William Lettis & Associates, Inc.

FINAL TECHNICAL REPORT

LATE HOLOCENE DISPLACEMENT OF THE CENTRAL CALAVERAS FAULT, FURTADO RANCH SITE, GILROY, CA

Submitted to:

U. S. Geological Survey
National Earthquake Hazards Reduction Program
Award Number 01-HQ-GR-0124

Submitted by:

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July 2003

WLA

July 2, 2003

Dr. John Unger
External Research – Final Report
U.S. Geological Survey
905A National Center
12201 Sunrise Valley Drive
Reston, VA 20192

RE: Award No. 01-HQ-GR-0124: "Late Holocene Displacement on the Central Calaveras Fault, Furtado Ranch, Gilroy, California"

Dear Dr. Unger:

Enclosed please find an unbound original and 5 bound copies of the Final Technical Report noted above for the National Earthquake Hazards Reduction Program. We are also submitting the same number of copies of the report Abstract as separate documents, and sending electronic versions of the report to you at <gd-erp-coordinator@usgs.gov>.

We are pleased to submit this report on the active Calaveras Fault, and provide information on the characteristics of this major potential seismic source in the San Francisco Bay area. We document a fault creep rate of about 15 mm/yr, and show the character of the creeping fault in the near surface via two exploratory trenches. In addition, we identify an adjacent fault strand that does not creep but exhibits evidence suggestive of possible late Holocene surface rupture. This information should be considered in future assessments of seismic hazard in the San Francisco Bay region.

We appreciate the opportunity to conduct this exciting and challenging work for the National Earthquake Hazard Reduction Program, and hope that the result of this effort help the program progress toward its goals. Please do not hesitate to call me if you have any questions (925-256-6070).

Sincerely,
WILLIAM LETTIS & ASSOCIATES, INC.

Keith I. Kelson
Principal Geologist
(e-mail: kelson@lettis.com)
enclosures

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Program Elements:

II: Earthquake Occurrence and Effects

U. S. Geological Survey
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Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 01-HQ-GR-0124. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

ABSTRACT

LATE HOLOCENE DISPLACEMENT OF THE CENTRAL CALAVERAS FAULT, FURTADO RANCH SITE, GILROY, CA

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The Calaveras Fault plays a major role in accommodating plate-motion slip in the San Francisco Bay region. Geodetic modeling, historical creep data and paleoseismic trenching suggest a fault slip rate of about 15 mm/yr on the Central Calaveras Fault, which extends from San Felipe Lake on the southeast to Calaveras Reservoir on the northwest. Within the uncertainty of limited geologic data, the long-term slip rate on the Central Calaveras Fault is consistent with the short-term rate estimated from aseismic creep and geodetic modeling. However, a critical question is whether or not the Central Calaveras Fault produces large-magnitude earthquakes, or whether the fault relieves strain only by aseismic creep and small to moderate earthquakes. Existing seismic source characterization models generally assume or strongly weight scenarios in which the fault may rupture in earthquakes up to magnitudes of about M6.2. Understanding the maximum size of earthquakes possible along the Central Calaveras Fault is critical to estimating probabilities of future earthquakes in the San Francisco Bay region.

The primary goal of this investigation of the Central Calaveras Fault at the Furtado Ranch site is to document the locations and rate of historic creep and to address the possibility of large-magnitude (M > 6.5) late Holocene surface-rupture earthquakes. The Furtado Ranch site contains the primary active strand of the fault, as shown by cultural features offset by juxtaposition of bedrock units, aseismic creep, and a series of linear closed depressions developed on Holocene alluvial-fan deposits. Our effort involved a survey of offset cultural features and excavation of two trenches across the fault. We surveyed a 29-year-old alignment array installed by the USGS in 1972, in order to provide a historic fault creep rate and identify the exact location(s) of actively creeping fault strands. This survey shows that the creeping fault trace is located along the west-facing scarp bordering the eastern side of the linear depression at

the site. The creeping fault strand is coincident with the primary fault strand exposed in the two trenches at the site. The survey data show that the creeping trace of the fault has right-lateral offset of 430 $\pm$ 30 mm across a well-defined zone less than 5 m wide. These data indicate a 29-year-long creep rate of 15 $\pm$ 1 mm/yr. This rate is consistent with the creep rate of about 16 mm/yr from the nearby Coyote alignment array and the 14 (+5, -6) mm/yr geologic rate from the San Ysidro Creek site.

We excavated two trenches across the linear depression at the site to expose the primary strands of the Central Calaveras Fault and document the presence or absence of possible indicators of surface rupture. The eastern fault strand is a complex, upward-widening structure that is a positive flower structure in trench T-1 and a negative flower structure in trench T-2. We observed no characteristics of this fault that are similar to other strike-slip faults known to have had surface rupture, such as fissure fills, scarp-derived colluvium or multiple fault terminations. The displacement on the eastern fault strand extends as a series of faults and fractures from the trench floor to the ground surface, within a zone about 2 to 3 m wide. The western fault strand also is about 2 to 3 m wide, but does not extend to the ground surface. This strand is overlain by unfaulted deposits that are more than 2,700 years old. The absence of creep along this strand, and the lack of displacement of 2,700-year-old deposits, shows that this strand has had a different deformational history compared with the eastern fault strand. The timing of movement on the western strand is different than that on the eastern strand, which continues to deform near-surface sediments via fault creep. Stratigraphic relations near the western fault strand are suggestive of the deposition of a scarp-derived colluvium following an episode of surface deformation prior to about 2,700 years ago. If this colluvium is related to a surface rupture, then such a rupture occurred more than about 2,700 years ago. This may suggest that the behavior of the fault has changed within the late Holocene from one involving surface rupture to one characterized by aseismic creep. Although it is easiest to assume that the Central Calaveras Fault has been dominated by aseismic creep deformation over the past few thousand years, at this point we cannot preclude the occurrence of surface rupture along the fault.

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1.0 INTRODUCTION

The primary goal of this investigation of the Central Calaveras Fault at the Furtado Ranch site is to document the locations and rate of historic creep and to address the possibility of late Holocene surface-rupture earthquakes. The Calaveras Fault plays a major role in accommodating plate-motion slip in the San Francisco Bay region. Geodetic modeling and historical creep data suggest a present-day fault creep rate of about 16 mm/yr on the central section of the fault (Galehouse and Lienkaemper, 2003 [in press]). Recent trenching at the San Ysidro Creek site, located approximately 3 km northwest of the Furtado Ranch site, provides a preliminary late Holocene slip rate on the Central Calaveras Fault of 14 (+5, -6) mm/yr (Baldwin et al., 2002; Kelson et al., 1997, 1998). Within the uncertainty of the geologic data, this long-term slip rate is consistent with the short-term rate based on aseismic creep and geodetic modeling. However, there is uncertainty regarding the seismogenic potential and seismic cycle of the Central Calaveras Fault (i.e., the rate and nature of strain accumulation / strain release on the fault). In particular, a critical question is whether or not the Central Calaveras Fault produces large-magnitude (M>6.5) earthquakes, or whether the fault relieves strain by aseismic creep in conjunction with small to moderate (M≤6.2) earthquakes. Understanding the maximum possible size of earthquakes along the Central Calaveras Fault is critical to estimating probabilities of future earthquakes in the San Francisco Bay region (Working Group on California Earthquake Probabilities [WGCEP], 2003).

Of the major potential seismic sources in the southern San Francisco Bay region, most of the relative plate motion is accommodated by the San Andreas and Calaveras faults, for which the current best estimates of slip rate are 17 ± 4 mm/yr and 15 ± 3 mm/yr, respectively (WGCEP, 2003). Paleoseismic data characterizing the behavior of these faults are critical for adequately assessing the seismic hazard in the southern Bay region. Because of recent rapid growth and the likelihood of continued urban expansion in the Santa Clara and Coyote Valleys, these faults pose a significant seismic hazard to the nearly 7 million people in the San Francisco Bay area (www.bayareacensus.ca.gov). Characterizing the primary seismogenic sources in this populated area is critical for adequately addressing seismic hazards in the region and estimating future earthquake probabilities.

