Bennett and Tinsley, 1995; Figure 2), are presented in Table 2. We further discuss the evidence favoring an injected or tilted origin for several of the liquefaction units in section 2.3.2 below.

Also within the unconformity zones are discontinuous fragments of dark brown silt with sand and clay (bright green areas described under *Notes* in Plates 2 and 3; also photographed in Figure 4c). The fragments have two probable origins: stream-bank collapse or injection. In the stream-bank collapse origin, the fragments are derived from the mid Holocene soil (unit 20e and 20f) that collapsed off a free-face formed during either (1) deposition within the paleo-channel margin by the inset Pajaro River (units 60 and 70a), or (2) collapse into a temporary void that occurred during lateral spreading. The slumping origin is clear in both walls of trench T-1 for large, 50-cm-wide blocks that have been rotated and translated north along the unconformity and lie adjacent to unit L-10. These larger blocks have similar color, texture, and filamentous carbonate as the adjacent unit 20f, and we log them as the same unit on Plates 1 and 2. Smaller fragments that occur within unit 60 in trench T-2, present at and near its lower contact with unit L-3, appear consistent with collapsed blocks from a free-face during deposition of the paleo-channel margin (Plate 3). Based on textural comparisons (Table 3) the dark brown fragments (samples S-19 and S-44) are much sandier than units 20f and 20e (samples S-7 and S-8). These data suggest that units 20f and 20e are not sources of the dark brown material and provide evidence against a stream bank collapse origin. An injection origin posits that the dark brown fragments are derived from sub-horizontal layers at depth that are interstratified with or overlie units that liquefied. Fragments of the dark brown silt were ripped up and incorporated with the liquefied materials during the dike injection processes (e.g., Tuttle, 2001). Although it is possible that a "collapse" source for these fragments comes from out of the plane of the trench wall, the grain-size distributions suggest that the fragments were injected from an underlying layer during earthquake-induced liquefaction.

Stratigraphic relations between the dark brown fragments, the liquefaction-related deposits, and the sub-horizontally laminated and cross-bedded sands favor the injection source in some cases, and the collapse source in other cases. The liquefaction-related injection origin is likely for several smaller fragments that align with the upper and lower contacts of several "L" units. For example, thin (~2-cm wide) dark brown fragments are aligned along both contacts of unit L-8 in trench T-1 (Plate 2), occur on both sides of L-2 and L-3 in trench T-2, and occur in unit L-2 in trench T-2 (Plate 3 and Figure 4c) On the other hand, a liquefaction-related injection origin appears inconsistent with the fragments that occur within laminated and cross-bedded sediment of unit 60 and near unit L-3.

Table 2 Grain-size Distributions for Liquefaction-Related Units

Sample No. [a]	Sample Location	Stratigraphic Unit	Sand (%) 4.75-0.075 mm	Silt (%) 0.075-0.005 mm	Clay (%) < 0.005 mm	D_{50} (mm)	Notes
Liquefaction (L) units and laminar sands from trenches T-1 and T-2 (this study)							
S-42	T-2 West Wall Meter 10	L-1	17	78	5	0.048	Finer grained than other L-units
S-43	T-2 West Wall Meter 10	L-3	48	48	4	0.071	Equivalent to L-8 through L-10 source?
S-13	T-1 West Wall Meter 13.5	L-7 / 60	84	14	2	0.178	
S-14	T-1 West Wall Meter 13.5	L-7 / 60	86	13	1	0.196	Unit L-7 similar to 1989 sand blow samples S4, S9
S-15	T-1 West Wall Meter 13	L-8	40	55	5	0.067	
S-20	T-1 West Wall Meter 14	L-9	50	44	6	0.073	
S-16	T-1 West Wall Meter 12.5	L-10a	46	48	6	0.071	L-8, L-9, and L-10 units derived from same source?
S-17	T-1 West Wall Meter 12	L-10b	50	44	6	0.074	
S-18	T-1 West Wall Meter 12	L-10d	48	46	6	0.073	
S-21	T-1 East Wall Meter 15	60	64	32	4	0.089	
S-22	T-1 East Wall Meter 15	70a	10	83	7	0.044	Units 60 and 70a not a source for liquefaction units exposed in T-1 or T-2
S-23	T-1 East Wall Meter 15	70a	23	74	3	0.056	
1989 Surface Samples (Bennett and Tinsley, 1995) [b]							
S4	Northwest of T-1		92	8	0	0.190	Sand with minor silt – similar to unit 60 / L-7
S9	Northwest of T-1		91	9	0	0.219	
S5	Northeast of T-2		69	27	4	0.094	Silty sand S5 and S7 are similar to trench unit 60 (S-21)
S7	Northeast of T-2		67	31	2	0.092	
S6	Northeast of T-2		58	39	3	0.082	
S8	Northeast of T-2		57	40	3	0.080	

[a] Sample collection and grain-size analysis by M. Bennett, USGS. See Appendix B.
[b] Samples collected from surface sand blows within the Miller Farms site following the 1989 Loma Prieta earthquake (Figure 2).

Table 3. Grain-Size Distributions for Dark Brown Fragments and Possible Sources

Sample No. [a]	Sample Location	Stratigraphic Unit	Sand (%) 4.75-0.075 mm	Silt (%) 0.075-0.005 mm	Clay (%) < 0.005 mm	D_{50} (mm)	Notes
Possible Source							
S-7	T-1 East Wall, Meter 9	20f	7	53	40	0.011	Buried A horizon [b] – organic accumulation in clay-rich distal overbank unit
S-8	T-1 East Wall, Meter 9	20e	2	42	56	0.004	Buried B horizon [b] – clay accumulation in clay-rich distal overbank unit.
Dark Brown Fragments							
S-19	T-1 West Wall, Meter 14	--	25	64	11	0.036	Similar to unit 70b – organic-rich silt with sand and minor clay – likely from channel-fill deposit below
S-44	T-2 West Wall, Meter 10	--	9	67	24	0.018	Less clay than 20e, f; closer to lower unit 20, plow zone, or 70b

[a] Sample collection and grain-size analysis by M. Bennett, USGS. See Appendix B.
[b] Soil profile described by J. Sowers, WLA. See Appendix A.

2.3.2 Evidence for Lateral Spreading, Primary Zone

Evidence for liquefaction and lateral spreading in the primary lateral spread zone is clear in all trench-wall exposures (Plates 1-3 and Figures 3 and 4). Northward translation of the younger floodplain sediments towards the Pajaro River has occurred by clastic dike injection, normal faulting, and structural tilting across and immediately north of the buttress unconformity separating mid Holocene and late Holocene floodplain deposits. The prominent zone of injected units and normal faulting is about one meter wide in trench T-1, which is an approximate amount of differential horizontal movement across the main zone of lateral spreading. Multiple injected clastic deposits are distinguishable based on truncations of fine lamina and abrupt changes in texture. Although we recognize multiple liquefaction deposits in the stratigraphy, we do not consider each deposit to represent a separate earthquake sequence. For example, individual earthquakes, including the 1989 Loma Prieta event, have produced multiple clastic dikes that connect at depth to different source layers (Holzer et al., 1994; Table 2). Furthermore, large aftershocks following a main shock can reactivate liquefaction-related venting and produce cross-cutting clastic dikes (Sims and Garvin, 1998).

Although several liquefaction-related deposits are preserved in the trench walls, their connections to source layers are not expressed clearly. Liquefaction units L-9 and L-10 in trench T-1, for example, are sandy-silt deposits that terminate downward at a zone of closely spaced normal faulting within laminated clean sands (units L-6 and 60; Plates 1 and 2). It is likely that the feeder dikes connecting units L-9 and L-10 to source sands lies in or out of the planes of the trench walls. Unit L-8, for example, connects to the trench floor on the west wall of trench T-1 (Plate 2), but appears to terminate against unit L-6 on the east trench wall (Plate 1). Both units L-9 and L-10 in trench T-1 are finer grained than units 60 and 70 (Table 2), and therefore must be derived from underlying units not exposed in the trench walls.

Steeply dipping normal faults penetrate the zone of clastic injection deposits in trench T-1, and appear to accommodate the majority of differential lateral movement across the buttress unconformity in trench T-2 (Plates 1-3 and Figures 3 and 4). Most normal faults, including several conjugate fault pairs, terminate upwards and downwards, and accommodate a few mm to about 5 cm of dip slip. Many minor faults, both within the primary and secondary deformation zones at the north end of trench T-1, are clear within sandy units where they cut lamina or unit boundaries, but are unclear within texturally massive units. Other laterally continuous normal faults accommodate greater amounts of dip-slip movement and extension than the shorter faults. In trench T-2, for example, a series of normal faults dipping about 60° north extends upward to unit L-3 from the base of the modern plow zone (unit 130) (Plate 3). The lower contact of unit 70a shows about 50 cm of down-to-the-north vertical and about 35 cm of horizontal displacement across the fault strands. Displacement is transferred down dip from the upper fault strand, across a series of south-dipping conjugate normal faults, to a lower fault strand. These faults terminate above or within unit L-3. Extension produced by the faulting appears to be accommodated by bedding-parallel slip along the north-dipping laminar sands of unit L-3, and to a lesser extent within unit 60.

Structural tilting also accommodates lateral spreading within the primary zone of deformation. In trench T-1, about 2.25 meters of unit 70a tilts ~13° south, towards the liquefaction zone and away from the Pajaro River (Plates 1 and 2 and Figure 3b). Unit 70b fills the depression left by the back-tilted section of unit 70a, and all overlying units dip gently to moderately northward. The southward tilting likely was caused by collapse of units 60 and 70a into a void created by the evacuation of sand, silt, and water during dike injection, a common phenomenon at earthquake-induced liquefaction sites (Li et al., 1996; Tuttle, 2001). Unit 70a is not structurally tilted in trench T-2, where a lesser volume of clastic diking occurred.

Two deposits in the lower stratigraphy of trench T-2—units L-2 and L-3—dip moderately north with parallel laminations dipping 20° to 30° north (Plate 2). Our preferred interpretation of these units is that they represent injected sandy silts during earthquake-induced liquefaction and lateral spreading. Although the penetrative laminations are unusual for dike sands, such laminations were documented in the conduit of sand boils associated with flood-induced liquefaction along the Mississippi River in 1993 (Li et al., 1996). Along the upper and lower contacts of these two units are discontinuous dark brown silty fragments, a few cm to about ten centimeters thick (Figure 4c). As mentioned above in Section 2.3.1, it is likely that these fragments were forced up from underlying layers during clastic diking events. It is permissible, however, that units L-2 and L-3 are structurally tilted to the north, and the inclined laminations originally were sub-horizontal and related to alluvial deposition.

2.3.3 Evidence for Lateral Spreading, Secondary Zone

Evidence for minor, secondary liquefaction and normal faulting is present within a 4-m-wide zone at the northern end of trench T-1, below the secondary lateral spread crack mapped on air photos following the 1989 Loma Prieta earthquake (Plate 1 and Figure 2). North- and south-dipping normal faults with displacements of < 1 cm to 4 cm are visible where they cut laminated deposits and unit contacts, but commonly cannot be traced through massive silt and sand deposits. The faults are of limited extent both in the strike and dip direction, and form a zone of down-to-the north normal faulting that accommodates north-south extension and minor lateral spreading towards the Pajaro River within a larger failed block.

It is unclear whether the faults within the secondary zone failed only during the 1989 earthquake, or whether some of the faults may have formed during prior earthquakes. One line of evidence suggesting that some of the faults in the secondary zone slipped during prior events comes from the cementation observed across them (C. Prentice, personal communication, 2003). Several of the faults in the secondary zone had slight cementation of sand grains, which created positive relief on the trench wall after lightly brushing the wall with a fine paint brush. Normal faults within fine sandy layers at the primary lateral spread zone tended to produce negative relief on the trench wall after lightly brushing it. The cementation of the sand and silt grains within the faults in the northern zone may have required several decades to form, indicating that the faults pre-date the 1989 earthquake. A second line of evidence for pre-1989 displacement on the northern zone comes from the upward terminations of several of the faults below unit 70 (Plate 1). Faults a through h, between stations 25 and 27 in the eastern trench wall, terminate at the unit 60-70a contact. Although we infer an event horizon on the primary lateral spread zone to be at the base of units 70b and 80a, the common upward termination directly below the event horizon is suggestive of a prior event. Alternatively, the upward terminations could reflect a contrast in ductility of the materials, and a different failure mechanism in response to strain. Because the total displacement on each individual fault within the northern fault zone is minor, and the total displacement across the zone is small compared to the displacement across the primary lateral spread zone, we interpret the northern zone to accommodate minor amounts of displacement within a larger block that fails repeatedly by lateral spreading during strong ground shaking.

2.4 Discussion

Evidence for multiple episodes of liquefaction and lateral spreading is clear in all trench wall exposures, and indicates that lateral spreading has been a repeatable phenomenon at this location (Plates 1-3). Most of the differential horizontal displacement has been localized adjacent to the buttress unconformity; minor amounts of extension have occurred within the secondary zone of deformation exposed at the northern end of trench T-1. Although we cannot preclude that additional differential horizontal or vertical motion has occurred north of our trench exposures during past lateral spreading events, our results suggest that the buttress unconformity that marks the boundary between susceptible, younger floodplain deposits and non-susceptible, mid Holocene deposits has provided a primary geologic control on the localization of lateral spreading failures.

2.4.1 Event Chronology, Primary Lateral Spread Zone

Cross-cutting relationships, structural tilting of layers, and measurements following the 1989 Loma Prieta earthquake suggest that at least three, and possibly four, episodes of lateral spreading occurred across the Miller Farms site. In the discussion below, we refer to the most recent event (1989) as event I, the penultimate event as event II, and successively earlier events as events III and IV.

Event I occurred in 1989, and resulted in about 33 to 40 mm of horizontal opening and 65 mm of down-to-the-north vertical offset across ground cracks near the location of trench T-1 (Holzer et al., 1994). An additional 48 mm of horizontal opening and net 12 mm of down-to-the-north vertical offset occurred across the broad northern lateral spread zone. No sand blows were observed at the ground surface near trenches T-1 or T-2, although sand blows in the younger floodplain deposits within about 150 m of the trenches were silty sands to sands with minor silt, and median grain sizes of 0.08 to 0.22 mm (Table 2; Bennett and Tinsley, 1995). The amount and style of deformation recorded at the surface are consistent with failure by normal faulting observed within trenches T-1 and T-2 at the primary and secondary lateral spread zones. Numerous normal faults that produced minor offset within the primary zone likely were formed or reactivated during the 1989 earthquake sequence.

Event II produced clastic diking in trench T-1 and normal faulting with minor clastic diking in trench T-2. Liquefaction deposit L-10 in trench T-1 is the most apparent manifestation of failure during event II, with injected sandy silts truncating units 100b in the north side and 40c on the south side of the failure zone, and truncated only by the modern plow zone unit 130a (Plates 1 and 2). The measured width of L-10—1.0 m—is an approximation for the horizontal opening during event II, because the 3.3 to 4.0 cm opening measured after the most recent event is less than 5% of the total width and is within the uncertainty of the event II displacement. It is unclear whether the other dike-injection L-units within trench T-1, including L-8, L-9, L-10a, and L-10b, were injected during the penultimate earthquake and its aftershocks or during a separate earthquake sequence, although below we speculate that L-9 was produced during event III. The similar grain-size distribution of the units L-8, L-9, L-10a, L10c, and L-10d indicate that similar source layers liquefied, and that the source layers were different than the source layers that produced sand blows from event I (Table 2).

In trench T-2, evidence for vertical displacement on the order of 50 cm across normal faults that cut the unit 60-70a contact exceeds the 6.5 cm of vertical offset observed at the surface, and provides the most direct evidence for event II there (Plate 3). Liquefaction units L-3 and L-2 may have intruded by dike injection during event II also. The numerous normal faults that appear to terminate at the upper boundary of unit L-3 (e.g., faults “g” and “f”), or within unit L-3 (fault “i”) appear to instead transfer normal displacement from the faults to slip parallel to laminations. Thus, unit L-3 likely pre-dates or formed contemporaneously with most normal faulting observed in the trench wall.

Because a clastic dike from event II truncates all but the youngest unit close to the primary lateral spread zone, we infer that the event occurred relatively recently. The obvious candidate is the 1906 San Francisco earthquake, which produced extensive liquefaction and lateral spreading in the vicinity of Miller Farms (Lawson et al., 1908; Youd and Hoose, 1978). No other historic earthquake between 1906 and 1989 produced liquefaction in the Watsonville area, and Youd and Hoose (1978) did not encounter evidence for liquefaction from the 1890 earthquake near Watsonville.

Event III is recorded most clearly in trench T-1 by the southward tilting of units 60 and 70a (Plates 1 and 2 and Figure 3b). The south dips of the unit 70a contacts and laminations in unit 60, which extend for about three meters north of the unconformity, were produced by deformational and not depositional processes. Most likely, the southern tilts were produced by gravitational collapse of the units in response to withdrawal of underlying sediments during clastic diking. Because unit 70b appears to fill in the depression created by the southern tilting, and overlying units show dips to the north, we interpret the event horizon marking event III to lie between the unit 70a-70b contact and the lower part of unit 70b. This event must have been different from event II because the event II-related liquefaction units L-10c and L-10d cut units stratigraphically above the event horizon for event III. Liquefaction unit L-9 cuts unit 70a and forms an irregular contact with the lower part of unit 70b. Thus, it is consistent that unit L-9 is an injected sand dike or sand blow that formed during event III.

The timing of event III is loosely constrained by two radiocarbon dates (Table 1). Detrital charcoal samples collected from units 60 and 80b bracket the event horizon, and their ages represent maximum limiting ages for the deposits. We infer that event III occurred after A.D. 1400 and prior to 1906, the presumed date of event II. This time period includes several historic and prehistoric events on the San Andreas fault zone, including ground-rupturing events near Watsonville at Mill Canyon and Arano Flat constrained to have occurred in A.D. 1720-1776, 1650-1730, 1520-1620, and 1430-1510 (T. Fumal, personal communication, 2003). We also note that the penultimate 1906-type event on the northern San Andreas fault, which may have occurred around A.D. 1600 (Knudsen et al., 2002), is within this time period.