The 130-km-long Calaveras Fault traverses the eastern margin of the southern Santa Clara Valley (Figure 1). The current fault model used by the Working Group on California Earthquake Probabilities (WGCEP, 2003) includes identification of three major sections of the fault, based on contemporary seismicity, structural relations with other major faults, rate of present-day creep, and geomorphic expression (Kelson et al., 1999; Kelson, 2001). These sections, which may or may not reflect actual earthquake rupture segments, are the (Figure 1):

- Northern Calaveras Fault (from the town of Danville to Calaveras Reservoir),
- Central Calaveras Fault (from Calaveras Reservoir to San Felipe Lake), and
- Southern Calaveras Fault (from San Felipe Lake to the Paicines Fault, near Hollister).

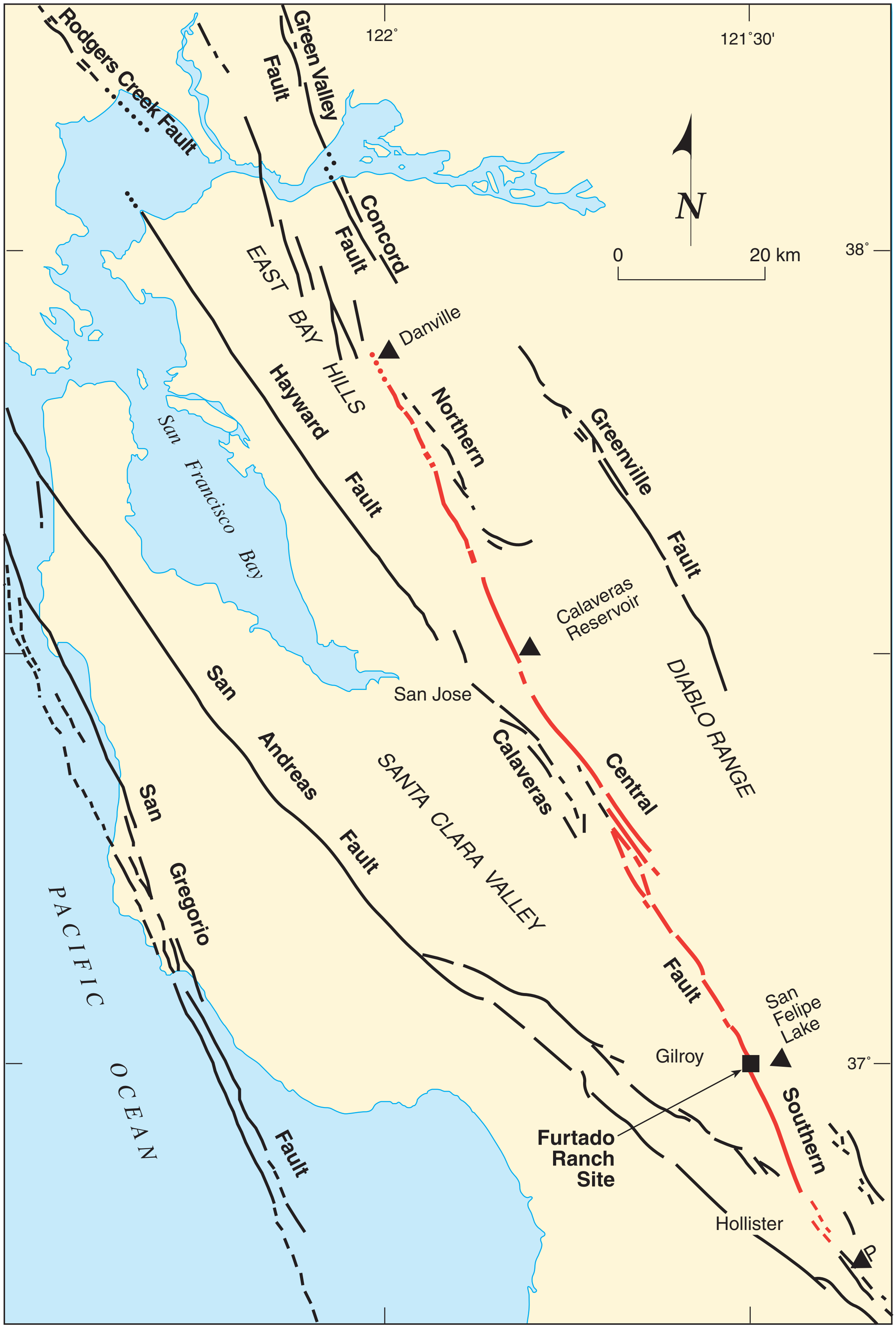

Figure 1. Regional map of the Calaveras Fault (red lines) showing northern, central, and southern fault sections and the Furtado Ranch Site. Filled triangles show locations of fault section boundaries (±5 km), P = intersection with the Paicines Fault.

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Studies funded by the U.S. Geological Survey's NEHRP and BAPEX programs demonstrate that the Northern Calaveras Fault has experienced multiple surface-rupturing earthquakes within the past few thousand years (Kelson et al., 1992, 1996; Baldwin et al., 1998; Simpson et al., 1999; Kelson and Randolph, 2000). In contrast, there is little or no evidence of Holocene surface fault rupture along the central or southern fault sections. Understanding the earthquake cycle on the southern and central sections of the Calaveras Fault, therefore, has strong implications to assessments of seismic hazard in the San Francisco Bay region. For example, the recent estimates of earthquake probabilities in the region by the WGCEP (2003) include a substantial amount of uncertainty related to a lack of definitive information on whether the Central and Southern Calaveras faults may produce earthquakes larger than **M**6.2. WGCEP (2003) heavily weights fault-rupture scenarios in which the central and southern fault sections produce only "floating" earthquakes less than or equal to magnitude M 6.2.

This research focuses on a site along the 70-km-long Central Calaveras Fault (Figure 2), which is characterized by abundant microseismicity (Bakun, 1980, 1984; Bakun and Lindh, 1985; Oppenheimer et al., 1990), and a high rate of creep. The simple average creep rate for 31 years of record from 1968 to 1999 is 16.3 mm/yr at the Coyote Ranch array near Coyote Lake (J. Galehouse, written comm., 1999). In addition to abundant microseismicity, the behavior of the Central Calaveras Fault is distinguished by the generation of recent moderate magnitude earthquakes (e.g., 1979 Coyote Lake **M**5.9, 1984 Morgan Hill **M**6.2, 1988 Alum Rock **M**5.1). A similar sequence occurred along the fault between 1891 and 1911 (Oppenheimer et al., 1990). WGCEP (1999, 2003) assumed that the 1984 Morgan Hill earthquake (**M**6.2) is a reasonable maximum magnitude event to occur on the Central Calaveras Fault. Alternatively, geologic relations exposed in trenches at San Ysidro Creek (Figure 2) may be interpreted as evidence of large surface-rupturing earthquakes along the Central Calaveras Fault, with three possible ruptures occurring between about 2,000 and 4,000 years ago (Baldwin et al., 2002; Kelson et al., 1997, 1998, 1999). This possibility is based on the presence of four distinct paleochannels that cross the fault and are progressively offset in 2 m increments. Geologic relations at the San Ysidro Creek site permit the interpretation that the relative position of each of the four paleochannels may be a direct result of coseismic offset along the fault. In part based on this recent information, the WGCEP (1999, 2003) included the possibility of large earthquakes on the Central and Southern Calaveras faults in their recent earthquake probability calculations. By weighting various fault-rupture models, which included scenarios of both moderate and large earthquakes, the WGCEP (1999, 2003) incorporated the uncertainties resulting from incomplete knowledge of long-term fault behavior and was able to track sources of uncertainty in the probability calculations. Through this effort, it is clear that the poorly known value of the maximum earthquake magnitude on the Central Calaveras Fault is a significant source of uncertainty in the regional hazard estimates.

Other than the recent research at San Ysidro Creek (Baldwin et al., 2002; Kelson et al., 1998), there is no other evidence of large earthquakes (**M**≥6.5) along the central or southern sections of the Calaveras Fault. Stenner et al. (1999) excavated two trenches at the Costa Ranch site on the Southern Calaveras Fault near Hollister, in part to address the question of whether or not the Southern Calaveras Fault can produce surface-rupturing earthquakes. These investigators noted

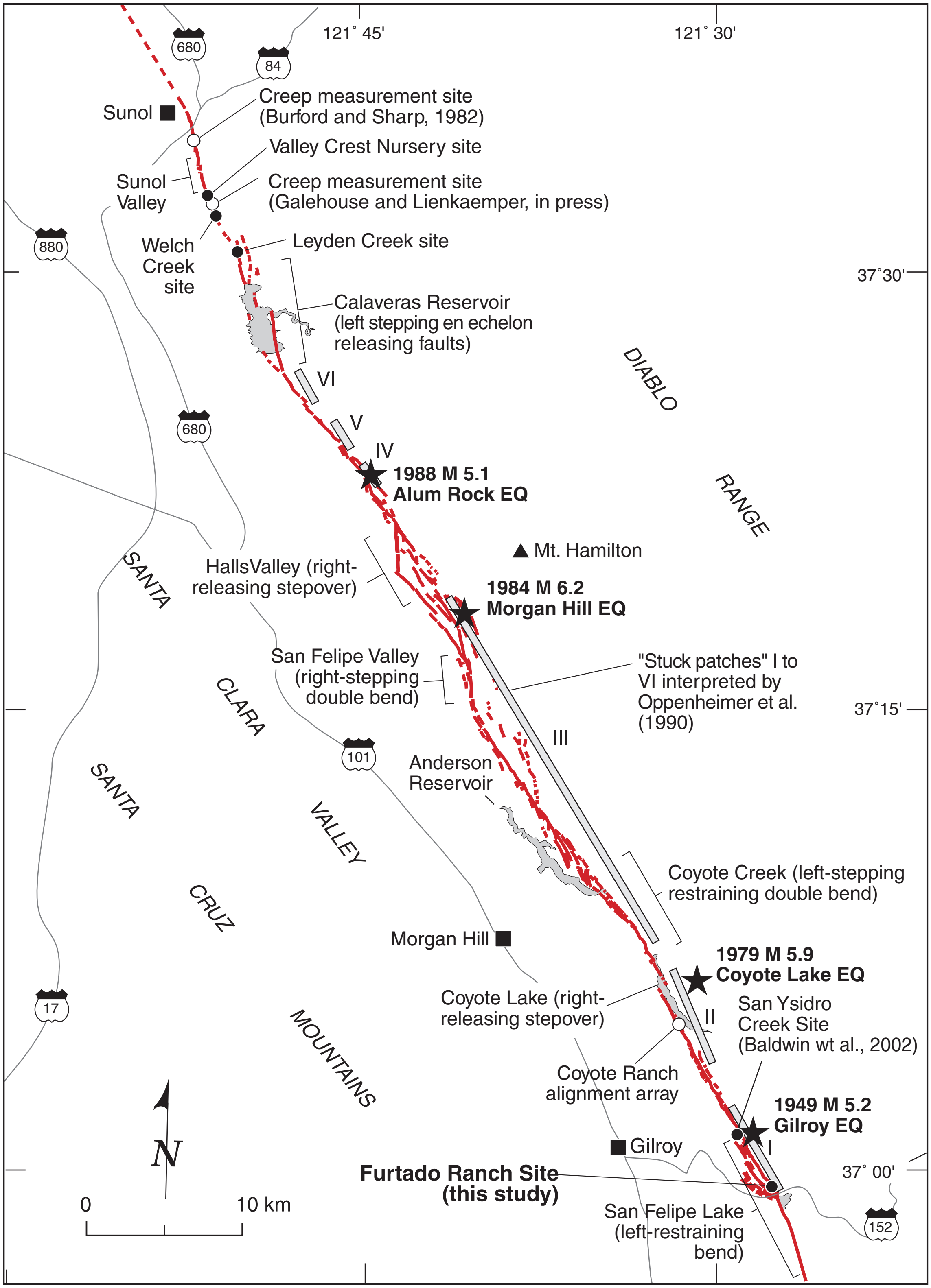

Figure 2. Simplified map of the Central Calaveras Fault, showing paleoseismic sites, existing creep measurement sites, and Furtado Ranch site. Historic M >5 earthquakes (stars) and "stuck patches" (bars labeled I to VI) from Oppenheimer et al. (1990). Fault traces from Witter et al. (in preparation).

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that there was insufficient evidence to determine whether late Holocene fault strands that were exposed in the trenches are related to either surface fault creep or large coseismic ruptures. Later work at the Costa Ranch site summarized by Stenner et al. (2000) suggests that all the deformation on the Southern Calaveras Fault can be explained by aseismic creep, although these workers also list several ambiguous stratigraphic relations that could be related to surface rupture. Because the behavior of the Southern Calaveras Fault may or may not be similar to that on the Central Calaveras Fault, the question of whether or not the Central Calaveras Fault may produce large surface-rupturing earthquakes remains unresolved. As noted above, this lack of information is a significant source of uncertainty in calculating earthquake probabilities in the San Francisco Bay region.

2.0
GEOLOGIC SETTING OF THE FURTADO RANCH SITE

The Furtado Ranch site lies near the southern end of the Central Calaveras Fault, about 1.5 km northwest of San Felipe Lake and about 3 km southeast of the San Ysidro Creek site (Figure 2). San Felipe Lake is interpreted as a possible boundary between the Central and Southern Calaveras faults, on the basis of differences in fault strike, microseismicity, and regional geomorphology (Kelson et al., 1998; WGCEP, 1999, 2003; Kelson, 2001). In contrast with the southern fault section, the Central Calaveras Fault has a slightly more westerly strike, has more abundant small and moderate earthquakes, and is within the Coast Ranges block rather than the Hollister alluvial plain. Although the Southern Calaveras Fault exhibits a single active trace across the Hollister plain, the Central Calaveras Fault near Furtado Ranch contains geomorphic evidence of multiple fault strands within a 1-km-wide zone (CDMG, 1982; Armstrong et al., 1980; Witter et al., in preparation). Most of these strands likely are secondary reverse fault splays related to a slight restraining bend at San Felipe Lake (Figure 3). The easternmost strand of the fault zone near Furtado Ranch is the most continuous and linear trace, and is associated with prominent tectonic geomorphology (i.e., sag ponds, scarps, linear swales, deflected drainages). Along the eastern fault strand, Cretaceous sandstone rocks on the east are juxtaposed against Plio-Pleistocene sedimentary rocks of the Santa Clara Formation on the west (EMCON, 1992). The easternmost fault strand thus is the major fault along which distinctly different rock types are in fault contact, and is interpreted as the primary strand of the Calaveras Fault (Figure 3). Other fault strands in the vicinity either die out to the northwest or merge with the fault strand that traverses the Furtado Ranch site.