It is possible that trench T-2 records a fourth unique event, event IV. Liquefaction units L-2 and L-3, which dip moderately to the north, are most likely injected sand deposits that intrude units 50 and 60.

However, truncations of the moderately dipping laminations of unit L-3 against the horizontal laminations of unit 60 (observed between stations 11 and 11.5) suggest a cross-cutting relationship that has a younger unit 60 cutting an older unit L-3 (Plate 3 and Figure 4c). In this scenario, the sequence of events would be: (1) emplacement of liquefaction-related unit L-3 during the event IV, (2) erosion of the former land surface and deposit intruded by L-3, (3) deposition of units 60 and 70a, and (4) liquefaction and south tilting of units 60 and 70a during event III. A simpler explanation of the apparent cross-cutting relationship between units 60 and L-3 is that the laminations, formed during dike injection, terminated against unit 60 along more gently dipping portions of the contact. Overall, the laminations are sub-parallel to both the unit 60 and unit L-2 contacts. Based on its simplicity, we presently prefer the latter explanation that does not require a fourth unique event.

2.4.2 Implications for Repeatability

2.4.2.1 Paleo-Earthquake Record at the Miller Farms Site

Lateral spreading recurred in a localized zone at least three, and possibly four times within the past several hundred years at the Miller Farms site along the Pajaro River floodplain. The most recent deformation event was the 1989 M 7.1 Loma Prieta earthquake, which caused ground cracking and minor normal faulting. It is probable that the 1906 M 7.8 San Francisco earthquake, which ruptured the San Andreas fault at least as far south as the Monterey Bay Area and caused widespread lateral spreading (Lawson, 1908), triggered the penultimate lateral spreading event recorded at our site. The more apparent manifestations of lateral spreading associated with the penultimate event – greater amounts of normal faulting (trenches T-1 and T-2) and clastic diking that extended to the ground surface (trench T-1) – probably reflects the greater magnitude, intensity, and duration of shaking of the 1906 earthquake than the most recent event. It is possible that the 1906 event, with attendant clastic diking and/or large normal faulting, obliterated or masked evidence for lesser-magnitude, 1989-type events such as the 1890, 1838, and possibly earlier event documented by Fumal et al. (2003). Unambiguous evidence for the ante-penultimate event (event III) is the structural tilting of units likely related to dike injection, which possibly occurred during the A.D. ~1600 event. Thus, the earthquake record preserved in the trench stratigraphy possibly underestimates the number of events that produced liquefaction and lateral spreading there, and only records large-magnitude events or local events with the greatest shaking intensity.

2.4.2.2 Geologic Controls on the Localization of Lateral Spreading

Lateral spreading along the Pajaro River near Watsonville appears to have a strong geologic control. The recurring failure within a narrow zone recorded in the trenches is perhaps surprising, given: (1) the variability in paleo-shaking intensity and duration among earthquakes recorded; (2) the possible differences in paleo-groundwater levels; and (3) the variable distances between lateral spreading and the free face, represented by the banks of the Pajaro River. The third consideration is observable from the 1989 lateral spread across Miller Farms (Figure 2). The lateral spread did not maintain a constant distance from the river bank free face but rather trended obliquely to the modern Pajaro River. The distance from the lateral spread to the free face at the river bank ranged from 250 m in the western portion of Miller Farms to 100 m at the trench site to zero where the lateral spread intersected the Pajaro River bank east of the Kiwi Fruit Arbor. The Pajaro River was likely in an identical position during the 1906 earthquake, given that the present river locally follows the border between Santa Cruz and Monterey Counties as it was defined in 1850.

A geologic contact, which our trenches reveal to be a buttress unconformity that dips about 60° north and extends at least five meters below the ground surface, appears to control the location of lateral spreading. The 1989 lateral spread closely followed the mapped geologic contact between older and younger floodplain deposits across the Miller Farms site (Holzer et al., 1994). Both the CPT and SPT data sets (Holzer et al., 1994; Bennett and Tinsley, 1995) and piezovane data (Charlie et al., 1998) at the Miller Farms site show contrasting geotechnical properties on either side of the contact: finer-grained, lower-susceptibility deposits south of the geologic contact within the mid-Holocene overbank deposits contrast with high-susceptibility, coarser-grained deposits north of the contact within the late-Holocene point-bar and proximal overbank deposits. As mentioned previously, sand blows and secondary cracks were limited to the younger floodplain sediments north of the contact, reflecting the higher susceptibility of the younger floodplain deposit.

The recurrence of lateral spreading at the Miller Farms site has implications for evaluating lateral spread hazards. Subsurface exposures of Pajaro River floodplain facies suggest that the juxtaposition of younger units and older units favors lateral spreading failure. This is a mapable contact used to evaluate liquefaction susceptibility (Dupré and Tinsley, 1980), and it is arguable that this contact should also be used to delineate a zone of high susceptibility to lateral spreading. Our results support the case that, in certain geologic environments, lateral spreading hazard may be identifiable as discrete zones of failure, similar to earthquake surface fault rupture. It is possible, at least in certain geologic environments, that geologic boundaries, and not distance from a free face, control the location of lateral spreading. If additional research documents repeated failures along mapable geologic contacts with contrasting strength properties in certain environments, mitigation measures correspondingly may be localized to the likely discrete locations of spreading.

3.0 CILKER ORCHARDS SITE, COYOTE CREEK

The Coyote Creek floodplain near Milpitas, California experienced widespread failures during both the 1868 Hayward and 1906 San Francisco earthquakes (summarized in Youd and Hoose, 1978), and is located close to the active Hayward, Calaveras, and San Andreas faults (Figure 1). The Cilker Orchards study site is at an elevation of about 15 feet above sea level and is located 4 km south of the southern margin of San Francisco Bay, where fluctuations in historic ground water levels are minimized by the Bay. Given fairly constant ground water conditions, the Coyote Creek site offers an excellent opportunity to test the hypothesis that lateral spreading is repeatable.

3.1 Geologic Setting

Coyote Creek flows along an alluvial plain that occupies the southern part of a broad structural basin occupied by the San Francisco Bay (Figure 1). The Cilker Orchards site is underlain by late Holocene levee deposits of Coyote Creek that are highly susceptible to liquefaction (Knudsen et al, 2000). Overflow channels and swales within the distal alluvial fan have been filled in by extensive agricultural grading and industrial development, although the present ground surface still slopes gently westward, away from the river channel. The Coyote Creek channel that borders the Cilker Orchards site to the west has been modified historically for flood control. Levees constructed in 1993 enclose portions of the natural levee deposits proximal to the channel and surround older, middle to late 19th century levees about three feet tall and 20 feet wide that closely parallel the ~3-m high river banks (Figure 6). The Cilker Orchards site is presently cultivated for annual vegetable crops. Between 1923 and 1985 the site hosted a pear and apple orchard; prior to that, cereal and/or vegetable crops were cultivated (W. Cilker, personal communication, 2003).

3.2 History of Lateral Spread Failures

Extensive liquefaction and lateral spreading occurred on the Coyote Creek distal alluvial fan during the 1868 Hayward and 1906 San Francisco earthquakes (Lawson, 1908, Youd and Hoose, 1978). The most dramatic and comprehensive observations of liquefaction-related phenomena in the area are presented by Taber (1906), Lawson (1908), and Weatherbe (1906), and are compiled by Youd and Hoose (1978). Lateral spreading during the 1906 earthquake was observed primarily adjacent to, and parallel to, the Coyote Creek stream channel, mainly along the artificial levee paths. Features described at the Cilker Orchards site include cracks and failures along the banks of the stream, fissures up to eight feet wide (and nearly equal depth), failed bridge abutments, spouting craters three to 15 inches (8 to 38 cm) in diameter in the adjacent fields, and twisted and staggered rows of trees in the adjacent orchards (Lawson, 1908; Weatherbe, 1906). A second zone of lateral spreading occurred near the former Boot Ranch house, 1500 to 2000 feet (460 to 610 meters) west of Coyote Creek (Lawson, 1908). This lateral spread produced a N43°W-trending graben with cracks about six inches (15 cm) wide and about one foot (30 cm) vertical displacement. Although the exact location of the Boot Ranch house is uncertain (S. Hoose, personal communication, 2003), the lateral spreading may have coincided with a north-flowing slough documented on historical maps of the site vicinity (B. Cilker, written communication, 2003).

Similar reports of lateral spreading exist for the 1868 Hayward earthquake along Coyote Creek, including ground cracking and failures parallel to the river banks (Lawson, 1908; Toppozada and Parke, 1982).

The 1989 Loma Prieta earthquake did not cause observable liquefaction along the Coyote Creek distal alluvial fan (EERI, 1990). Egan et al. (1992) performed a detailed geotechnical assessment of the Cilker

Orchards site following the 1989 event to examine why liquefaction did not occur in this area that both liquefied historically and has been mapped as having high susceptibility (Knudsen et al., 2000). They concluded that the duration of strong ground shaking from this more distant earthquake was not sufficient to trigger liquefaction, and thus lateral spreading, in the Coyote Creek area.

3.3 Previous work at the Cilker Orchards site

The Egan et al (1992) study provides valuable geotechnical borehole and CPT data for the site that we utilized to locate our trench. The study sampled the floodplain along two transects on the Cilker Orchard site. The southern transect, their B-B' (shown in Figures 3 and 5 in Egan et al., 1992), revealed a saturated, susceptible sequence of fine sands and silts about 3.7 meters (12 feet) below the ground surface that thins westward and extends at least 150 meters (500 feet) west of Coyote Creek.

3.4 Results

We located our trench above the susceptible deposits identified in the Egan et al (1992) study, extending from the base of the 1993 levee 93 meters (300 feet) to the west (Figure 6). Because the massive 1993 levee was constructed partially over and west of the circa-1906 levee, we were unable to excavate within 38 meters (125 feet) of the banks of Coyote Creek and within 21 meters (70 feet) of the circa-1906 levee path, where most of the reported cracking and lateral spreading apparently occurred. However, the reports of "twisted and shifted trees in the orchard" (Weatherbe, 1906) after the 1906 event held promise that lateral spreading extended into the floodplain. Furthermore, our trench site provided a test as to whether lateral spreading occurred within deposits identified as highly susceptible to liquefaction both based on regional mapping (Knudsen et al., 2000) and site-specific geotechnical studies (Egan et al., 1992).

A rubber-tire backhoe with a 36-inch bucket excavated a 93-m- (300-foot-) long trench (trench T-1) to a depth of 1.5 m (5 feet), with the exception of an 8-m- (26-foot-) wide section excavated to a maximum depth of 3 m (10 feet) (Plate 4). We cleaned all trench walls to expose fresh surfaces, and logged the south trench wall at a scale of 1 inch = 1 meter (about 1:40). Groundwater was encountered in a hand-auger hole beneath the deep portion of the trench at 3.2 m (10.5 feet) below the ground surface. We did not excavate to the susceptible layer of loose to medium dense silty sands and sandy silts identified by Egan et al (1992).

<u>3.4.1 Trench Stratigraphy</u>

Trench T-1 exposed a uniform, layered sequence of fine sand to sandy silt levee/proximal overbank deposits that record a latest Holocene history of aggradation (Plate 4). The trench did not show evidence for lateral spreading, although two sub-vertical sand dikes exposed at stations 3.0 and 25.5 record liquefaction of underlying deposits. The 10- to 50-cm-thick layers vary from clean, cross-bedded sands indicating predominantly bedload transport to massive silty sands and sandy silts with abundant silty rip-up clasts, indicating deposits of suspended load in sediment-laden flood waters. A few units—notably unit 65—contain laminar silts that show abrupt contortions that we interpret as dewatering structures likely related to rapid deposition of suspended load, perhaps at the tail end of the flood hydrograph as discharge decreased. The units generally parallel the ground surface, and dip gently away from Coyote Creek. The amount of scour between depositional events is unclear, as abrupt unconformities were not identified, and unit truncations may be explained by facies boundaries, and not unconformities. One exception may be the overflow channel deposits within unit 50. This unit coarsens from silty sand at the east and west ends of the trench to medium-coarse sand with pebbles between about stations 50 and 65. Within the coarse facies the unit appears to scour slightly into underlying unit 40.

Limited dating control is provided by large mammal bones and a radiocarbon analysis of a single detrital charcoal samples (Plate 4 and Table 2). Bones collected from unit 50 include bovine(?) rib and leg bones at stations 4.5 and 12, respectively, and a mandible, likely from an elk, at station 51. As cattle have occupied the central California region since their introduction in the late 18th Century, the presence of bovine bones indicate that unit 50, and likely the entire sequence, is less than a few hundred years old. A large piece of detrital charcoal sampled from a charcoal-rich horizon at the base of unit 40 (RC-312, trench meter 75) yielded a calibrated radiocarbon date of AD 1670 to 1950 (Table 2). Thus, it is permissible, although not certain, that the stratigraphy in the trench pre-dates the 1886 and 1906 earthquakes, and the sand dikes represent liquefaction from one (or both) of those events. Because the detrital charcoal sample provides only a maximum limiting age for the deposits in unit 40 and above in the trench, it is possible that the stratigraphy in the trench completely post-dates 1906. Although we consider this unlikely, the implication of this scenario is that the sand dikes in the trench would represent liquefaction from the 1989 Loma Prieta earthquake that was not expressed at the surface following that event (Egan et al., 1992).

Table 4. Radiocarbon Age and Calibration of Charcoal Sample, Cilker Orchards Site

Sample Code	Lab No.[a]	Age[b], 14C yr B.P. ± 1 σ	13C/12C Ratio	Calibrated Date[c] (95.4 % confidence)	Probab-ility (%)[d]	Sample Location	Stratigraphic Unit
CC-RC312	187519	120 ± 40	-25.8 ‰	Cal AD 1670 to 1780 Cal AD 1800 to 1950	36.2 59.2	Coyote Cr. T1	Unit 40

[a] Sample pretreatment and analysis at Beta Analytic Laboratories, Miami, Florida
[b] AMS technique
[c] Calibration with OxCal v.3.9 (Bronk Ramsey, 2001) using atmospheric data of Stuiver et al. (1998)
[d] Percent probability of age interval

Sediment samples collected for pollen analysis throughout the trench stratigraphy had poor pollen preservation, and were not useful for determining the presence or absence of a non-native grass species introduced in the late 18th century (L. Reidy, written communication; Appendix B).

3.4.2 Evidence for Paleoliquefaction and Lateral Spreading

Trench T-1 exposed two thin (three- to five-mm-wide) sand dikes at stations 3.0 and 25.5 (Plate 4), which demonstrate that liquefaction disrupted the strata exposed in the trench. Both dikes cropped out on opposite trench walls, and have similar cross-trench strikes of N60°W (at meter 3) and N55°W (at meter 25.5). This orientation is roughly sub-parallel to a northwest-trending reach of Coyote Creek near the trench site (Figure 6). The dikes are filled with clean sand, although they appear to tap different source beds (or at least different facies within the same bed): the station 3 dike contains fine sand and the station 25.5 dike contains medium sand.

The dikes terminate upwards in different horizons, but it is doubtful that the different upward terminations represent separate dike injection events. Although the station 3 dike terminates at the lower contact of unit 70 and was traced downward to the maximum depth explored (Plate 4), the station 25.5

dike terminates upward within unit 50, and terminates downward within the upper few centimeters of unit 14 on both trench walls. The clean, medium sand within the station 25.5 dike is clearly distinguishable from the silty fine to medium sand of unit 14, but is similar to the saturated, clean, medium sand of unit 8 recovered in the hand-auger boring at a depth of four meters below the ground surface. We infer that the sand dike has a discontinuous lateral extent, and thus penetrates the source bed (at or below unit 8) into or out of the planes formed by the trench walls. Thus, the upward extent of the station 25.5 dike exposed in the trench walls is likely a poor indicator of the ultimate upward termination of the dike.

3.5 Discussion

Evidence for lateral spreading was not encountered within the trench exposure, located above susceptible deposits that likely had strong ground shaking during historical earthquakes. Evidence for liquefaction is recorded in the two sand dikes that were most likely produced during the 1906 earthquake.

The opportunity for further study of paleo-lateral spreading along the Coyote Creek distal alluvial fan near the Cilker Orchards site appears limited. Excavation closer to the 1906 levee is hampered by the construction of the improved levees in 1993, earth moving within the flood-control facility, and its present zoning as an ecologically sensitive corridor.

4.0 CONCLUSIONS

4.1 Summary of Results from the First-Year Study

During our first year of funding, we excavated two trenches across a lateral spread that failed within the Pajaro River floodplain near Watsonville during the 1989 Loma Prieta earthquake, and a single trench within natural levee deposits of the distal alluvial fan of Coyote Creek near Milpitas in the vicinity of reported lateral spreading from the 1906 and 1868 earthquakes (Figure 1). Exploratory trenches across the late Holocene floodplain of Pajaro River, near Watsonville, northern California, successfully revealed evidence for repeated sand injection and lateral spreading at a predictable location along a buttress unconformity between mid Holocene floodplain deposits and late Holocene to historic fluvial deposits of an aggraded inset river terrace of Pajaro River (Dupré and Tinsley, 1980). We excavated two trenches across a 1.7 km-long lateral spread formed after the 1989 Loma Prieta earthquake, on the Miller Farms study site (Holzer et al., 1994). In addition to liquefaction-related features produced in 1989, the trench walls revealed evidence for two to three prior lateral spread failures and associated liquefied sand bodies at the same location. Significant lateral spreading did not occur elsewhere within the trenches despite the presence of deposits susceptible to liquefaction. This result suggests that lateral spreading is controlled at least as much by geologic boundary conditions as by geotechnical parameters such as distance from a free face or duration of strong ground motion.

In this first-year study, three trenches at two study sites produced significant and exciting results and stimulated several ideas regarding the repeatability of lateral spreading:

(1) Trenches across the 1989 lateral spread along the Pajaro River near Watsonville revealed evidence for multiple lateral spreading events within a narrow zone that coincides with a mapped geologic contact; little internal deformation has occurred within the failed block.

(2) The repeated lateral spreading appears to have strong geologic control – it recurs at a buttress unconformity between nonsusceptible and susceptible floodplain deposits, and not at an arbitrary location within the susceptible floodplain deposits.

(3) Lateral spreading occurred, and likely recurred, along this geologic contact that does not parallel the Pajaro River bank free face and is located up to 200 meters from the free face.

(4) Lateral spreading likely recurred along the same zone during several causative earthquakes of contrasting magnitude, shaking intensity, and shaking duration.

(5) Because the failure zone at Miller Farms occurred along a mapable geologic contact, careful site-specific investigations have the potential to identify and characterize these zones, perhaps with the ability to predict the location and magnitude of future lateral spread failure.

(6) A trench across the Coyote Creek floodplain near Milpitas that crosses susceptible late Holocene levee deposits did not find evidence for lateral spreading. Although a single radiocarbon date suggests depositional history between A.D. 1670 and 1950 (Table 4), sand dikes confirm that underlying sediments have liquefied historically. Because the floodplain did not show evidence of liquefaction following the 1989 Loma Prieta earthquake, the sand dikes probably are related to earlier historical events, including the 1906 San Francisco and 1886 Hayward earthquakes.

(7) The Cilker Orchards site provides a potential test case for geotechnical models that predict the location of lateral spreading based on material susceptibility, free-face geometry, and ground-motion parameters (e.g., Egan et al., 1992).

4.2 Future Work

The results of our first-year study provide questions and goals for future work. It appears that, at least in certain geologic environments, careful geological and geotechnical studies may identify zones of past, repeated lateral spread failure, and thereby have the potential to anticipate locations of future lateral spreads. Our successful trench excavations of the Pajaro River floodplain at the Miller Farms site show that lateral spreading has been repeatable along a readily identifiable geologic and geotechnical boundary, and has not occurred randomly within the younger floodplain deposits that are highly susceptible to liquefaction. On the basis of this result, we consider a hypothesis that in fluvial environments, steeply dipping unconformities between laterally accreted point-bar and channel deposits and vertically accreted distal floodplain deposits within a critical distance from a free-face represent boundaries that localize lateral spread failure. Lateral spreading in this fluvial geomorphic environment is controlled by geologic boundary conditions, and is neither random nor exclusively a function of geotechnical and seismological parameters. We hope to test this idea at additional sites of historic lateral spread failure, including at Ferris Farms, on the opposite side of Pajaro River directly north of Miller Farms (Figure 2). Here, previous detailed geotechnical investigations (Holzer et al., 1994; Bennett and Tinsley, 1995) and Quaternary geologic mapping (Dupré and Tinsley, 1980) suggest a setting similar to Miller Farms.

In contrast, lateral spreading in more distal fluvial environments, particularly in deltaic or estuarine environments, may be less likely to be repeatable, and thus less predictable. Lateral spreading during the 1989 Loma Prieta earthquake occurred over broad zones along the tidally influenced, distal Salinas River channel in the Monterey Bay lowlands (Bennett and Tinsley, 1995; Tinsley et al., 1998). A preliminary evaluation of geotechnical data indicates that no abrupt geotechnical or geological boundary condition persists. Thus, the distributed pattern of lateral spreading in this distal environment may reflect a less predictable setting, and lateral spreading hazard may be considered “random” across such a zone of high susceptibility deposits close to a free face.

A collaborative approach is critical to test this approach: Geotechnical studies designed to identify boundaries between susceptible and non-susceptible units must be combined with detailed geologic studies of stratigraphic facies and depositional environment in order to identify the presence or absence of abrupt geologic (and geotechnical) boundaries that may localize lateral spreading failure. Continuation of detailed subsurface investigations at sites of historical lateral spreading in contrasting depositional environments will contribute significantly toward understanding the predictability of lateral spreads and how best to characterize and map the locations of potential future lateral spreads on future probabilistic permanent ground deformation maps.

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FIGURES AND PLATES

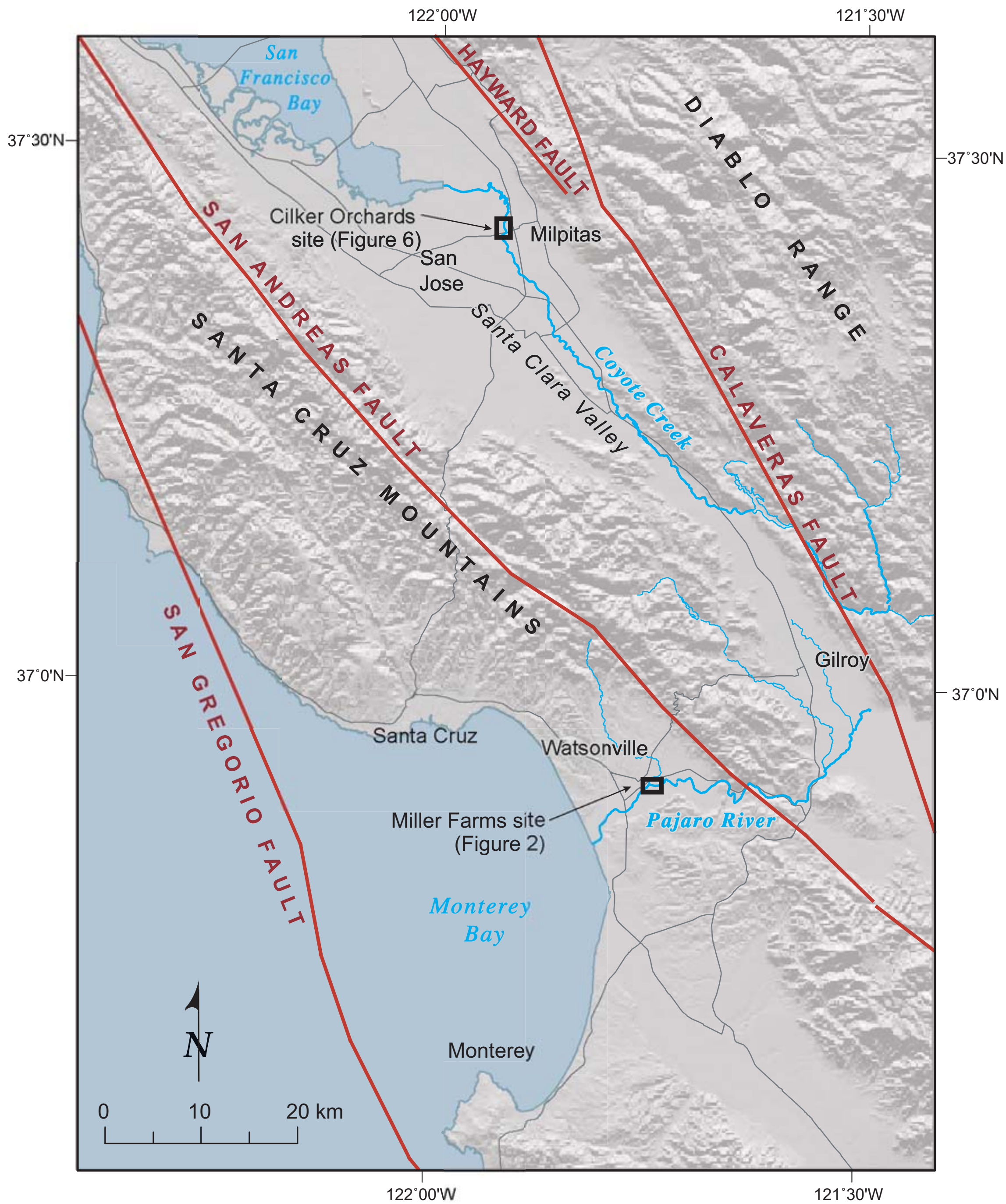


Figure 1. Regional map of the southern San Francisco Bay and Monterey Bay areas, showing locations of the Miller Farms study site on the Pajaro River and Cilker Orchards study site on Coyote Creek. Generalized traces of the San Andreas, Calaveras, Hayward, and San Gregorio faults are in red. Gray lines are major area roads.

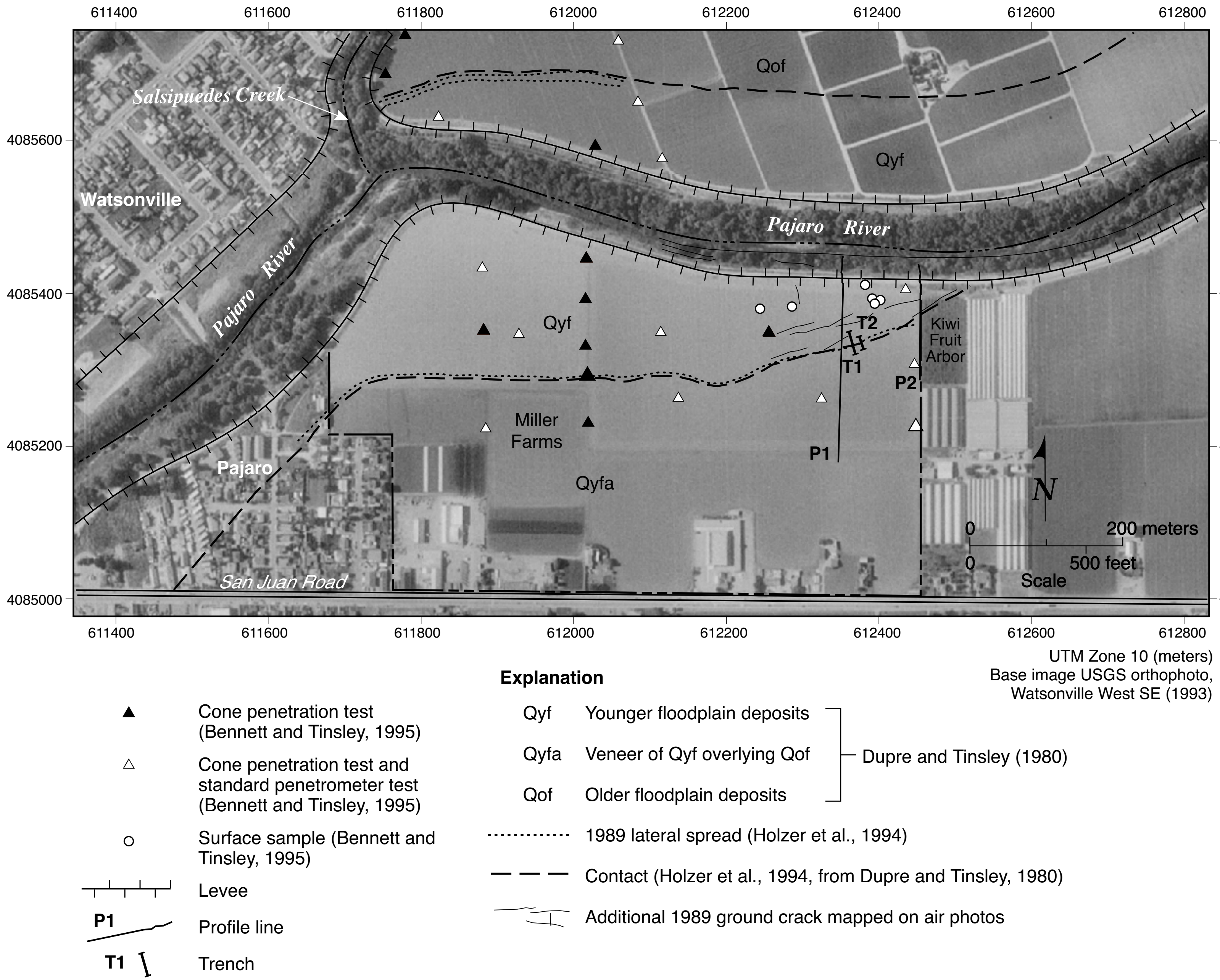


Figure 2. Map of Miller Farms site showing the 1989 lateral spreads, Quaternary deposits, locations of CPT and SPT samples, and trench locations.

A)

B)

Figure 3. A) View of the west wall, trench T-1, Miller Farms site, towards the north. Mid-Holocene floodplain deposits at the left side of the photo are juxtaposed against younger point-bar, channel, and proximal levee deposits at the right end of the photo. A zone of clastic dikes (bounded by pink and yellow flags) and normal faults (red flags) provides evidence of past lateral spreading (see Plate 2). String grid is 1 meter. B) View to the south from the floor of trench T-1, Miller Farms site. The base of Unit 70a, marked by the light blue flags, is structurally tilted to the south for about three meters directly north of the lateral spread failure zone (the close concentration of pink and red flags in the middle distance). The structural tilting occurred during the ante-penultimate lateral spread event.

A)

B)

C)

Figure 4. Photographs of trench T-2, west wall, in the zone of lateral spreading (See Plate 3 for log of trench wall). A) Upper portion of lateral spread zone, showing older floodplain deposits (on left-hand side of photo, under dark blue flags) and veneer of younger floodplain deposits (left-hand side of photo, above blue flags), juxtaposed against younger point-bar and levee deposits (right-hand part of photograph). Red flags mark normal faults within the unconformity zone that accommodated lateral spreading. B) Lower portion of unconformity and lateral spread zone. Red flags delineate normal faults that have accommodated the majority of lateral spreading failure at this location. C) Detail of the contact between units 60 and L-3. Unit 60 has sub-horizontal laminations cut by numerous steeply dipping normal faults. Unit L-3 has inclined laminations dipping north (down to the right). Dark brown silty fragments that separate the two units may have been intruded during clastic dike injection of unit L-3.

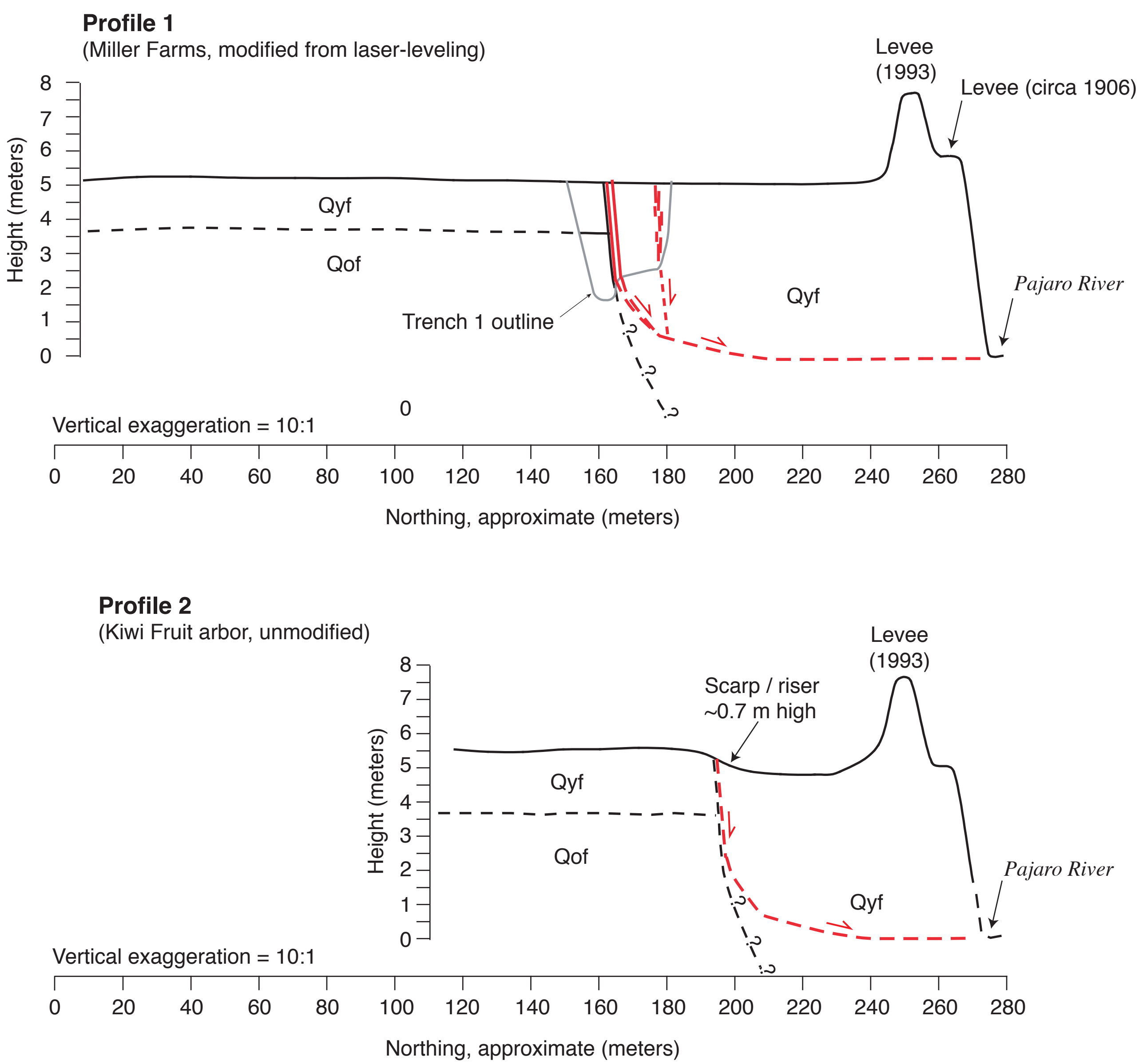


Figure 5. Profiles 1 and 2 across the Pajaro River floodplain, and generalized cross-section showing lateral spread failure plane along the contact between older floodplain deposits and younger channel, point-bar, and proximal floodplain deposits. Although the land along Profile 1 has been repeatedly laser-leveled for agriculture, Profile 2 borders the laser-leveled area, and likely represents a natural profile. The scarp, likely, is related to the contact with the younger channel and point-bar deposits aggrading to form an inset terrace. Vertical displacement during lateral spread events likely contribued to the scarp formation. See Figure 2 for profile locations.