The primary fault strand of the Calaveras Fault at Furtado Ranch is associated with distinctive fault geomorphology, including linear closed depressions, linear drainages, and prominent, east- and west-facing fault scarps (Figure 4). Late Holocene to historic surficial deposits overlie this fault strand. As shown on Figure 4, a moderate-size drainage basin present east of the fault has deposited alluvial-fan sediments into the linear valley along the fault. We informally call this drainage "Windmill Creek" because of the presence of a windmill on the alluvial fan near the creek. The alluvial fan slopes to the southwest toward a linear fault scarp along the western side of the valley, and alluvial sediments have been deposited across the fault and against the linear fault scarp (Figure 5). The well-preserved morphology of the fan suggests that it is probably middle to late Holocene in age. Presently, Windmill Creek flows southwest toward the fault, and then turns to flow northwest along the fault for about 1 km (Figure 4). Late Holocene alluvium deposited by Windmill Creek along this northwest-trending reach of the channel is inset into the alluvial-fan deposits.

A prominent linear depression is present along the primary fault strand at Furtado Ranch, where the distal end of the alluvial fan is traversed by the fault (Figure 5). This depression is about 100 m long, 10 m wide, and about 2 m deep, and is developed on the alluvial-fan sediments. At present, the depression receives colluvial sediment from the northeast-facing fault scarp bordering its western margin, and perhaps rarely receives alluvial sediment from overbank flooding along Windmill Creek. A second, smaller topographic low is located between this

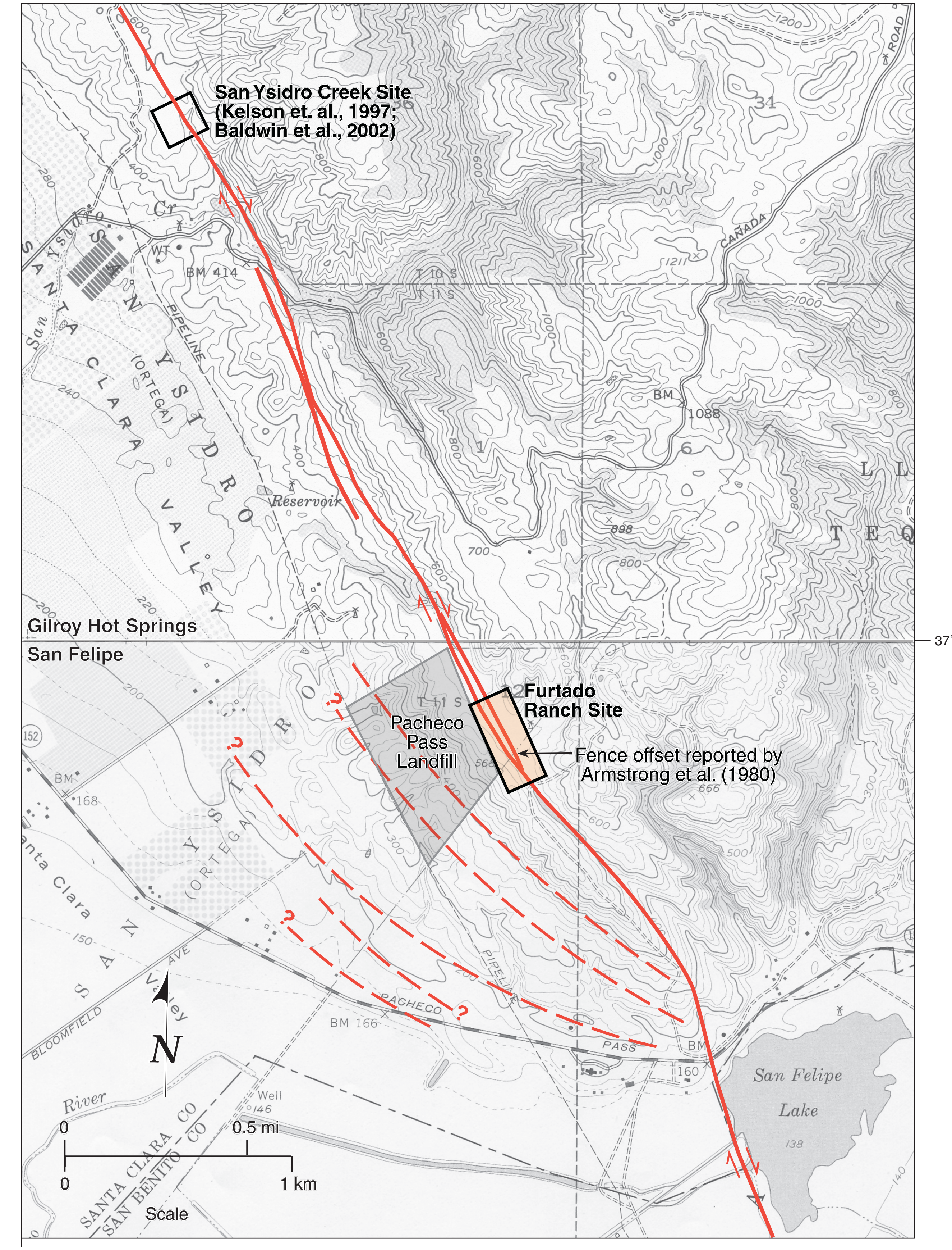


Figure 3. Topographic map showing location of the Furtado Ranch site and previously mapped strands of the Calaveras Fault (Armstrong et al., 1980; CGS, 1982; Witter et al., in preparation).