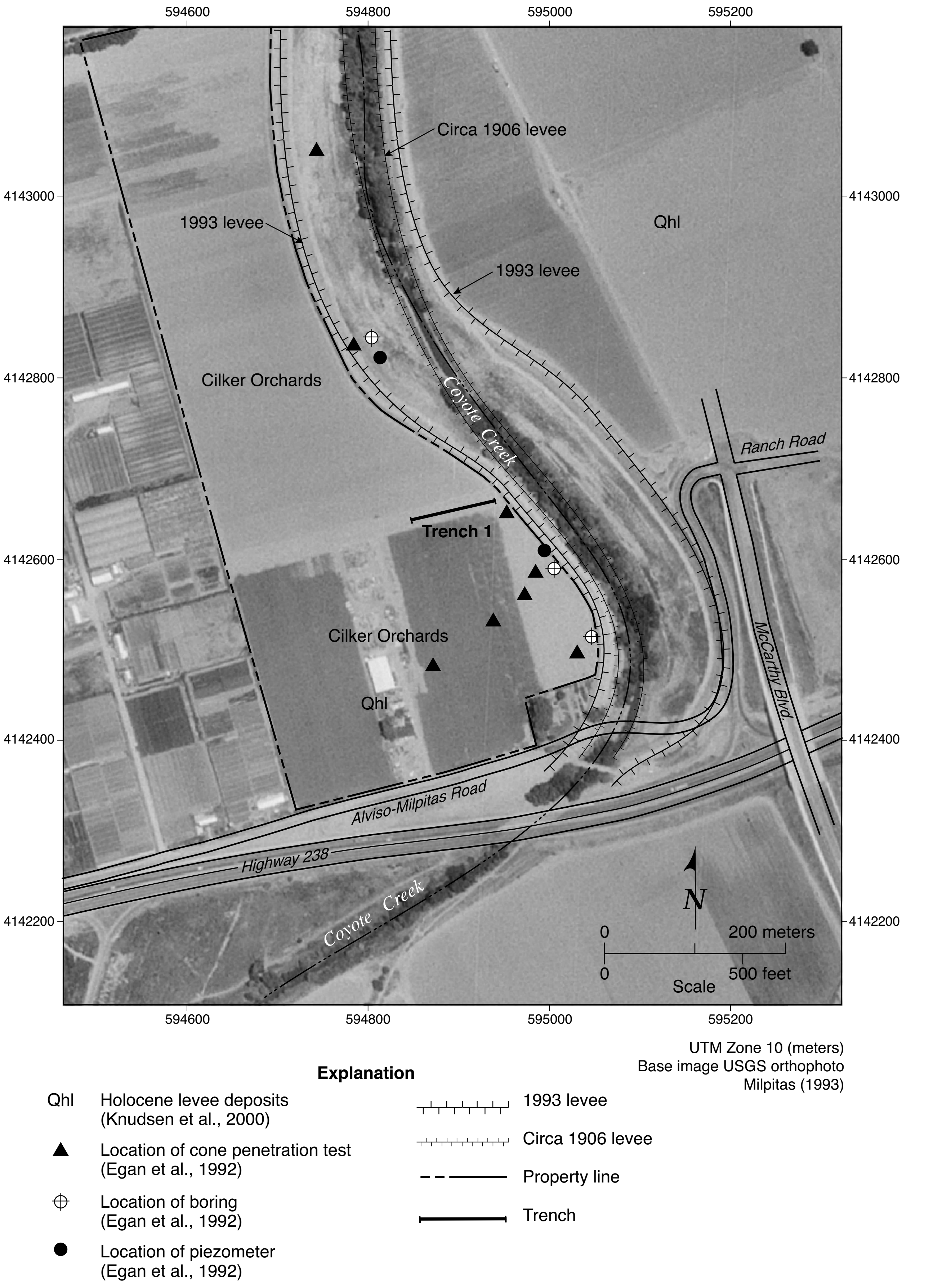


Figure 6. Map of Cilker Orchards site showing Coyote Creek and levees, geotechnical test locations, and trench.

Explanation

Symbols

- Fault, dashed where less certain
- 32° Dip of lamination
- P-2 ▲ Pollen sample
- S-30 ● Grain-size analysis sample

Unit Descriptions

South of unconformity [Qof of Dupré and Tinsley (1980), middle Holocene]:

10a SAND, fine with silt and minor clay (SM); brown (10YR 4/3); moist; massive; loose; low plasticity; poorly graded; does not effervesce to HCl; basal contact not exposed. [ALLUVIUM (proximal overbank or point-bar deposits)].

10b SILT with fine sand and clay (ML); dark brown (10YR 3/3); moist; massive; loose; low plasticity; poorly graded; minor organic accumulation; slight effervescence to HCl; clear to gradual, smooth basal contact. [ALLUVIUM (proximal overbank or point-bar deposits) with minor soil development].

20a SILT with fine sand and clay (MH); brown (10YR 4/3); moist; massive; loose; medium plasticity; poorly graded; does not effervesce to HCl; clear and smooth basal contact. [ALLUVIUM (overbank deposits)].

20b CLAY with silt (CH); olive-brown (2.5Y 4/3); moist; stiff; medium to high plasticity; poorly graded; very few (<1%) carbonate nodules in pore spaces average 8mm long; locally abundant detrital charcoal near lower part of unit; clear and smooth basal contact. [ALLUVIUM (overbank deposits)].

20c SILT with clay (ML); mottled olive-brown (2.5Y 4/4) and reddish yellow; damp; stiff; medium plasticity; poorly graded; does not effervesce to HCl; evidence of bioturbation common; gradual and smooth to wavy basal contact. [ALLUVIUM (overbank deposits)].

20d SILT with minor clay and sand (ML); light olive-brown (2.5Y 5/4), with few yellowish-red mottles; damp; very stiff; low plasticity; poorly graded; does not effervesce to HCl, except for rare carbonate nodules in pore spaces that average 8mm long; evidence of bioturbation common; clear to gradual and smooth basal contact. [ALLUVIUM (overbank deposits) with a buried Cox soil horizon].

20e CLAY with silt (CH); mixed dark olive-brown (2.5Y 3/3) and light olive-brown (2.5Y 5/4); damp; very stiff; medium plasticity; poorly graded; very few (~1%) stage I filamentous carbonate in root pores, decrease downwards; few (3 to 5%) carbonate nodules in pore spaces average 8 mm long; thin clay coatings on pore walls and on ped faces; peds are sub-angular to angular, 2 to 3 cm in diameter; light olive-brown color mixed with dark olive-brown at the base of the unit along root casts(?); gradual and wavy basal contact. [ALLUVIUM (distal overbank deposits) with a buried Bt soil horizon].

20f SILT with clay and minor sand (MH); dark grayish brown (2.5Y 4/2) (moist); dry; very stiff; medium plasticity; poorly graded; organic accumulation; common stage I filamentous carbonate in pore spaces; peds angular to sub-angular, blocky, 1 to 2 cm in diameter; few obvious krotovina (rodent burrows), bioturbation near the upper boundary; clear and wavy basal contact. [ALLUVIUM (distal overbank deposits) with a buried A soil horizon with carbonate accumulation].

Unit Descriptions (continued)

South of unconformity [Qyfa of Dupré and Tinsley (1980), late Holocene]:

30a Unit 30a: SILT with minor clay and very fine sand (ML); light yellowish brown (2.5Y 6/3); dry; very stiff; low plasticity; poorly graded; slight effervescence to HCl; sharp and smooth to irregular (where stirred by bioturbation) basal contact. [ALLUVIUM (proximal overbank deposits)].

30b Unit 30b: SILT with minor clay and very fine sand (ML); light yellowish brown (2.5Y 6/4); dry; massive; very stiff; low plasticity; poorly graded; discontinuous, thin organic accumulation at upper contact; does not effervesce to HCl; sharp and smooth to irregular (where stirred by bioturbation) basal contact. [ALLUVIUM (proximal overbank deposits) with minor incipient soil development].

40a SILT with minor clay and very fine sand (ML); light yellowish brown (2.5Y 6/4); dry; very stiff; low plasticity; poorly graded; does not effervesce to HCl; rare bioturbation disrupts continuity of unit; sharp and smooth basal contact. [ALLUVIUM (proximal overbank deposits)].

40b SILT with very fine sand (ML); light yellowish brown (2.5Y 6/4); dry; massive; very stiff; low plasticity; poorly graded; does not effervesce to HCl; sharp and smooth to irregular (where stirred by bioturbation) basal contact. [ALLUVIUM (proximal overbank deposits)].

40c SILT with very fine sand and clay (ML); light olive brown (2.5Y 5/3); dry; massive; very stiff; medium plasticity; poorly graded; many 0.5-1 mm roots, few roots to 4 mm; bioturbation common to abundant; clear and wavy basal contact. [ALLUVIUM (proximal overbank deposits)].

130a SILT with clay and very fine sand (ML); grayish brown (2.5Y 5/2); dry; massive; very stiff; medium plasticity; poorly graded; abundant roots 0.5 mm; many 1-4 mm roots; sub-horizontal and vertical soil partings; organic accumulation; clear to gradual and wavy basal contact. [ALLUVIUM (proximal overbank deposits) and modern plow zone].

North of unconformity [Qyf of Dupré and Tinsley (1980), late Holocene]:

60 SAND, fine with silt (SM); light yellowish brown (2.5Y 6/3); 64% sand, 32% silt, 4% clay, D50 = 0.089; dry; loose; poorly graded; laminations and elongate cross beds 1 to 3 mm; southern portion of unit inclined to south, towards unconformity, indicating structural tilting related to liquefaction and/or lateral spreading; basal contact not exposed. [ALLUVIUM (point-bar deposits), locally deformed].

70a SILT with very fine sand (ML); light olive-brown (2.5Y 5/3); 83% silt, 10% sand, 7% clay (lower part); 74% silt, 23% sand, 3% clay (upper part); slightly damp and friable to dry and loose; massive except for fine laminations and fine cross beds in sandier upper part of unit; upper part of unit also contains convolute bedding, flame structures, and small, discontinuous subvertical sand dikes consistent with liquefaction (<3%) carbonate nodules ~1 mm diameter; where unit is not overlain by 70b, the upper contact is defined by a discontinuous organic-rich zone about 5 cm thick that indicates incipient soil development; clear and smooth to wavy basal contact. [ALLUVIUM (point-bar or proximal overbank deposits), deformed, with incipient soil development].

70b SILT with very fine sand and clay (ML); olive-brown (2.5Y 4/2 to 4/3); slightly damp to dry; stiff, slightly plastic, massive, poorly graded; wedge-shaped deposit that tapers away from unconformity; minor organic accumulation indicated by olive brown color; sharp to clear and wavy to irregular basal contact. [ALLUVIUM or COLLUVIUM (scarp-derived material and reworked point-bar or proximal overbank deposits), possibly in a marsh-like environment due to organic accumulation].

Unit Descriptions (continued)

80a SILT (ML); light yellowish brown (2.5Y 6/3); dry; stiff; nonplastic; massive to weakly laminated; poorly graded; clear and smooth basal contact. [ALLUVIUM (proximal overbank deposits)].

80b SILT with clay and very fine sand (ML); olive-brown (2.5Y 4/3); dry; stiff; slightly plastic; massive; poorly graded; wedge-shaped deposit that merges with Units 70b and 90c towards the unconformity; organic accumulation indicated by olive brown color; sharp to clear and smooth to wavy basal contact. [ALLUVIUM or COLLUVIUM (scarp-derived material and reworked point-bar or proximal overbank deposits), possibly in a marsh-like environment due to organic accumulation].

90a SAND, very fine, with silt (SM); light olive-brown (2.5Y 5/3); dry; stiff; nonplastic; massive; distinguishable from overlying Unit 90b by lack of silt rip-up clasts; sharp to clear and smooth to wavy basal contact. [ALLUVIUM (point-bar or proximal overbank deposits)].

90b SILT with minor very fine sand and clay (ML); light olive-brown (2.5Y 5/3); dry; stiff; nonplastic; massive with silt and soil rip-up clasts to 1 cm; well graded; detrital (?) carbonate nodules up to 3 mm in diameter; clear to gradual and smooth lower contact. [ALLUVIUM (proximal overbank deposits)].

90c SILT with very fine sand and clay (ML); olive-brown (2.5Y 4/3); dry; stiff; slightly plastic; massive; poorly graded; organic accumulation indicated by olive brown color decreases away from unconformity; unit distinguishable from underlying 80a by increase in silt/clay rip-up clasts; clear to gradual and smooth basal contact. [ALLUVIUM (proximal overbank deposits), with organic accumulation from possible marsh-like environment close to the unconformity].

100a SILT with minor very fine sand and minor clay (ML); light yellowish brown (2.5Y 6/3) with light olive brown (2.5Y 5/3) interbedded laminae in upper 3 cm of unit; dry; stiff; nonplastic; fine laminar bedding; sharp and smooth to wavy basal contact. [ALLUVIUM (overbank deposits)].

100b SILT with very fine sand (ML); light yellowish brown (2.5Y 6/3); dry; moderately stiff; nonplastic; massive with silty rip-up clasts; moderately graded; clear to gradual and wavy basal contact. [ALLUVIUM (proximal overbank deposits)].

110a SILT (ML); light yellowish brown (2.5Y 6/3); dry; stiff; nonplastic; massive; coarsens upwards to very fine sand; clear and smooth basal contact. [ALLUVIUM (proximal overbank deposits)].

110b SAND with silt and SILT with fine sand (SM and ML); grayish brown (2.5Y 5/2); dry; loose to stiff; nonplastic; cross-bedded silty sands at base to more massive sandy silts with rip-up clasts to 2 cm in diameter; locally bioturbated; sharp to clear and wavy basal contact. [ALLUVIUM (overflow channel and point-bar deposits), may represent historic change to higher energy environment, although no cultural artifacts were encountered].

110c SILT with fine sand (ML); grayish brown (2.5Y 5/2); dry; loose; nonplastic; fine cross-beds; sharp and wavy basal contact. [ALLUVIUM (overflow channel and point-bar deposits)].

110d SAND with silt and SILT with fine sand (SM and ML); grayish brown (2.5Y 5/2); dry; moderately stiff; nonplastic; fine laminar bedding and cross-beds; unit coarsens to north, locally extensively bioturbated; clear and wavy to locally irregular basal contact where it overlies Unit 100c, gradual basal contact where it overlies Unit 110b. [ALLUVIUM (overflow channel and point-bar deposits)].

120 SILT with sand (ML); light yellowish brown (2.5Y 6/3); dry; stiff; nonplastic; massively bedded with rip-up clasts; unit may be subdivided in northern end of trench based on slight changes in concentration of silt/clay rip-up clasts, and local content of organic material (incipient soil?); locally strongly bioturbated; clear and wavy to irregular basal contact. [ALLUVIUM (proximal overbank deposits)].

130b SILT with fine sand and minor clay (ML); grayish brown (2.5Y 5/2); dry, very stiff, low plasticity, massive, poorly graded, abundant roots 0.5 mm; many 1 to 4 mm roots; subhorizontal and vertical soil partings; organic accumulation; higher sand concentration and less clay than lateral equivalent Unit 130a; clear to gradual and wavy basal contact. [ALLUVIUM (proximal overbank deposits) and modern plow zone].

Unit Descriptions (continued)

Liquefaction deposits (in unconformity zone):

L-6 (Unit 60) SAND, fine with silt (SM); light yellowish brown (2.5Y 6/3); dry to damp; loose to medium dense; poorly graded; laminations and elongate cross beds 1 to 3 mm; some areas lack laminae and are massive; L-6 disrupted by closely spaced normal fault, predominantly north-dipping; laminae bounded by faults often appear inclined or tilted as if dragged or rotated by faulting. [FAULTED AND ROTATED ALLUVIUM].

L-7 (Unit 60) SAND, fine with silt (SM); light yellowish brown (2.5Y 6/3); 85% sand, 13% silt, 2% clay, D50 = 0.187; coarser than unit 60 to north, but similar color and laminated character; dry to damp; loose; alternating very fine sand and fine sand laminations <1 to 1 to 5 mm thick; laminae dip moderately north near southern contact, and dip south near northern contact with L-8, possibly caused by drag folding or warping along boundaries of sub-unit; locally cut by high-angle normal faults. [DEFORMED AND FAULTED ALLUVIUM].

L-8 SILT, sandy (ML); brownish gray; 55% silt, 40% sand, 5% clay, D50 = 0.067 mm; dry to damp; loose to medium dense; poorly graded; predominantly massive, although locally present laminae dip north 30° to 35°, subparallel to the margins of the sand body. In the east wall of Trench 1, the lower margin of this unit appears to obscure north-dipping bedding of Unit 60. Unit L-8 terminates downward at Unit L-6 (faulted Unit 60) on the east wall of Trench 1, and to the floor of the trench on the west wall of Trench 1; slightly finer grained material than Units L-9 and L-10 may indicate different source bed. [CLASTIC DIKE RELATED TO LIQUEFACTION].

L-9 SILT, sandy (ML); gray to brownish gray; 50% sand, 44% silt, 6% clay, D50 = 0.073 mm; notably coarser than adjacent Unit 70a; dry to damp; medium dense; massive; randomly dispersed silty rip-up clasts up to 0.5 to 1 cm; weak laminations occur locally, 1 to 2 mm thick; some laminations dip moderately south; unit appears to intrude lower contact of Unit 70b; east wall contains silty sub-unit. Unit L-9 terminates downward at Unit 70 and Unit L-6 (faulted Unit 60); connection with deeper source layer presumed to occur outside of the plane of the trench walls; may share same source as Unit L-10 based on similar grain-size distribution. [CLASTIC INJECTION FEATURE RELATED TO LIQUEFACTION].