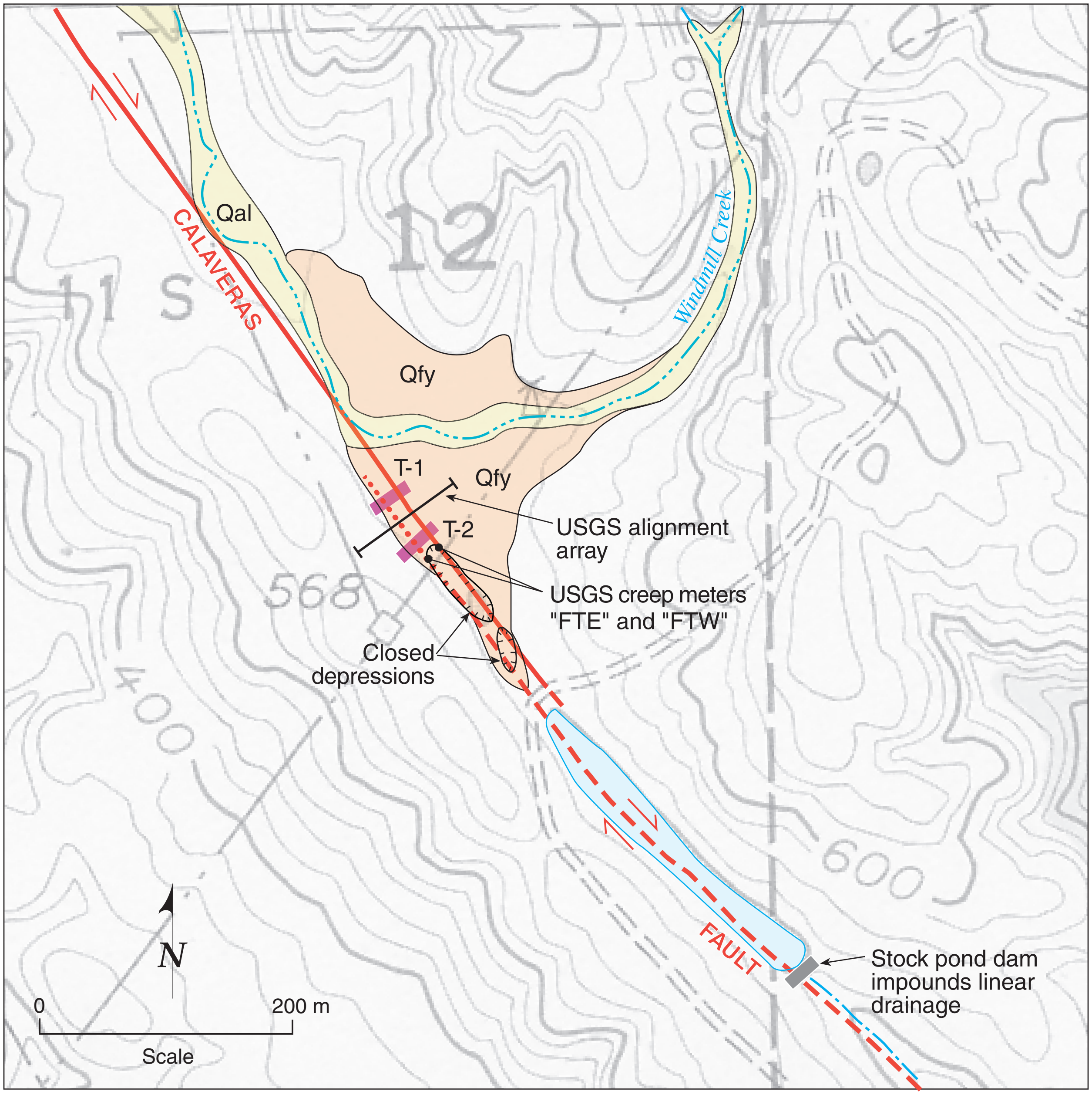


Figure 4. Simplified surficial geologic map of the Furtado Ranch site, showing the main strand of the Calaveras Fault, USGS alignment array, USGS creep meters (Furtado Ranch East, "FTE"; Furtado Ranch West "FTW"), and trench localities T-1 and T-2. Qfy: Holocene alluvial fan; Qal: Holocene alluvium.

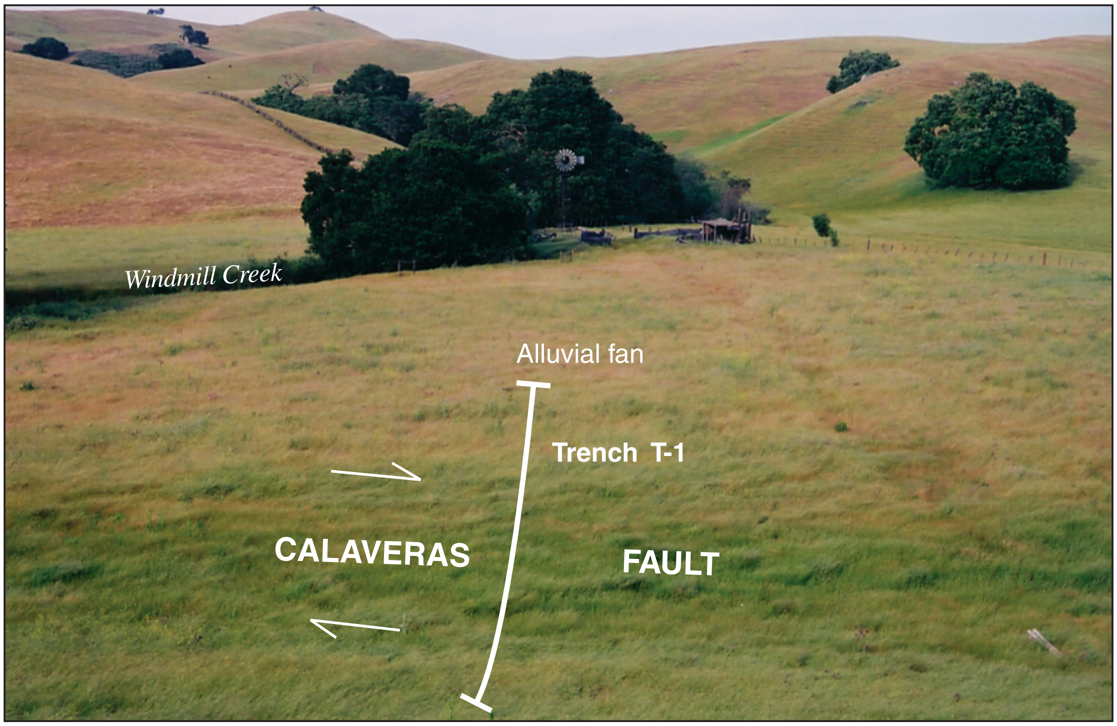


Figure 5a. Photograph of the Windmill Creek alluvial fan at the Furtado Ranch site (looking northeast), showing location of the Calaveras Fault.

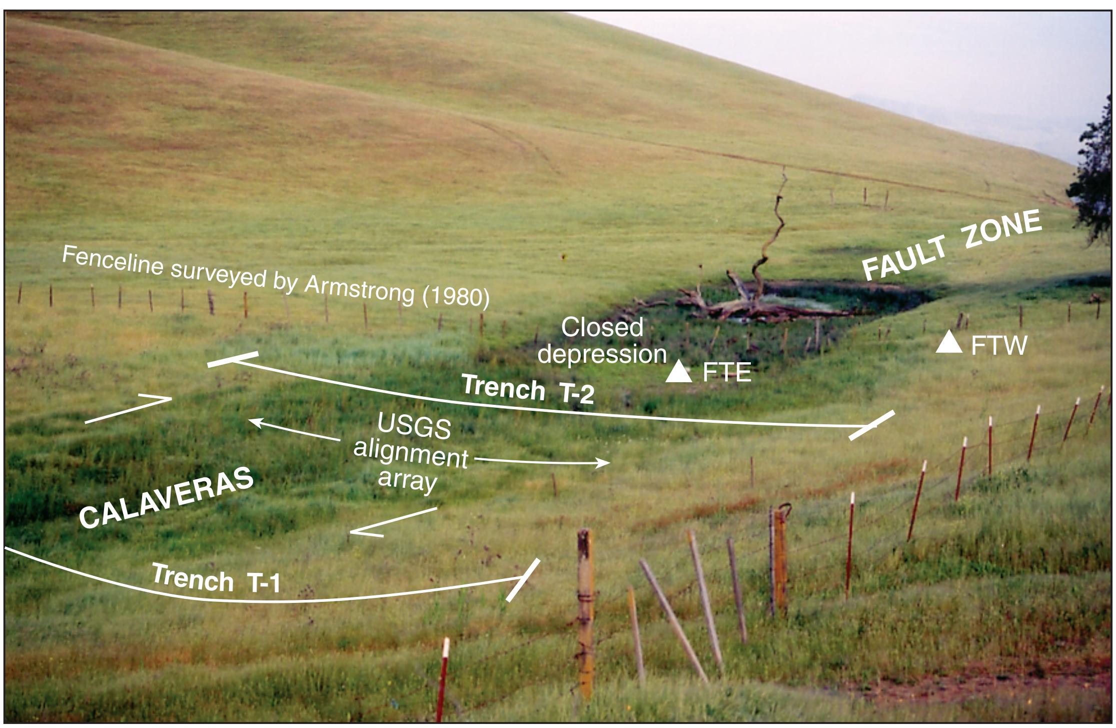


Figure 5b. Photograph of the Furtado Ranch trench site (looking southeast) showing closed depression, USGS creep meters (FTE and FTW shown by triangles), USGS alignment array, and location of trenches T-1 and T-2.

closed depression and the linear stock pond southeast of the site (Figure 4). These features suggest a possible right-stepping, *en echelon* pattern of surface deformation in the site vicinity. In addition, based on analysis of 1:24,000-scale air photos taken in 1974, there was a third linear depression along the fault, about 200 m northwest of the existing depression. This third depression was within an area that has been modified by grading (EMCON, 1992), and is no longer present. We interpret that the presence of the linear depressions along the fault at the site is suggestive of a small component of extension along the fault in the site vicinity.