L-10 SILT, sandy (ML); brownish gray; 48% sand, 46% silt, 6% clay, D50 = 0.073 mm; medium dense; unit divided into four subunits: L-10a, b, c, and d. L-10a is predominantly massive but with some subhorizontal to gently south-dipping weak laminations parallel to the lower contact with Unit 30(?); Unit L-10b is a very fine sand to silt bed approximately 1 cm thick that appears draped over L-10a and terminates at the south end near Unit 40a; unit L-10c is massive with fewer and less prominent laminae; L-10d contains conspicuous mica grains and is mostly massive with gently to moderately north-dipping laminae that locally parallel the lower boundary. Unit L-10 terminates downward at units L-9 and L-6 (faulted Unit 60); connection with deeper source layer presumed to occur outside of the plane of the trench walls; may share same source as Unit L-9 based on similar grain-size distribution. [CLASTIC DIKE RELATED TO LIQUEFACTION].

L-11 SILT, with sand (ML); light yellowish brown to light olive-brown; dry; medium dense to dense; massive; associated with slump block, within zone of liquefaction dike injection and normal faulting, but not clearly related to stratigraphy north or south of the deformation zone; common subrounded fragments or "clasts" of brown clayey silt lie within this unit and along the margins of the liquefaction dikes, although the origins of the clayey silt fragments are not clearly injected from below or slumped by gravitational collapse from above. [REWORKED ALLUVIUM WITHIN DEFORMATION ZONE].

L-12 SAND, silty (SM); 51 to 55% sand, 38 to 40% silt, 7 to 9% clay; dry; loose; three subvertical injection dikes within units 80a and 90c near north end of trench; two dikes align with normal faults; all dikes terminate downward within Unit 80a, terminate upward at base of Unit 100b or within Unit 90c. [CLASTIC DIKE RELATED TO LIQUEFACTION].

Notes

1. Discontinuous, brown silty soil A horizon overlies Unit L-10d. Sand from L-10d appears to penetrate up and through the soil, which is possibly the remainder of Unit 90c or Unit 40c.
2. Fault strike, dip = N80°E, 70°N.
3. Sand present along cracks (minor injected sand dikes)
4. Fault offsets, northern fault zones:

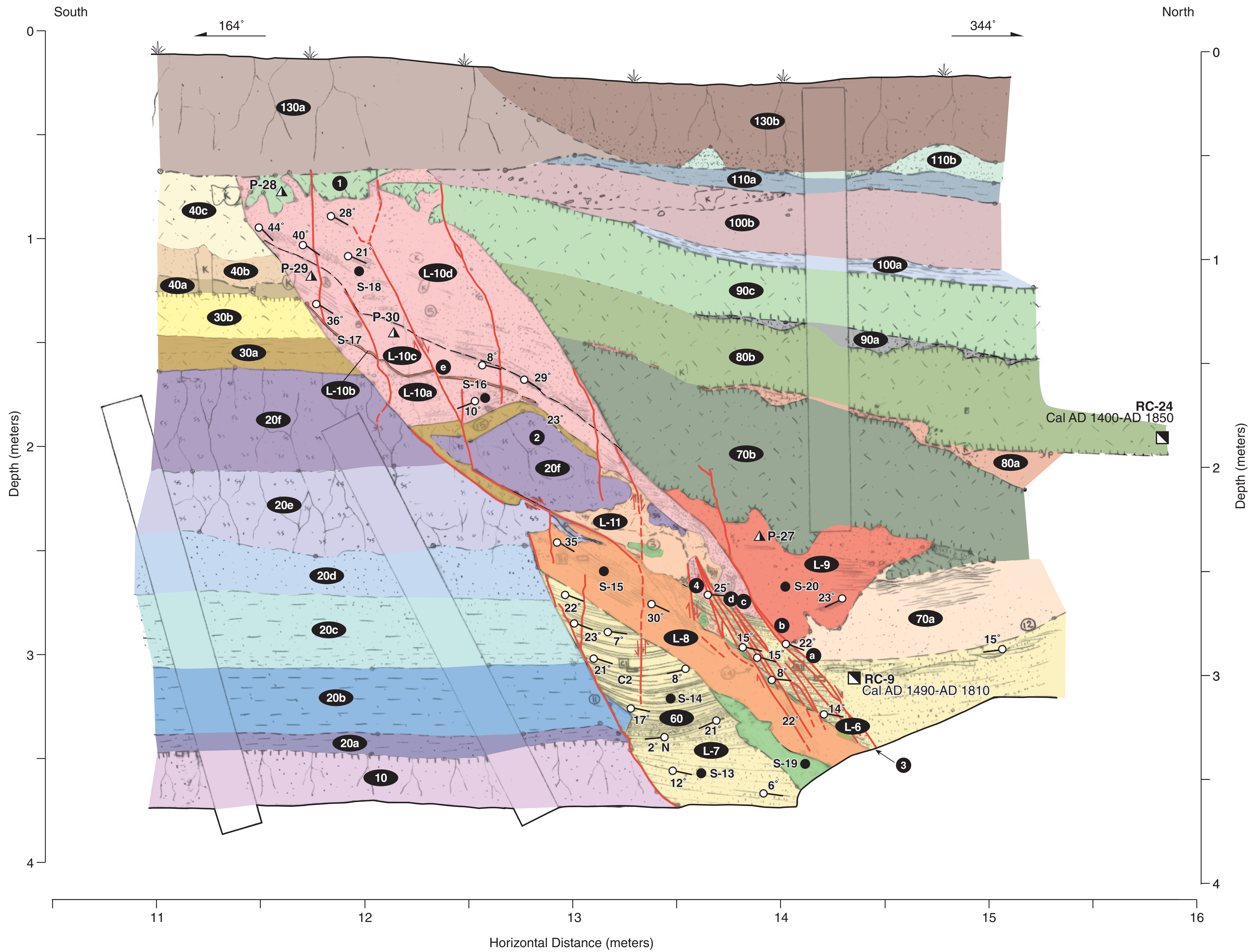
Fault	Vertical Offset (cm)	Down to the North (N) or South (S)
a	0.3	N
b	0.3	N
c	0.7	N
d	0.5	S
e	0.8	S
f	0.2	S
g	0.2	S
h	0.5	N
i	2.0	S
j	1.7	N
k	3.2	N
l	3.8	S
m	2.5	N
n	3.0	N
o	1.8	N
p	1.8	N
q	1.9	N
r	2.1	N
s	1.0	N
t	2.9	N

REPEATABILITY OF LATERAL SPREADING

Miller Farms Trench T-1, East Wall

WLA William Lettis & Associates, Inc. | Plate 1

1574 Lateral Spread



Explanation

Symbols

Fault, dashed where less certain

15° Dip of lamination

RC-24 Radiocarbon sample

S-15 Gain-size analysis sample

P-28 Pollen sample

Notes

1. Discontinuous, brown silty soil A horizon overlies Unit L-10d. Sand from L-10d appears to penetrate up and through the soil, which is possibly the remainder of Unit 90c or Unit 40c.
2. Slump block of Unit 20f and overlying silt Unit 30a emplaced by rotation and translation. Estimated dip slip is 36 cm.
3. Brown silty fragments (shown in green) are either derived from Unit 20 during stream bank collapse or injected with silt and sand dikes during liquefaction events.
4. Total estimated vertical offset of the top of Unit 60 is 37 to 41 cm.

Measurement	Apparent Dip	Dip slip (cm)
a	46 N	8 to 11
b	47 to 50 N	13 to 17
c	50 N	3 to 4
	63 N	3 to 4
d	53 N	5 to 8
e	67 N	4 to 4.5

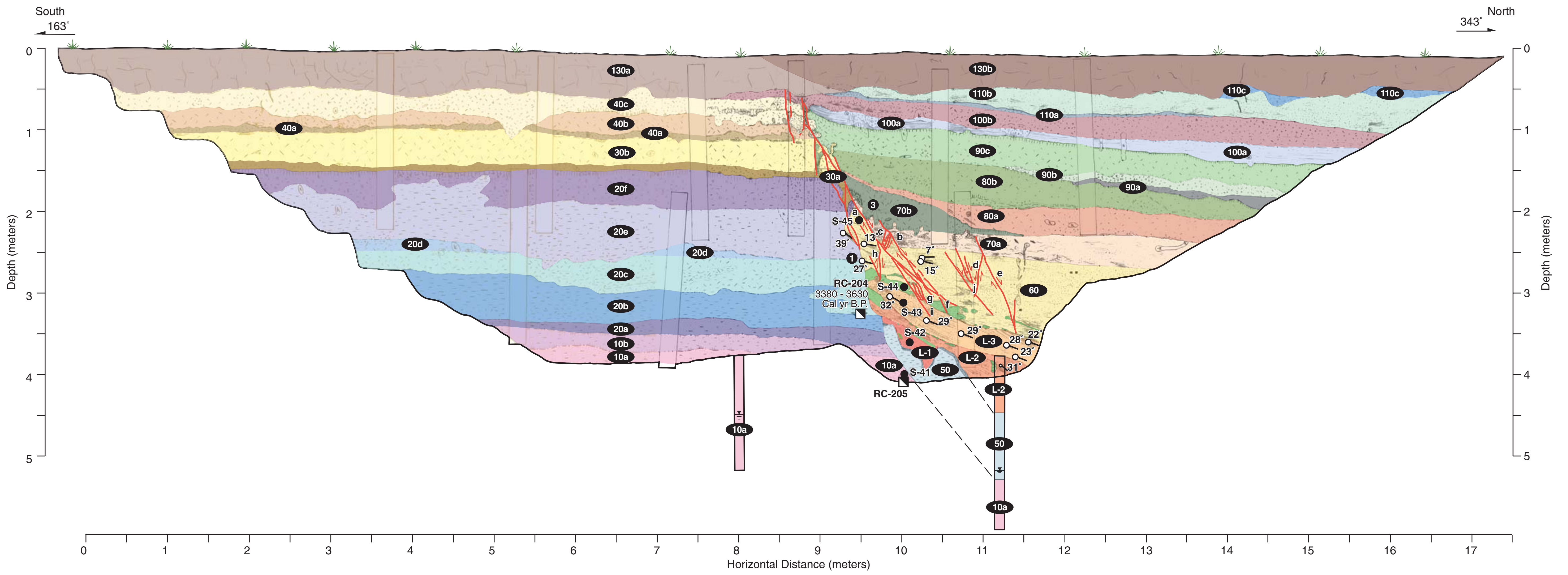
For unit descriptions see Plate 1.

REPEATABILITY OF LATERAL SPREADING

Miller Farms Trench T-1, West Wall

WLA William Lettis & Associates, Inc. | Plate 2

1574 Lateral Spread



Symbols

Fault, dashed where less certain

Dip of lamination

RC-201 Radiocarbon sample

S-30 Sample for grain-size analysis

Explanation

Unit Descriptions

North of unconformity [Qyf of Dupré and Tinsley (1980), late Holocene]:

130b SILT with fine sand and minor clay (ML); grayish brown (2.5Y 5/2); dry, very stiff, low plasticity, massive, poorly graded, abundant roots 0.5 mm; many 1 to 4 mm roots; subhorizontal and vertical soil partings; organic accumulation; higher sand concentration and less clay than lateral equivalent unit 130a; clear to gradual and wavy basal contact. [ALLUVIUM (proximal overbank deposits) and modern plow zone].

110c SILT with fine sand (ML); grayish brown (2.5Y 5/2); dry; loose; nonplastic; fine cross-beds; sharp and wavy basal contact. [ALLUVIUM (overflow channel and point-bar deposits)].

110b SAND with silt and SILT with fine sand (SM and ML); grayish brown (2.5Y 5/2); dry; loose to stiff; nonplastic; cross-bedded silty sands at base to more massive sandy silts with rip-up clasts to 2 cm diameter; locally bioturbated; sharp to clear and wavy basal contact. [ALLUVIUM (overflow channel and point-bar deposits), may represent historic change to higher energy environment, although no cultural artifacts were encountered].

110a SILT (ML); light yellowish brown (2.5Y 6/3); dry; stiff; nonplastic; massive; coarsens upwards to very fine sand; clear and smooth basal contact. [ALLUVIUM (proximal overbank deposits)].

100b SILT with very fine sand (ML); light yellowish brown (2.5Y 6/3); dry; moderately stiff; nonplastic; massive with silty rip-up clasts; moderately graded; clear to gradual and wavy basal contact. [ALLUVIUM (proximal overbank deposits)].

100a SILT with minor very fine sand and minor clay (ML); light yellowish brown (2.5Y 6/3) with light olive brown (2.5Y 5/3) interbedded laminae in upper 3 cm of unit; dry; stiff; nonplastic; fine laminar bedding; sharp and smooth to wavy basal contact. [ALLUVIUM (overbank deposits)].

90c SILT with very fine sand and clay (ML); olive-brown (2.5Y 4/3); dry; stiff; slightly plastic; massive; poorly graded; organic accumulation indicated by olive brown color decreases away from unconformity; unit distinguishable from underlying 80a by increase in silt/clay rip-up clasts; clear to gradual and smooth basal contact. [ALLUVIUM (proximal overbank deposits), with organic accumulation from possible marsh-like environment close to the unconformity].

90b SILT with minor very fine sand and clay (ML); light olive-brown (2.5Y 5/3); dry; stiff; nonplastic; massive with silt and soil rip-up clasts to 1 cm; well graded; detrital (?) carbonate nodules up to 3 mm diameter; clear to gradual and smooth lower contact. [ALLUVIUM (proximal overbank deposits)].

Unit Descriptions (continued)

90a SAND, very fine, with silt (SM); light olive-brown (2.5Y 5/3); dry; stiff; nonplastic; massive; distinguishable from overlying unit 90b by lack of silt rip-up clasts; sharp to clear and smooth to wavy basal contact. [ALLUVIUM (point-bar or proximal overbank deposits)].

80b SILT with clay and very fine sand (ML); olive-brown (2.5Y 4/3); dry; stiff; slightly plastic; massive; poorly graded; wedge-shaped deposit that merges with Units 70b and 90c towards the unconformity; organic accumulation indicated by olive brown color; sharp to clear and smooth to wavy basal contact. [ALLUVIUM or COLLUVIUM (scarp-derived material and reworked point-bar or proximal overbank deposits), possibly in a marsh-like environment due to organic accumulation].

80a SILT (ML); light yellowish brown (2.5Y 6/3); dry; stiff; nonplastic; massive to weakly laminated; poorly graded; clear and smooth basal contact. [ALLUVIUM (proximal overbank deposits)].

70b SILT with clay and very fine sand (ML); olive-brown (2.5Y 4/2 to 4/3); slightly damp to dry; stiff, slightly plastic, massive, poorly graded; wedge-shaped deposit that tapers away from unconformity; minor organic accumulation indicated by olive-brown color; sharp to clear and wavy to irregular basal contact. [ALLUVIUM or COLLUVIUM (scarp-derived material and reworked point-bar or proximal overbank deposits), possibly in a marsh-like environment due to organic accumulation].

70a SILT with very fine sand (ML); light olive-brown (2.5Y 5/3); 83% silt, 10% sand, 7% clay (lower part); 74% silt, 23% sand, 3% clay (upper part); slightly damp and friable to dry and loose; massive except for fine laminations and fine cross beds in sandier upper part of unit; upper part of unit also contains convolute bedding, flame structures, and small, discontinuous subvertical sandy dikes or plumes consistent with sediment loading or liquefaction; few (<3%) carbonate nodules ~1 mm diameter; where unit is not overlain by 70b, the upper contact is defined by a discontinuous organic-rich zone about 5 cm thick that indicates incipient soil development; clear and smooth to wavy basal contact. [ALLUVIUM (point-bar or proximal overbank deposits), deformed, with incipient soil development]

60 SAND, fine with silt (SM); light yellowish brown (2.5Y 6/3); 64% sand, 32% silt, 4% clay, D50 = 0.089; dry; loose; poorly graded; laminations and elongate cross beds 1 to 3 mm; southern portion of unit inclined to south, towards unconformity, indicating structural tilting related to liquefaction and/or lateral spreading; basal contact sharp and irregular to planar where it overlies injected L-3 deposit. [ALLUVIUM (point-bar deposits), locally deformed].

Unit Descriptions (continued)

50 CLAY, silty or SILT, clayey and minor sand (ML-CL); yellowish brown to bluish gray; moist; soft; plastic; slight organic accumulation, but color is significantly lighter than overlying dark brown silty clay and clayey silt soil fragments; sharp and smooth basal contact along steeply dipping unconformity with Qof units [ALLUVIUM (overbank or quiet water channel-fill deposits?)].

South of unconformity [Qyfa of Dupré and Tinsley (1980), late Holocene]:

130a SILT with clay and very fine sand (ML); grayish brown (2.5Y 5/2); dry; massive; very stiff; medium plasticity; poorly graded; abundant roots 0.5 mm; many 1-4 mm roots; sub-horizontal and vertical soil partings; organic accumulation; clear to gradual and wavy basal contact. [ALLUVIUM (proximal overbank deposits) and modern plow zone].

40c SILT with very fine sand and clay (ML); light olive-brown (2.5Y 5/3); dry; massive; very stiff; medium plasticity; poorly graded; many 0.5-1 mm roots, few roots to 4 mm; bioturbation common to abundant; clear and wavy basal contact. [ALLUVIUM (proximal overbank deposits)].

40b SILT with very fine sand (ML); light yellowish brown (2.5Y 6/4); dry; massive; very stiff; low plasticity; poorly graded; does not effervesce to HCl; sharp and smooth to irregular (where stirred by bioturbation) basal contact. [ALLUVIUM (proximal overbank deposits)].