Active aseismic creep is documented at the Furtado Ranch site by an offset historic fenceline, three USGS creepmeters, and a USGS alignment array. These strain gauges provide an excellent opportunity to identify the locations and amounts of historic creep along the fault. On the basis of fenceline surveys by Armstrong et al. (1980), creep is occurring along the main fault strand mapped at the Furtado Ranch site. Armstrong et al. (1980) estimated that the fenceline at Furtado Ranch is approximately about 170 years old and, based on data from this and other sites in the area, estimated a creep rate of about 10 to 15 mm/yr along the Calaveras Fault. A sketch map provided by Armstrong et al. (1980) suggests that the creeping fault zone is about 15 to 20 m wide. However, our observations show that most of the fence posts are only marginally stable, and that this piercing line presently does not provide well-constrained creep rate data.

In June 1972, three creepmeters were installed by the USGS at the Furtado Ranch site: one within the linear depression ("FTE", Figure 4), one directly west of the depression ("FTW"), and one along the fault about 300 m northwest of the depression ("FTN", Nason et al., 1974). We located creepmeters FTE and FTW during our reconnaissance (Figure 4), but were unable to locate creepmeter FTN. Unfortunately, all three of the creepmeters were abandoned in January 1973, after the three sites were flooded during winter rains. Although the creepmeters do not provide well-constrained data on the creep rate, the locations of the equipment provide at least a suggestion of the locations of actively creeping fault zone(s). In addition, the USGS installed an alignment array in 1972 across the main fault zone at the site (Figure 6). This array is located across the fault zone directly northwest of the closed depression and consists of 15 survey benchmarks, with spacings of 5 to 10 m. These benchmarks presently can be readily found in the field, and our survey of this array provides a well-constrained 29-year record of the rate and location of creep at the site.

Figure 6. (A) Photograph of the Windmill Creek alluvial fan at the Furtado Ranch site, showing location of the USGS alignment array across Calaveras Fault, looking northeast. (B) Close-up photograph of the USGS alignment array, looking northeast, showing benchmarks numbered 5 through 14. (C) Close-up photograph of a typical USGS benchmark, set in concrete, within the alignment array at Furtado Ranch site.

3.0
RESULTS

We investigated the Central Calaveras Fault at the Furtado Ranch site through two field-based tasks. We first documented the location and rate of historic surface creep at the site through electronic surveying of the existing USGS alignment array (Figure 7). Second, we attempted to address whether or not coseismic surface-fault ruptures have occurred on the Central Calaveras Fault by excavating two trenches across the closed depression. Our approach was first to identify the primary creeping strands of the fault through surveying of the alignment array, and then to document the near-surface characteristics of the primary fault strand(s) in the shallow excavations across the fault zone. In addition to documenting the location of the creeping strand, the trenching effort was targeted at determining whether stratigraphic or geologic features that could be related to surface fault rupture, such as scarp-derived colluvium or sediment-filled fissures, are present at the site. We anticipated that if the geologic relations suggest that surface rupture has occurred recently along the fault, alluvial and colluvial deposits at the site may provide a means to estimate the timing of the rupture(s) and, thus, possibly to develop a rupture-event chronology.

3.1 Survey of Alignment Array

<u>3.1.1 Approach and Methods</u>

The alignment array at the Furtado Ranch site was installed in 1972, and consists of 15 standard brass benchmarks set into 6-in-diameter concrete monuments, presumably constructed in a straight line across the fault zone (Figures 5 and 6). Each brass monument includes a center-punched cross and an identification number. Monuments are numbered sequentially from west to east. We completed a detailed survey of the alignment array, using a Topcon GTS-303 total station. The total station was set up at the southwestern end of the alignment array, and the backsight prism northeast of the northeastern benchmark (Figure 7). We consistently placed the survey prism directly on the center-punched mark on the brass benchmark to minimize survey error. We believe that the uncertainty in surveyed locations of the individual monuments is on the order of a few millimeters.

Spacing of the monuments varies along the alignment (Figure 8); spacing is approximately 10 m at the western end (between monuments 1 and 3) and at the eastern end (between monuments 13 and 14). Spacing between the other monuments is approximately 5 m. It appears that the variation in spacing was used to obtain a dense coverage of survey monuments across what was thought to be the actively creeping fault trace, while also including several stations farther east and west as longer distance baseline stations. There are at least two vintages of survey monuments in the array. For instance, the spacing between monuments 12 and 13 is 10 m. It appears that sometime after the creeping trace was located (between monuments 10 and 11), monument 12.5 was added between monuments 12 and 13 to refine the near-fault creep rate and location (Figure 8). We do not know the year in which this addition was made to the array.

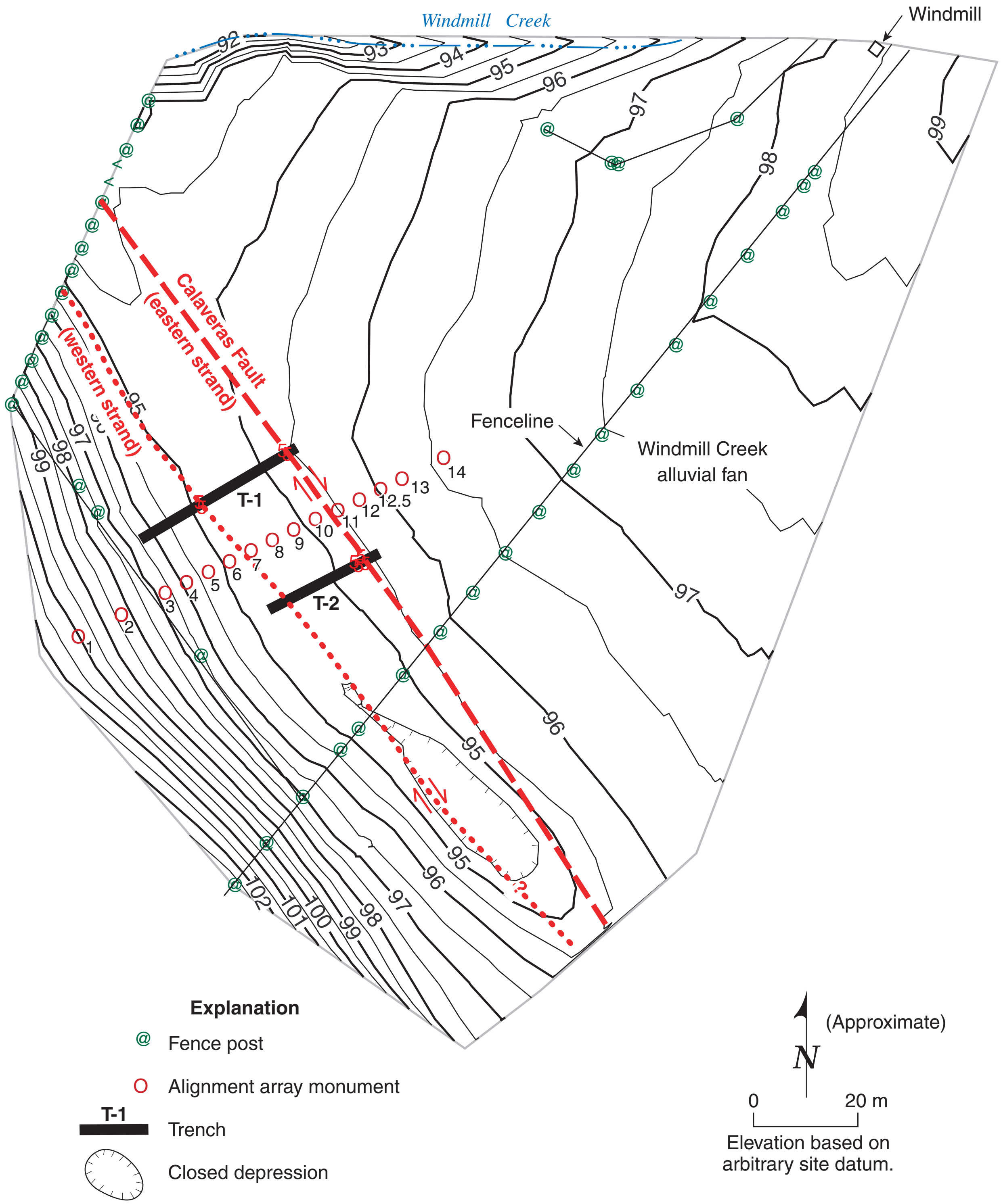


Figure 7. Detailed site topographic map, showing closed depression along the Central Calaveras Fault, trench locations T-1 and T-2, and the USGS alignment array.