40a SILT with minor clay and very fine sand (ML); light yellowish brown (2.5Y 6/3); dry; very stiff; low plasticity; poorly graded; does not effervesce to HCl; rare bioturbation disrupts continuity of unit; sharp and smooth basal contact. [ALLUVIUM (proximal overbank deposits)].

30b SILT with minor clay and very fine sand (ML); light yellowish brown (2.5Y 6/4); dry; massive; very stiff; low plasticity; poorly graded; discontinuous, thin organic accumulation at upper contact; does not effervesce to HCl; sharp and smooth to irregular (where stirred by bioturbation) basal contact. [ALLUVIUM (proximal overbank deposits) with minor incipient soil development].

30a SILT with minor clay and very fine sand (ML); light yellowish brown (2.5Y 6/3); dry; very stiff; low plasticity; poorly graded; slight effervescence to HCl; sharp and smooth to irregular (where stirred by bioturbation) basal contact. [ALLUVIUM (proximal overbank deposits)].

Unit Descriptions (continued)

South of unconformity [Qof of Dupré and Tinsley (1980), middle Holocene]:

20f SILT with clay and minor sand (MH); dark grayish brown (2.5Y 4/2) (moist); dry; very stiff; medium plasticity; poorly graded; organic accumulation; common stage I filamentous carbonate in pore spaces; peds angular to sub-angular, blocky, 1 to 2 cm in diameter; few obvious krotovina (rodent burrows), bioturbation near the upper boundary; clear and wavy basal contact. [ALLUVIUM (distal overbank deposits) with a buried A soil horizon with carbonate accumulation].

20e CLAY with silt (CH); mixed dark olive-brown (2.5Y 3/3) and light olive brown (2.5Y 5/4); damp; very stiff; medium plasticity; poorly graded; very few (~1%) stage I filamentous carbonate in root pores, decrease downwards; few (3 to5%) carbonate nodules in pore spaces average 8mm long; thin clay coatings on pore walls and on ped faces; peds are sub-angular to angular, 2 to 3 cm diameter; light olive brown color mixed with dark olive brown at the base of the unit along root casts(?); gradual and wavy basal contact. [ALLUVIUM (distal overbank deposits) with a buried Bt soil horizon].

20d SILT with minor clay and sand (ML); light olive-brown (2.5Y 5/4), with few yellowish-red mottles; damp; very stiff; low plasticity; poorly graded; does not effervesce to HCl, except for rare carbonate nodules in pore spaces that average 8 mm long; evidence of bioturbation common; clear to gradual and smooth basal contact. [ALLUVIUM (overbank deposits) with a buried Cox soil horizon].

20c SILT with clay (ML); mottled olive-brown (2.5Y 4/4) and reddish-yellow; damp; stiff; medium plasticity; poorly graded; does not effervesce to HCl; evidence of bioturbation common; gradual and smooth to wavy basal contact. [ALLUVIUM (overbank deposits)].

20b CLAY with silt (CH); olive-brown (2.5Y 4/3); moist; stiff; medium to high plasticity; poorly graded; very few (<1%) carbonate nodules in pore spaces average 8mm long; locally abundant detrital charcoal near lower part of unit; clear and smooth basal contact; black organic material from reddish (burned) soil at trench 2 meter 9.5 has a calibrated radiocarbon date of 3380 to 3630 Cal yr B.P. [ALLUVIUM (overbank deposits)].

20a SILT with fine sand and clay (MH); brown (10YR 4/3); moist; massive; loose; medium plasticity; poorly graded; does not effervesce to HCl; clear and smooth basal contact. [ALLUVIUM (overbank deposits)].

Unit Descriptions (continued)

10b SILT with fine sand and clay (ML); dark brown (10YR 3/3); moist, massive; loose; low plasticity; poorly graded; minor organic accumulation; slight effervescence to HCl; clear to gradual, smooth basal contact. [ALLUVIUM (proximal overbank or point-bar deposits) with minor soil development].

10a SAND, fine with silt and minor clay (SM); brown (10YR 4/3); moist; massive; loose; low plasticity; poorly graded; does not effervesce to HCl; basal contact not exposed. [ALLUVIUM (proximal overbank or point-bar deposits)].

Liquefaction units (in unconformity zone):

L-1 SILT, with sand (ML); 78% silt, 17% sand, 5% clay, D50 = 0.048; yellowish brown; very moist; soft; massive or possible very fine sub-horizontal laminations; moderately well sorted; lithic rich with mica grains; sharp and irregular lower contact, possible conduit through Unit 50 suggested on opposite trench wall. [INJECTION DEPOSIT related to liquefaction, or possibly ALLUVIUM].

L-2 SILT, with sand (ML); yellowish brown to mottled gray with reddish brown mottles; moist; soft; mm-scale laminations dip about 30 degrees north, subparallel to upper contact with L-3 but truncate against L-3 contact at the north end; moderately well sorted; lithic rich with mica grains; bounded above and below by discontinuous dark brown lean clay (clayey SILT) fragments, including a large fragment that abuts the unconformity at the up-dip end. [CLASTIC DIKE RELATED TO LIQUEFACTION or possibly ALLUVIUM (structurally tilted to north by about 30 degrees if not injected sand)].

L-3 SILT, sandy (ML); 48 % silt, 48 % sand, 4% clay, D50 = 0.071; grain-size composition similar to liquefaction units in Trench 1; yellowish-brown; moist; soft; 0.5 to 2 mm-scale laminations dip about 28-32 degrees north, continuous over lengths greater than 40 cm, and parallel upper and lower contacts with L-2, Unit 60 except for at north end; laminations observed to flow around a 9 cm-long rounded clayey silt fragment on the opposite trench wall; fragments of lean clay (clayey SILT), dark brown, are discontinuous along upper and lower boundaries of L-3, and occasionally lie within the deposit; most faults appear to terminate at the upper contact with Unit 60, although a few faults can be traced into L-3. [CLASTIC DIKE RELATED TO LIQUEFACITON].

Notes

1. Strike of unconformity measured across the trench is N74°E.
2. Brown silty fragments (shown in green) are either derived from Unit 20 during stream-bank collapse or injected with silt and sand during liquefaction events
3. Fault offsets

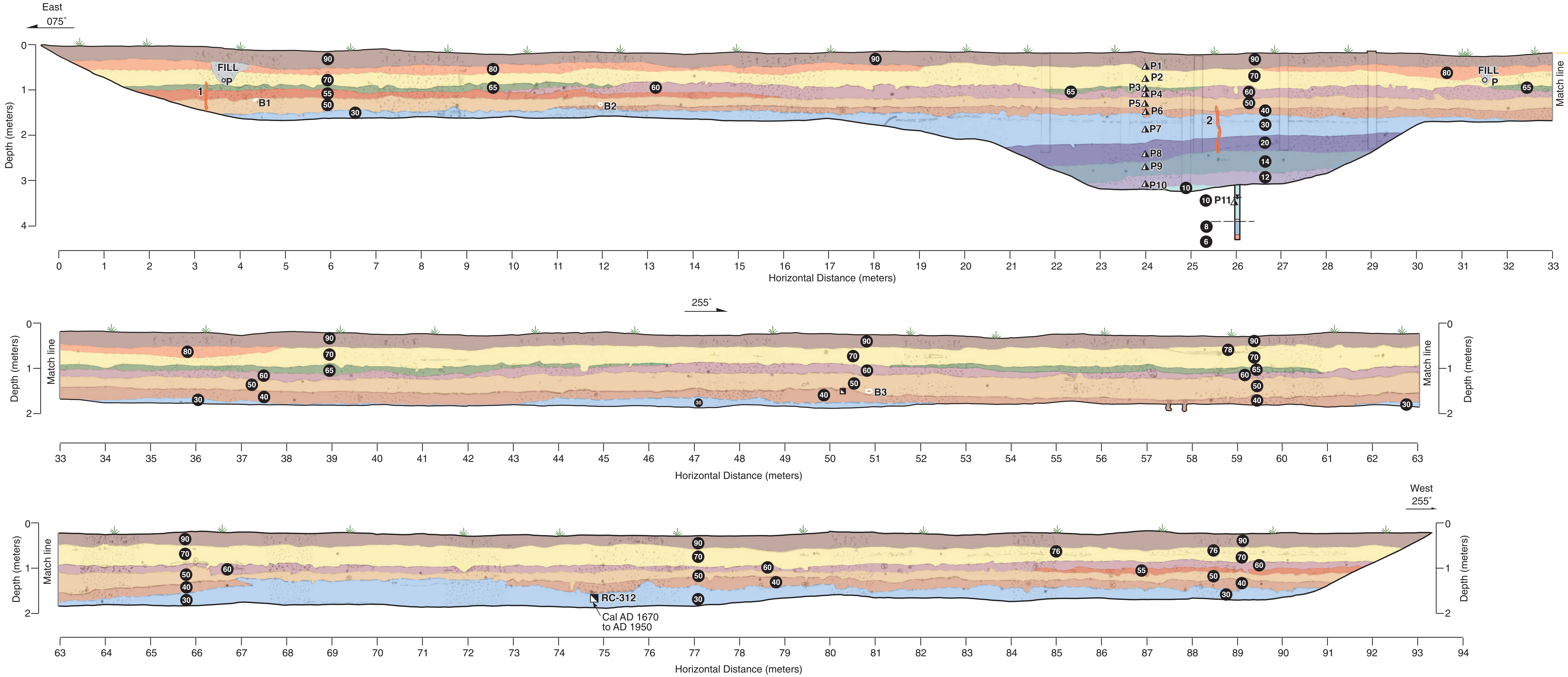
Fault	Dip	Dip Slip (cm)
a	60°N	45
b	55°N	14
c	70°S	3.7 (across three faults)
d	80°S	0.6
e	60°N	3.0
f	60°N	9.0
g	50°N	10
h	85°N	1.2
i	55°N	3
j	50°N	1

REPEATABILITY OF LATERAL SPREADING

Miller Farms Trench T-2, West Wall

WLA William Lettis & Associates, Inc. | Plate 3

1574 Lateral Spread



Explanation

Unit Descriptions

90 SAND, silty with clay (SM); light yellowish brown (2.5Y 6/4); dry; very stiff at east end of trench to soft in middle and west end; massive; poorly graded; rare pebbles, subangular to subrounded, 0.5 to 1 cm; abundant fine and very fine roots; blocky, angular peds at east end of trench; organic accumulation; basal contact gradual to clear and wavy. [ALLUVIUM (proximal overbank deposits) and MODERN PLOW ZONE].

80 SILT, with sand (ML); light yellowish brown (2.5Y 6/3); dry; very stiff; poorly graded; massive; common very fine and fine root pores; slight effervescence to HCl; fine disseminated detrital charcoal locally 5 to 10%; basal contact gradual and wavy. [ALLUVIUM (proximal overbank deposits), likely disturbed by historic plowing].

70 (including 78) SAND, very fine, silty (SM); light olive-brown (2.5Y 5/4); slightly moist to dry; stiff; poorly graded; massive mostly, with local sandy beds 0.5 to 2 cm, subhorizontal and contorted; effervescence to HCl; fine carbonate nodules in root pores; common silt rip-up clasts 3 to 5 mm in diameter, locally abundant at base of unit; Unit 78 is a local lens of finely laminated to cross-bedded silts and very fine sands; basal contact clear and wavy. [ALLUVIUM (proximal overbank deposits), locally deformed by liquefaction related to rapid sediment loading and/or strong ground shaking].

65 SILT, sandy (ML), olive-brown (2.5Y 4/4) with light yellowish brown (2.5Y 6/4) laminae; moist; soft; slight effervescence to HCl; laminae, 1 to 4 mm, abruptly contorted to sub-vertical and broken for much of the unit; silty rip-up clasts present where laminae are absent; basal contact gradual to clear and wavy. [ALLUVIUM (proximal overbank deposits to quiet water settling of suspended fines), deformed by liquefaction related to rapid sediment loading and/or strong ground shaking].

60 SAND, very fine, silty (SM) and SILT (ML); olive-brown (2.5Y 4/4); damp; soft; mixed laminar silts to fine cross-bedded silty very fine sand and massive with silt rip-up clasts; slight effervescence to HCl to locally present fine carbonate nodules in pores; laminae distorted where present, similar to Unit 65; basal contact clear and wavy. [ALLUVIUM (proximal overbank deposits), locally deformed by liquefaction related to rapid sediment loading and/or strong ground shaking].

55 SAND, silty to SILT, sandy (SM-ML), olive-brown (2.5Y 4/4); damp; soft; poorly graded; massive with abundant rip-up clasts to finely bedded with discontinuous, contorted beds; basal contact clear and wavy [ALLUVIUM (proximal overbank deposits)], locally deformed by liquefaction related to rapid sediment loading and/or strong ground shaking].

Unit Descriptions (continued)

50 SAND, fine silty (SM) to SAND, coarse (SP); olive-brown (2.5Y 4/4); damp; soft; poorly graded; massive with irregular patches of fine sand and locally apparent rip-ups; slight effervescence to HCl, and few carbonate nodules ~2 mm in diameter; abundant very fine pores; locally common detrital charcoal; unit coarsens to coarse to medium sand between trench meters 46 to 62; basal contact clear and wavy [ALLUVIUM (proximal overbank or distributary channel deposits)].

40 SAND, silty (SM); olive-brown (2.5Y 4/3); damp; soft; poorly graded; massive; sand content increases in lower part of unit; locally abundant patches of silt either rip-up clasts or bioturbation; basal contact clear and wavy. [ALLUVIUM (proximal overbank deposits)].

30 SAND, fine with silt (SP); light olive-brown (2.5Y 5/4); damp; soft; poorly graded; fine cross beds to laminar locally, elsewhere massive with silty rip-up clasts; slight effervescence to HCl; few 3 mm root pores; basal contact clear and wavy to planar. [ALLUVIUM (proximal overbank or secondary channel deposits)].

20 SILT, sandy (ML); olive-brown (2.5Y 4/3); damp; soft; low plasticity; poorly graded; massive; slight coarsening in upper 10 cm; slight mottling to gray along root pores; basal contact clear to gradual and planar. [ALLUVIUM (proximal overbank deposits)].

14 SAND, with silt (SP-SM); olive-gray (5Y 4/2) with brown mottles; moist; soft to very soft; poorly graded; massive; basal contact clear to gradual and wavy. [ALLUVIUM (proximal overbank deposits)].

12 SAND, silty with clay (SM); olive-gray (5Y 4/2); moist; soft to very soft; poorly graded; massive; lower contact clear and slightly wavy. [ALLUVIUM (proximal overbank deposits)].

10 SAND, fine to medium, with silt (SP); olive-gray (5Y 4/2); moist to wet; poorly graded; massive; basal contact not exposed. [ALLUVIUM (distributary channel or point-bar deposits)].

8 SAND, fine to medium (SP); wet; poorly graded; few fine gravel clasts, subrounded; basal contact not exposed. [ALLUVIUM (distributary channel or point-bar deposits)].

6 SAND, medium, (SP); wet; poorly graded; few fine gravel clasts rounded to subrounded; basal contact not exposed. [ALLUVIUM (channel deposits)].

Notes

1 Clastic dike, fine to medium sand; 3 mm wide; upward termination to base of Unit 70; continues downward to bottom of trench; similar upward, downward terminations on opposite (north) trench wall; N60°W strike measured across the trench.

2 Clastic dike, medium to coarse sand; 3 to 5 mm wide; upward termination within Unit 50; downward termination within upper part of Unit 14; similar upward, downward terminations on opposite (north) trench wall; sand in dike is coarser, better sorted than Unit 14; N55°W strike measured across the trench.

Symbols

Clastic sand dike

B Bone
- B1 Bovine rib bone
- B2 Bovine leg(?) bone
- B3 Elk(?) manible with teeth

P Irrigation pipe

RC-312 Radiocarbon sample

P8 Pollen sample

REPEATABILITY OF LATERAL SPREADING

Cilker Orchards Trench T-1, South Wall

WLA William Lettis & Associates, Inc. | Plate 4

1574 Lateral Spread

APPENDIX A

SOIL PROFILE DESCRIPTION, MILLER FARMS TRENCH T-1

(from J. Sowers)

SOIL PROFILE DESCRIPTION

William Lettis & Associates, Inc.

Profile: SP-1,

Site: Pervatich site / MF — Pajaro River lateral spread

Elevation: Slope: Job #:

Site description: Leveled field adjacent to the Pajaro River, in trench across lateral spread feature from 1989 earthquake. At 10.4 m in T1

Date: 9-12-03
Time: 1pm - 5:30
By: JMS

Depth (cm)	Horizon	Boundary	Color dominant	Color mottles	Structure	Gravel	Consistence	Texture	Clay films	Salts & silica	Notes: (pores, roots, HCl test samples, pH, etc.)
0–43	Ap	w, g	2.5YR 5/2 grayish brown (d)		1 m gr	0	wet: so po; dry: sh h	SiL, <5% clay	0		Bioturbated. Plowed. Fine sandy silt. Many v. fi-med roots.
43–69	A1	c, i	2.5Y 5/2 (d)		m, 1, 2, m gr	0	wet: so po; dry: sh h	SiL, <5% clay	0		Bioturbated many krotovinas. Boundary with C horizon below is very irregular. Many v.fi-med roots.
grn-bl; 69–106	C1	a s	2.5Y 6/3 (d)		m	0	wet: so po; dry: so	Fine sand; SL, ~0% clay	0	k I	Massive silt/fine sand. Lg decayed root @ 106. K = few root hole linings. Stratigraphic lower boundary
blue; 106–146	C2	a w	2.5Y 6/3 light yellowish brown (d)		m	0	wet: so po; dry: so	Fine sand; LS, ~0% clay	0	k I	Sl. darker color at top than C1. Massive silty fine sand. Separate flood event from C1 ? K = few root hole linings
dk bl; 146–159	II Ak1b	w, g	2.5Y 4/2, 5/2 (d) grayish brown - dark grayish brown (m)			0	wet: s p	SiCL, clay ~25%	0	k I	Some mixing of overlying C2 material in this horizon. Gray clayey silt with many $CaCO_3$ filaments. Many v. fine root holes 159
~lime; 159–196	II Ak2b	c w	2.5Y 4/2 dark grayish brown (d)		1 m pr sbk	0	wet: vs vp; dry: h	SiCL, clay ~40	0	k I	Gray clayey silt. Many v-fine root holes. $CaCO_3$ primarily as filaments (root hole fillings). K more abundant here than below. Some faint $CaCO_3$ coatings on ped faces. 196

Buried soil

Notes: All colors are on ped faces or broken surfaces of massive units.

Figure A1. Soil Profile description (sheet 1 of 2) for Trench 1 East wall, meter 10.5, by J. Sowers, William Lettis & Associates, Inc.

SOIL PROFILE DESCRIPTION

William Lettis & Associates, Inc.

p. 2 of 2

Profile: SP-1 | Site: Pajaro River, Pervatich site
Elevation: | Slope: | Job #:
Site description:

Date: 9-12-03
Time: 1pm-5:30pm
By: JMS

Depth (cm)	Horizon	Boundary	Color: dominant	Color: mottles	Structure	Gravel (size, rnd, %)	Consistence (wet, moist, dry)	Texture	Clay films	Salts & silica	Notes: (pores, roots, HCl test samples, pH, etc.)
225	II Btb	c, i	10YR-2.5Y 3/2, 4/2 (d); very dark grayish brown (m)		1–2, m, pr, abk	0	vs, vp; h	C; clay ~ 90%	2, d, pf, po	k, I → V	Weak prismatic structure w/ stronger blocky structure. Dark gray clay. "Filaments" of $CaCO_3$ lining root holes on ped faces. Tr. fine hard nodules, 0.5-1cm.
~orn 243	II Bt/Cb	g, i	dark grayish brown (d); 10YR-2.5Y 4/2 (m)	2.5Y 5/4, 5/3 (silt)	2, m, sbk	0	vs, vp; h, vh	SiC; clay ~75%	2, d, pf, po	k, I; tr. hard nodules	Streaks & tongues of Bt material "invading" the buff silt is charact. of this horizon. Many v. fine root holes
257	II C1	c, w	2.5Y 5/4 light olive brown (d)		m	0	ss, ps; h	Si; clay < 5%	-0-		Dry, buff silt. Many v. fine root holes
283	II C2	a, s, c	2.5Y 5/3 light olive brown (m)		m, 1, f, sbk	f, r, 10; concretions; 75 ?	fr	SiC; clay ~60%	v1, f, pf	-0-	Silty clay, sl. moist
gr-gr 325	II C3	s, g	olive brown (d); 2.5Y 4/3 (m)		1, f, sbk	f, r, 10	vs, vp; fr	C; clay = 90%	v1, 1, pf	-0-	Moist clay. Gray & orn mottles. streaks, Black to dk gray blebs and small chunks of charcoal & decomposed organics.
bl-gr 360 B.T.	II C4	N/A	10YR 3/2 (m)		m	0	so, po; vfr	S; fi-med; clay < 5%	-0-	-0-	Moist fine-med sand. Some gray & orn. mottles

Notes:

— over for notes →

May be more. Difficult to tell whether shiny surfaces are clay films or pressure faces

Figure A2. Soil Profile description (sheet 2 of 2) for Trench 1 East wall, meter 10.5, by J. Sowers, William Lettis & Associates, Inc.

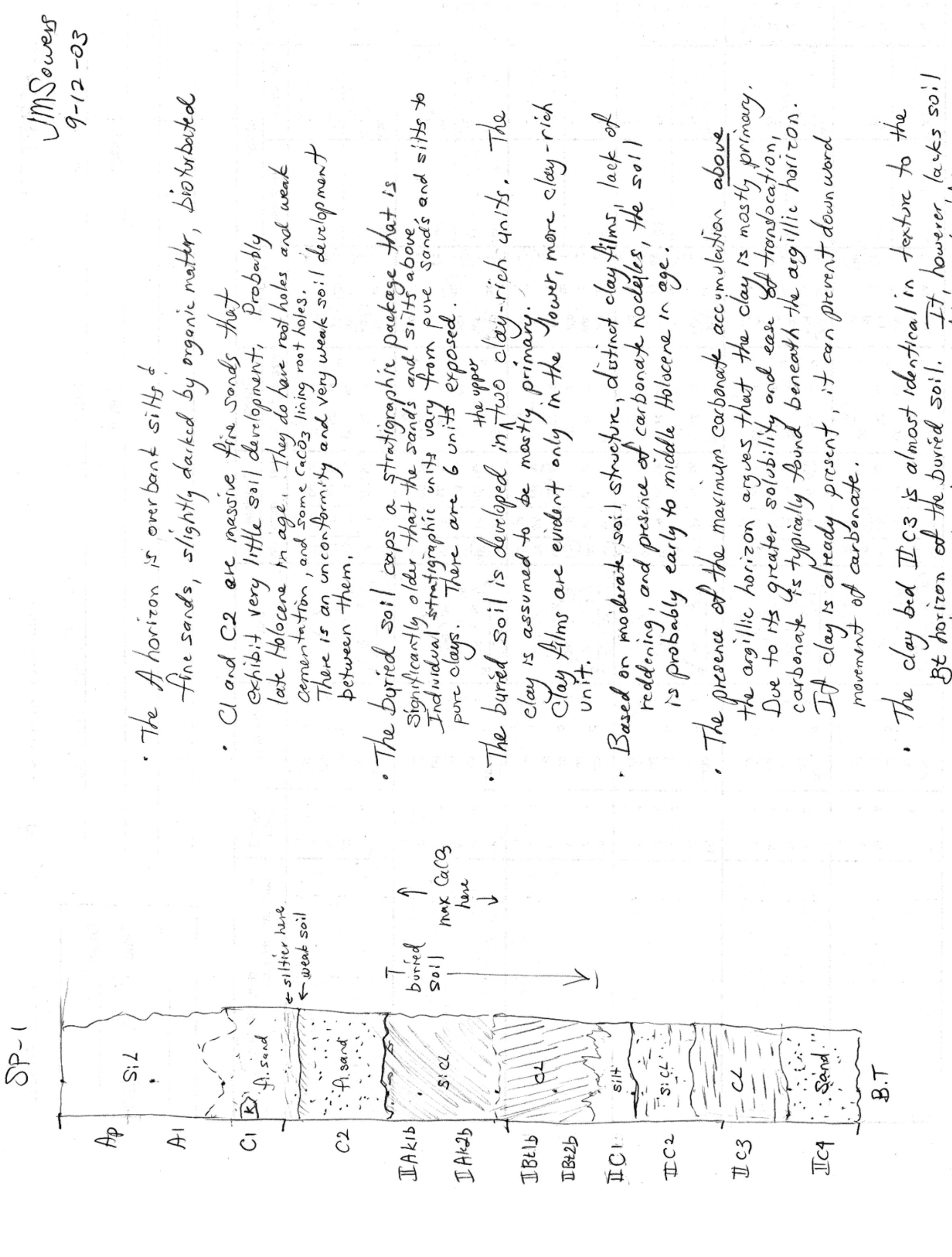


Figure A3. Soil Profile sketch for Trench 1 East wall, meter 10.5, by J. Sowers, William Lettis & Associates, Inc.

APPENDIX B

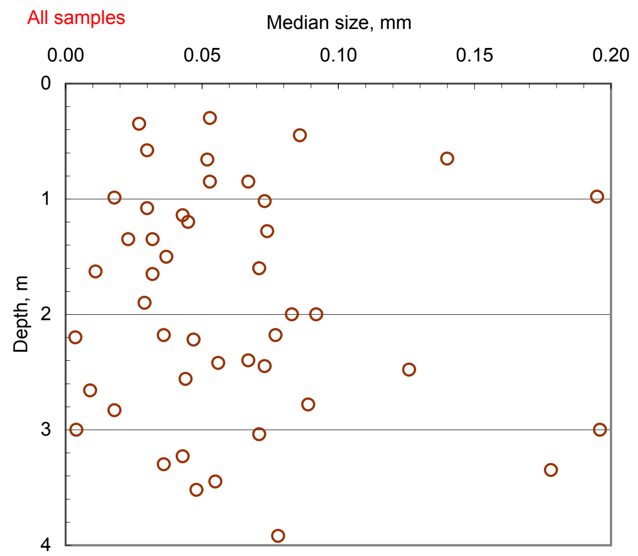
GEOTECHNICAL SOIL PROPERTIES, MILLER FARMS TRENCHES T-1 AND T-2

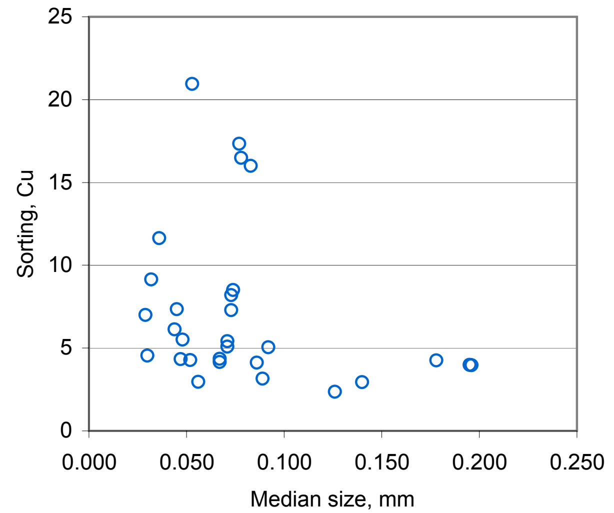
(from M. Bennett)

Pervetich/Miller Farm site

Samples collected 9/16/2003 by Mbennett with direction from Rob Witter and Steve Thompson of William Lettis and Associates

Index #	Site	*Sample number*	Depth, m	Depth, ft	Gravel >4.75 mm	Sand 4.75-0.075 mm	Silt 0.075-0.005 mm	Clay <0.005 mm	D50 mm	Cu	Liquid limit	Plastic limit	PI	USC	Description	Date sampled	Grain size check	Trench wall	Trench met	Trench Unit	Surficial Geology
1	CMF	S1	0.35	1.15	0	18	62	20	0.027						with sand	9/16/2003	100	1 e	9.0	130a	Qpaf
2	CMF	S2	0.58	1.90	0	16	70	14	0.030						with sand	9/16/2003	100	1 e	9.0	40c	Qpaf
3	CMF	S3	0.85	2.79	0	32	63	5	0.053						sandy	9/16/2003	100	1 e	9.0	40b	Qpaf
4	CMF	S4	0.99	3.25	0	5	81	14	0.018							9/16/2003	100	1 e	9.0	40a	Qpaf
5	CMF	S5	1.14	3.74	0	8	81	11	0.043							9/16/2003	100	1 e	9.0	30b	Qpaf
6	CMF	S6	1.35	4.43	0	4	83	13	0.023							9/16/2003	100	1 e	9.0	30a	Qpaf
7	CMF	S7	1.63	5.35	0	7	53	40	0.011							9/16/2003	100	1 e	9.0	20f	Qpaf
8	CMF	S8	2.2	7.22	0	2	42	56	0.004							9/16/2003	100	1 e	9.0	20e	Qpaf
9	CMF	S9	2.66	8.73	0	2	66	32	0.009							9/16/2003	100	1 e	9.0	20c	Qpaf
10	CMF	S10	3	9.84	0	3	36	61	0.004							9/16/2003	100	1 e	9.0	20b	Qpaf
11	CMF	S11	3.23	10.60	0	24	54	22	0.043							9/16/2003	100	1 e	9.0	20a	Qpaf
12	CMF	S12	3.45	11.32	0	39	45	16	0.055							9/16/2003	100	1 e	9.0	10b	Qpaf
13	CMF	S13	3.35	10.99	0	84	14	2	0.178	4.3				SM	SAND with silt	9/16/2003	100	1 w	13.6	L7	Qpaf-Qhaf contact
14	CMF	S14	3	9.84	0	86	13	1	0.196	4.0				SM	SAND with silt	9/16/2003	100	1 w	13.5	L7	Qpaf-Qhaf contact
15	CMF	S15	2.4	7.87	0	40	55	5	0.067	4.4				ML	Sandy SILT	9/16/2003	100	1 w	13.2	L8	Qpaf-Qhaf contact
16	CMF	S16	1.6	5.25	0	46	48	6	0.071	5.1				ML	Sandy SILT	9/16/2003	100	1 w	12.5	L10A	Qpaf-Qhaf contact
17	CMF	S17	1.28	4.20	0	50	44	6	0.074	8.5				ML	Sandy SILT	9/16/2003	100	1 w	12.0	L10C	Qpaf-Qhaf contact
18	CMF	S18	1.02	3.35	0	48	46	6	0.073	8.2				ML	Sandy SILT	9/16/2003	100	1 w	12.0	L10D	Qpaf-Qhaf contact
19	CMF	S19	3.3	10.83	0	25	64	11	0.036	11.6					with sand	9/16/2003	100	1 w	14.2	ayey fragme	Qpaf-Qhaf contact
20	CMF	S20	2.45	8.04	0	50	44	6	0.073	7.3					Sandy SILT	9/16/2003	100	1 w	14.1	L9	Qpaf-Qhaf contact
21	CMF	S21	2.78	9.12	0	64	32	4	0.089	3.2				SM	Silty SAND	9/16/2003	100	1 e	15.0	60_	Qhaf
22	CMF	S22	2.56	8.40	0	10	83	7	0.044	6.1				ML	silt	9/16/2003	100	1 e	15.0	70a	Qhaf
23	CMF	S23	2.42	7.94	0	23	74	3	0.056	3.0				ML	silt with sand	9/16/2003	100	1 e	15.0	70a	Qhaf
24	CMF	S24	2.18	7.15	0	17	62	21	0.036					ML	silt with sand	9/16/2003	100	1 e	15.0	70b	Qhaf
25	CMF	S25	0.3	0.98	0	37	51	12	0.053	20.9						9/16/2003	100	1 e	21.0	130b	Qhaf
26	CMF	S26	0.45	1.48	0	59	39	2	0.086	4.1				SM	Silty SAND	9/16/2003	100	1 e	21.0	120a	Qhaf
27	CMF	S27	0.65	2.13	0	82	18	0	0.140	2.9				SM	Silty SAND	9/16/2003	100	1 e	21.0	110d	Qhaf
28	CMF	S28	0.66	2.17	0	33	63	4	0.052	4.3					sandy	9/16/2003	100	1 e	20.8	110c	Qhaf
29	CMF	S29	0.85	2.79	0	45	53	2	0.067	4.2					sandy	9/16/2003	100	1 e	21.0	110b	Qhaf
30	CMF	S30	0.98	3.22	0	87	12	1	0.195	4.0				SM	Silty SAND	9/16/2003	100	1 e	21.2	110b	Qhaf
31	CMF	S31	1.08	3.54	0	7	86	7	0.030	4.5				ML		9/16/2003	100	1 e	21.0	110a	Qhaf
32	CMF	S32	1.2	3.94	0	26	66	8	0.045	7.3				ML	silt with sand	9/16/2003	100	1 e	20.8	100c	Qhaf
33	CMF	S33	1.35	4.43	0	15	74	11	0.032	9.1					lean clay with sand	9/16/2003	100	1 e	21.0	100a	Qhaf
34	CMF	S34	1.5	4.92	0	20	65	15	0.037						lean clay with sand	9/16/2003	100	1 e	21.0	90c	Qhaf
35	CMF	S35	1.65	5.41	0	14	72	14	0.032					ML	silt	9/16/2003	100	1 e	21.0	90b	Qhaf
36	CMF	S36	1.9	6.23	0	3	87	10	0.029	7.0				ML	silt	9/16/2003	100	1 e	21.0	80a	Qhaf
37	CMF	S37	2.22	7.28	0	11	85	4	0.047	4.3				ML	silt	9/16/2003	100	1 e	21.0	70a	Qhaf
38	CMF	S38	2.48	8.14	0	85	14	1	0.126	2.4				SM	Silty SAND	9/16/2003	100	1 e	21.0	60_	Qhaf
39	CMF	S39	2	6.56	0	55	38	7	0.083	16.0				SM	Silty SAND	9/16/2003	100	1 e	26.7	L11	Qhaf
40	CMF	S40	2.18	7.15	0	51	40	9	0.077	17.3				SM	Silty SAND	9/16/2003	100	1 e	27.0	L12	Qhaf
41	CMF	S41	3.92	12.86	0	53	38	9	0.078	16.5				SM	Silty SAND	9/16/2003	100	2 w	10.0	10a	Qhaf
42	CMF	S42	3.52	11.55	0	17	78	5	0.048	5.5				ML	silt with sand	9/16/2003	100	2 w	10.1	51/L1	Qhaf
43	CMF	S43	3.04	9.97	0	48	48	4	0.071	5.4				ML	sandy silt	9/16/2003	100	2 w	10.0	54/L3	Qhaf
44	CMF	S44	2.83	9.29	0	9	67	24	0.018					CL	lean clay	9/16/2003	100	2 w	10.0	ayey fragme	Qhaf
45	CMF	S45	2	6.56	0	65	32	3	0.092	5.1				SM	Silty SAND	9/16/2003	100	2 w	9.5	60_	Qhaf