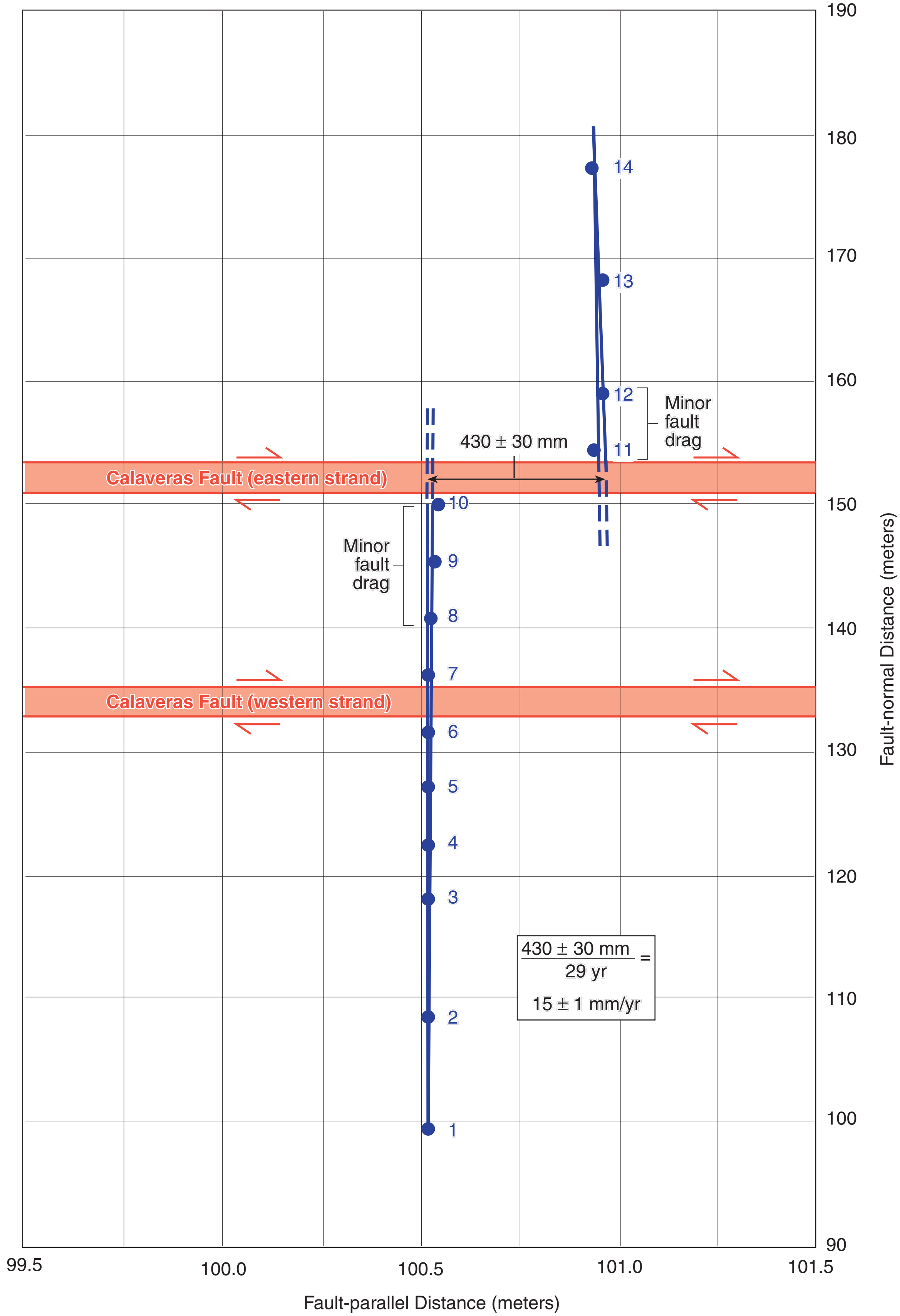


Figure 8. Graphical representation of the USGS alignment array, as surveyed on September 29, 2001, showing right-lateral offset along the eastern fault strand at the Furtado Ranch site. Note this plot is exaggerated parallel to the fault strands to illustrate fault offset.

3.1.2. Survey Results

Surveying of the alignment array reveals a discrete offset of the array between monuments 10 and 11, which are spaced 5 m apart. Figure 6 magnifies the amount of offset through an exaggerated scale parallel to the fault strike. Through this plot, it is possible to interpret that there is some possible minor distributed deformation between monuments 8 and 10, in a sense consistent with "drag" along a dextral fault. Similarly, there may be some "drag" between monuments 11 and 12, although variability in original monument linearity makes this ostensible deformation less certain. Given projections of best-fit lines toward the obvious array discontinuity (between monuments 10 and 11) yields a cumulative dextral offset of 430 ± 30 mm (Figure 8). This value was obtained by extrapolating best-fit lines to the monuments east and west of the creeping fault, and measuring the distance between these lines at the midpoint between monuments 10 and 11. This displacement gives a 29-year creep rate of 15 ± 1 mm/yr (Figure 8).

We estimate the errors associated with the surveying of the alignment array by first noting that the monuments west of the creeping trace are very linear and show no deviations from the best-fit line more than one centimeter. The monuments east of the creeping fault show some deviation from a best-fit line, but again none more than one centimeter. Because the uncertainty associated with the location of any monument likely is on the order of only a few millimeters, we conservatively estimate a total uncertainty in our measurement of dextral offset of 30 mm.

3.2 Trench Investigation

3.2.1 Approach and Methods

We excavated two trenches across the linear depression at the Furtado Ranch site, one on either side of the USGS alignment array (Figure 7). The trenches extended from the colluvial slope west of the depression, across the depression, and onto the alluvial-fan surface east of the main fault strand (Figures 9 and 10). After cleaning the trench walls with a high-pressure water stream, we flagged stratigraphic and structural relations and documented the trench exposures via electronic surveying equipment and manual logging. In conjunction with detailed topographic surveying of the trench site (Figure 7), we surveyed the trenches to the same arbitrary vertical datum, so that elevations of correlative units can be compared between the two trenches. Several datable charcoal fragments collected from the deposits were submitted to the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore Laboratories, where they were treated and analyzed by Dr. Gordon Seitz. After documentation of the trench exposures and peer review by interested researchers, the trenches were backfilled, and the site was restored to its original state. The trenches were open from September 24 to November 9, 2001.