All samples
Median size, mm
0.00
0.05
0.10
0.15
0.20
Depth, m
0
1
2
3
4


Sorting, Cu
Median size, mm
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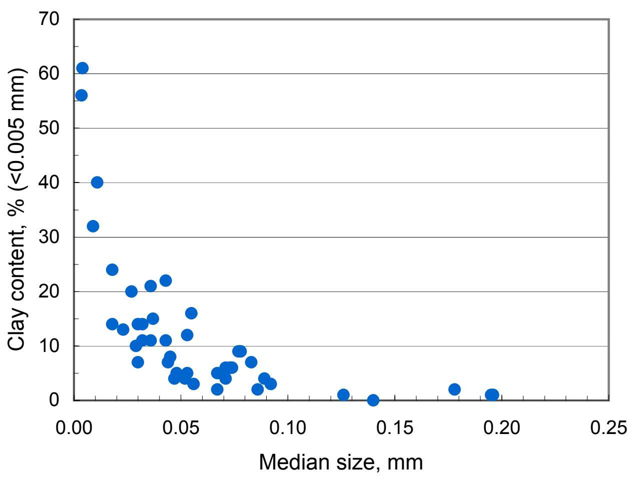
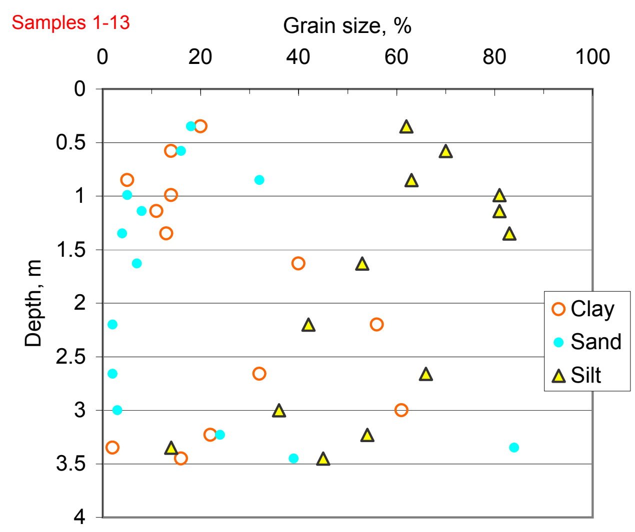
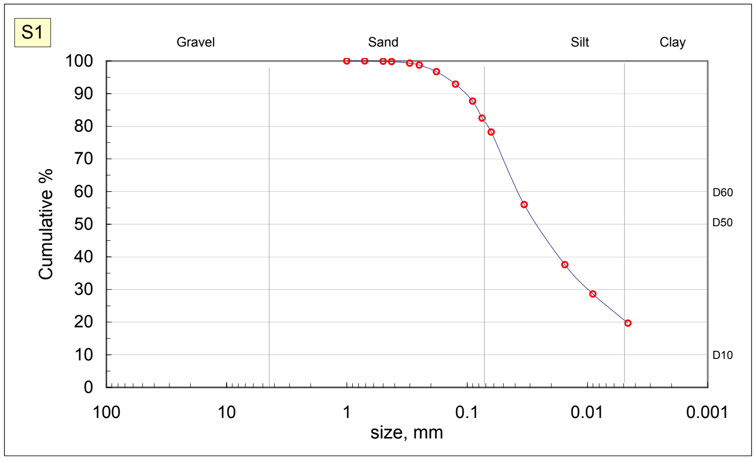
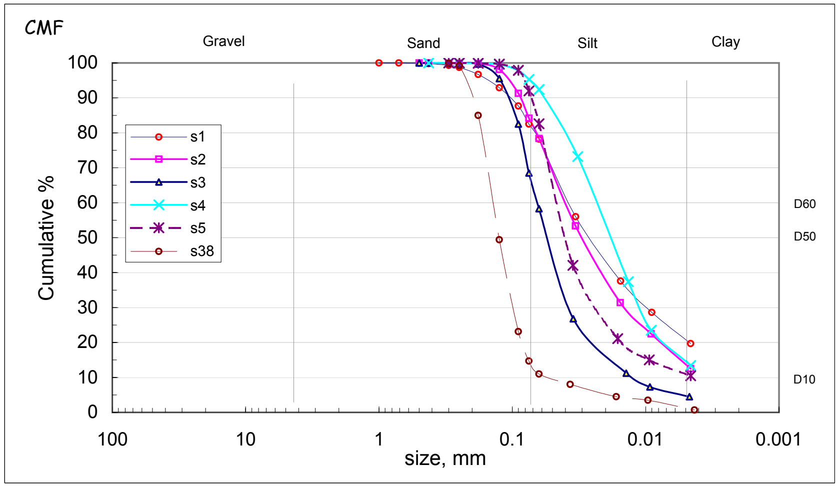
0.050
0.100
0.150
0.200
0.250
0
5
10
15
20
25


Clay content, % (<0.005 mm)
Median size, mm
0.00
0.05
0.10
0.15
0.20
0.25
0
10
20
30
40
50
60
70

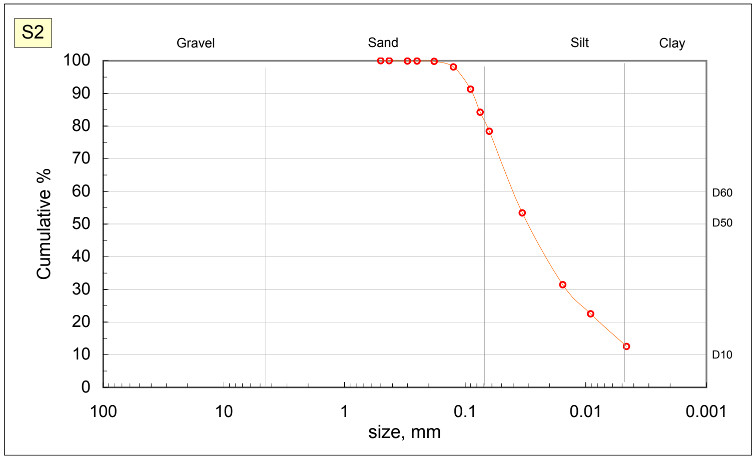

Samples 1-13
Grain size, %
0
20
40
60
80
100
Depth, m
0
0.5
1
1.5
2
2.5
3
3.5
4
Clay
Sand
Silt

size, mm	%finer	S1
16		
12.7		
8		
4.75		
4		
3.35		
2		
1.7		
1	100	
0.71	100	
0.5	99.9	
0.425	99.8	
0.3	99.3	
0.25	98.7	
0.18	96.7	
0.125	92.9	
0.09	87.7	
0.075	82.5	
0.063	78.2	
0.0335	56	
0.0154	37.6	
0.0090	28.6	
0.0046	19.7	

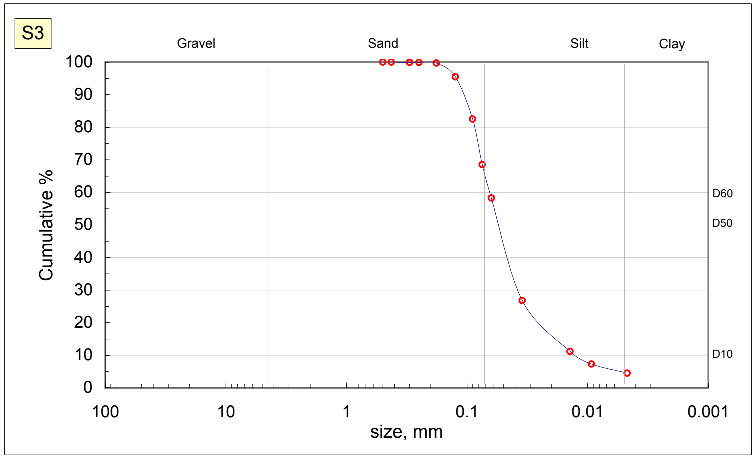




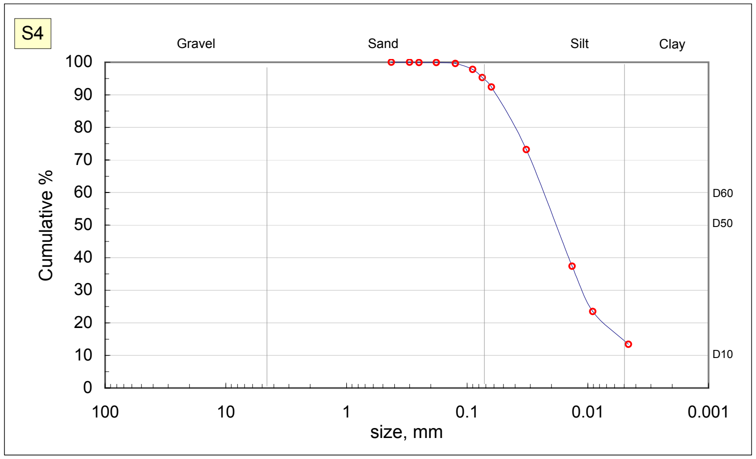
size, mm	%finer	S2
16		
12.7		
8		
4.75		
4		
3.35		
2		
1.7		
1		
0.71		
0.5	100	
0.425	100	
0.3	99.9	
0.25	99.9	
0.18	99.8	
0.125	98.1	
0.09	91.3	
0.075	84.2	
0.063	78.4	
0.0336	53.4	
0.0155	31.4	
0.0091	22.5	
0.0046	12.5	



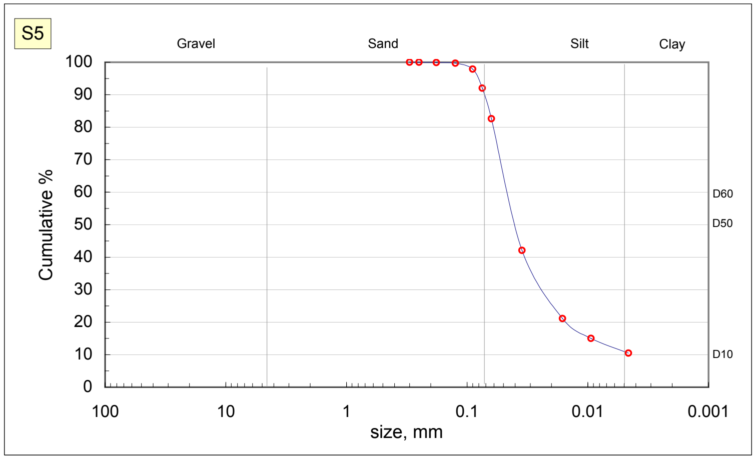
size, mm	%finer	S3
16		
12.7		
8		
4.75		
4		
3.35		
2		
1.7		
1		
0.71		
0.5	100	
0.425	100	
0.3	99.9	
0.25	99.9	
0.18	99.7	
0.125	95.5	
0.09	82.5	
0.075	68.5	
0.063	58.3	
0.0349	26.8	
0.0140	11.2	
0.0093	7.3	
0.0047	4.5	



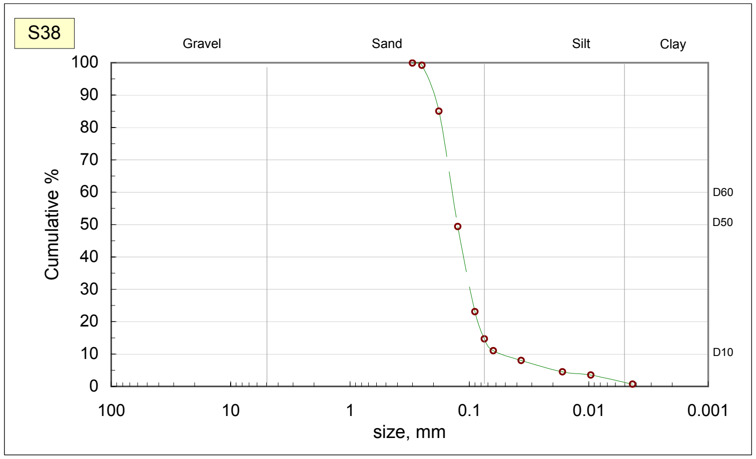
size, mm	%finer	S4
16		
12.7		
8		
4.75		
4		
3.35		
2		
1.7		
1		
0.710		
0.500		
0.425	100	
0.300	100	
0.250	99.9	
0.180	99.9	
0.125	99.6	
0.090	97.8	
0.075	95.3	
0.063	92.4	
0.0323	73.2	
0.0135	37.4	
0.0091	23.5	
0.0046	13.4	



size, mm	%finer	S5
16		
12.7		
8		
4.75		
4		
3.35		
2		
1.7		
1		
0.710		
0.500		
0.425		
0.300	100	
0.250	100	
0.180	99.9	
0.125	99.7	
0.090	97.9	
0.075	92	
0.063	82.6	
0.0351	42.1	
0.0162	21.1	
0.0094	15.0	
0.0046	10.5	

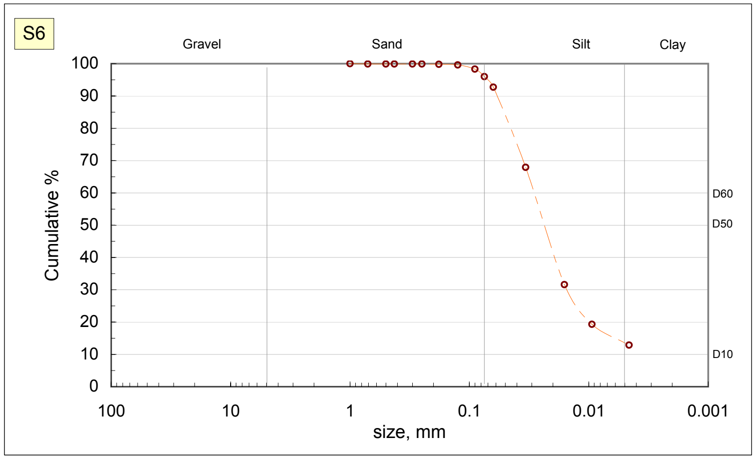


size, mm	%finer	S38
16		
12.7		
8		
4.75		
4		
3.35		
2		
1.7		
1		
0.710		
0.500		
0.425		
0.300	99.9	
0.250	99.2	
0.180	85	
0.125	49.4	
0.090	23.1	
0.075	14.7	
0.063	11	
0.0368	8.0	
0.0166	4.5	
0.0096	3.5	
0.0043	0.7	



size, mm	%finer
16	
12.7	
8	
4.75	
4	
3.35	
2	
1.7	
1	100
0.710	99.9
0.500	99.9
0.425	99.9
0.300	99.9
0.250	99.9
0.180	99.8
0.125	99.6
0.090	98.3
0.075	96
0.063	92.7
0.0338	67.9
0.0160	31.6
0.0094	19.3
0.0046	12.9

S6



APPENDIX C

POLLEN ANALYSES, MILLER FARMS AND CILKER ORCHARDS STUDY SITES

(from L. Reidy)

Pollen Samples, Pervetich/Miller Farm (Pajaro River) Trench 1
Samples Collected by Liam Reidy and Steve Thompson, 9/15/03
Samples Analyzed by Liam Reidy, University of California Berkeley Pollen Lab, 10-12/03

Sample	Depth below surface (m)	Stratigraphic Unit	Pollen Preservation	Presence	*Erodium*	Control Spores
P1	2.95	60	very poor	none-very rare	no	yes
P2	2.85	60	very poor	none-very rare	no	yes
P3	2.55	80a	very poor	none-very rare	no	yes
P4	2.40	80a	very poor	none-very rare	no	yes
P5	1.95	90c	very poor	none-very rare	no	yes
P6	1.60	110a	very poor	none-very rare	no	yes
P7	1.00	120	very poor	none-very rare	no	yes
P8	0.53	120	very poor	none-very rare	no	yes
P9	2.30	70a	very poor	none-very rare	no	yes
P10	1.95	80a	very poor	none-very rare	no	yes
P11	1.55	80b	very poor	none-very rare	no	yes
P12	1.47	90a	very poor	none-very rare	no	yes
P13	1.23	90c	very poor	none-very rare	no	yes
P14	1.02	100a	very poor	none-very rare	no	yes
P15	0.81	100b	very poor	none-very rare	no	yes
p16	0.63	110a	very poor	none-very rare	no	yes
P17	1.36	30a	very poor	none-very rare	no	yes
P18	1.13	30b	very poor	none-very rare	no	yes
P19	1.00	40a	very poor	none-very rare	no	yes
P20	0.90	40b	very poor	none-very rare	no	yes
P21	1.53	20f	very poor	none-very rare	no	yes
P22	1.85	20f	very poor	none-very rare	no	yes
P23	2.32	20d	very poor	none-very rare	no	yes
P24	2.70	20c	very poor	none-very rare	no	yes
P25	3.00	20b	very poor	none-very rare	no	yes
P26	3.33	10b	very poor	none-very rare	no	yes
P27	2.20	L-9	very poor	none-very rare	no	yes
P28	0.64	90c?	very poor	none-very rare	no	yes
P29	1.04	L-10c	very poor	none-very rare	no	yes
P30	1.32	L-10c	very poor	none-very rare	no	yes
P31	0.64	40c	very poor	none-very rare	no	yes

Pollen Samples, Cilker Orchards (Coyote Creek) site Trench 1, meter 24
Samples Collected by Rob Witter, 10/7/03
Samples Analyzed by Liam Reidy, University of California Berkeley Pollen Lab, 10/29/03

Sample	Depth below surface (m)	Stratigraphic Unit	Pollen Preservation	Presence	*Erodium*	Control Spores
P1	0.30	90	Poor	Rare	No	Yes
P2	0.55	70	Poor	Rare	No	Yes
P3	0.80	65	Poor	Rare	No	Yes
P4	0.90	60	Poor	Rare	No	Yes
P5	1.10	50	Poor	Rare	No	Yes
P6	1.30	40	Poor	Rare	No	Yes
P7	1.70	30	Poor	Rare	No	Yes
P8	2.25	20	Poor	Rare	No	Yes
P9	2.50	14	Poor	Rare	No	Yes
P10	2.90	12	Poor	Rare	No	Yes
P11*	3.20	10	Poor	*Fair*	No	Yes

*Sampled from hand-auger hole at Trench meter 26