3.2.2 Trench Stratigraphy

Geologic Units

The linear depression at the Furtado Ranch site presently receives colluvial sediment from the northeast-facing fault scarp bordering its western margin, minor slopewash colluvium from the Windmill Creek alluvial-fan surface, and possibly fine-grained alluvium from Windmill Creek during overbank flooding events. The colluvial sediments derived from the hillslope west of the

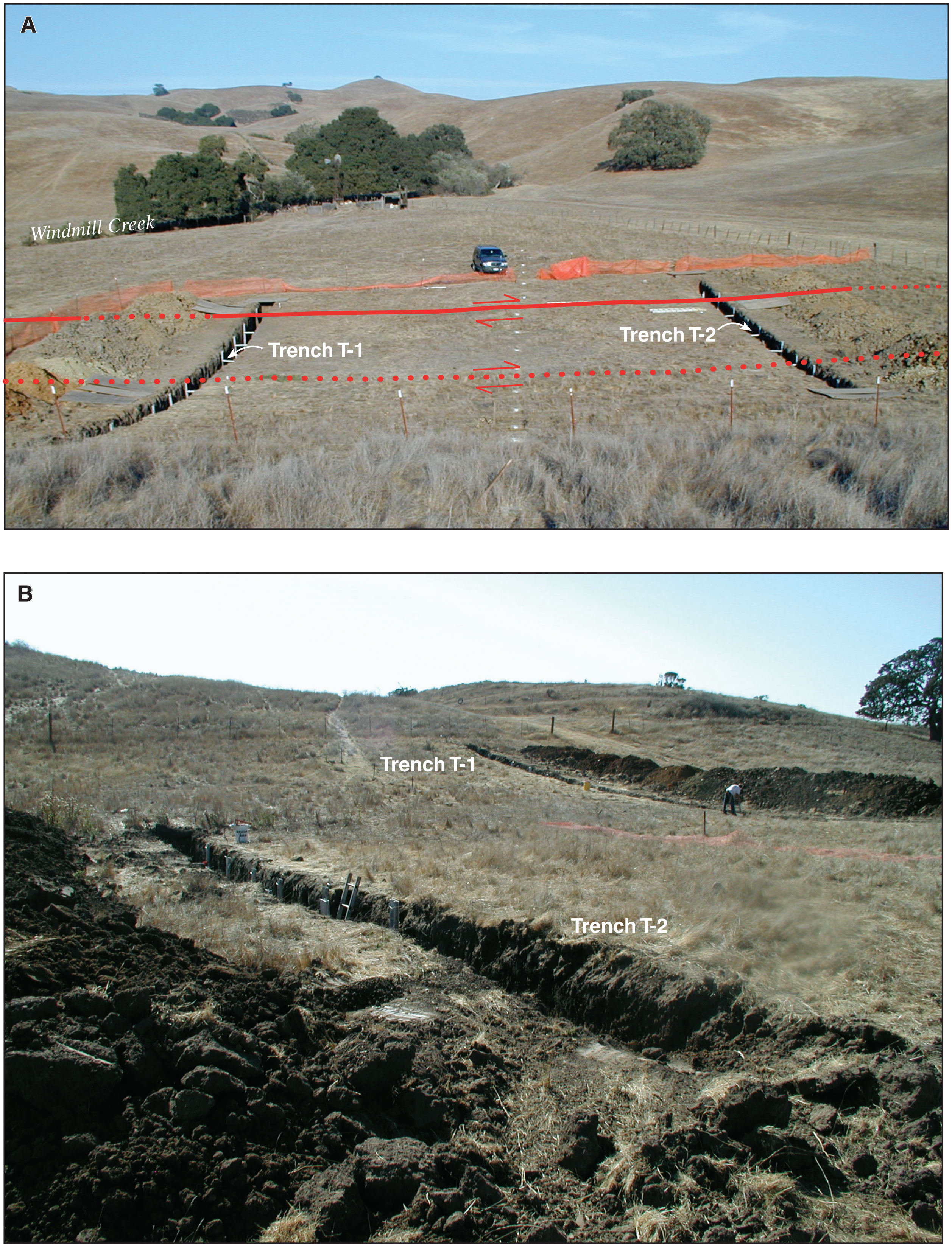
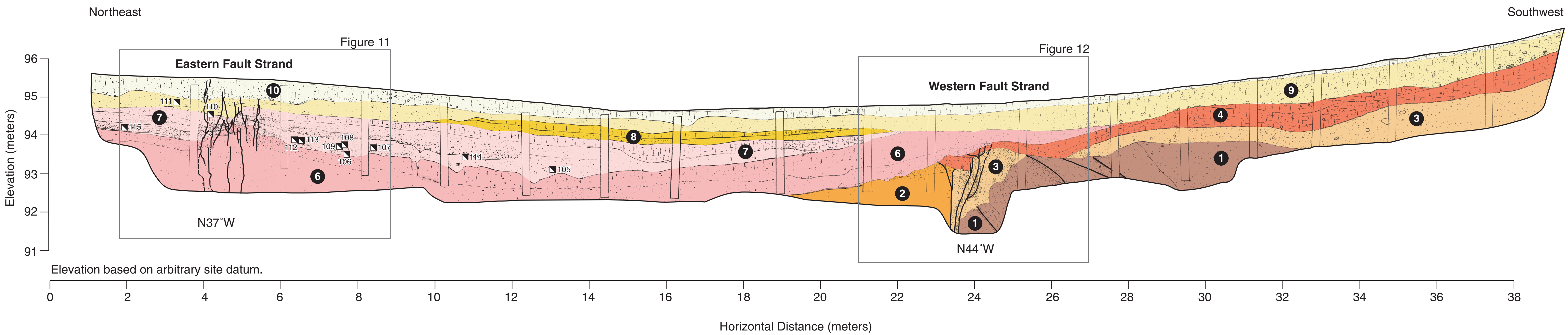


Figure 9. (A) Photograph of the Furtado Ranch site, showing trenches T-1 and T-2, looking northeast.
(B) Photograph of trenches T-1 (distance) and T-2 (foreground) at the Furtado Ranch Site, looking west.



Explanation

Lithologic Descriptions

Unit 10: Holocene alluvium (associated with present-day ground surface). Dark grayish brown (10YR 4/2) GRAVELLY SAND. In eastern part of site, dark grayish brown (10YR 4/2) GRAVELLY SAND with 10 to 30% clasts, some silt, clasts are subrounded, up to 8 cm; Near the east-central partof site, grades to dark grayish brown (10YR 4/2) SANDY SILT with fewer small pebbles and granules (5%), and in the center of the depression grades to very dark grayish brown (10YR 3/2) CLAYEY SILT with little or no gravel. In the western part of site, grades back to dark grayish brown (10YR 4/2) GRAVELLY SAND, and is a thin colluvial mantle on underlying units. Abundant bioturbation throughout unit, and clear smooth basal contact. May have been affected by cultural modifications such as local cut-fill operations or agricultural soil mixing. Soil characteristics throughout unit include: many vesicular pores, common fine roots, medium to coarse subangular blocky to platy soil structure (present-day soil A horizon).

Unit 9: Holocene alluvium. Dark brown (10YR 4/3) to dark grayish brown (10YR 5/4) GRAVELLY SAND to brown (10YR 5/3) SILTY SAND with gravel; fine to coarse sand, 20% to 30% silt; 2 to 5 cm thick laminae; gravel up to 5 cm, subrounded to subangular; fine subangular blocky soil structure; dry, hard; abrupt basal contact; overall, consists of multiple interfingering alluvial strata in the eastern and central parts of the site, grading into colluvium in the western part of the site.

Unit 8: Holocene alluvium. Pale brown (10YR 6/3) SILTY SAND grading upward to brown (10YR 5/3) CLAYEY SILT with fine sand; trace granules; mottled 15% yellowish brown (10YR 5/6), many vesicular and tubular pores; dry, hard; abrupt smooth basal contact; uppermost part represents weakly developed soil A horizon.

Unit 7: Holocene alluvium. Yellowish brown (10YR 5/6 to 10YR 5/4) SILTY SAND; fine to coarse sand, moderately well sorted; coarse sandy to pebbly interbeds, with subrounded clasts up to 7 cm; dry, hard; rare charcoal fragments; many beds fine upward from GRAVELLY SAND to SILTY SAND or GRAVELLY CLAY; in center of depression, finer-grained sand, no gravel, some clay; abrupt smoot contact; uppermost part is a dark grayish brown (10YR 4/2) GRAVELLY CLAY with subangular blocky soil structure.

Unit 6: Holocene alluvium. The eastern and central part of unit is dark yellowish brown (10YR 4/4) SAND with clay and gravel; fine to medium sand; gravel (10% to 15%), subangular clasts up to 1.5 cm, orange-brown and red-brown sandstone clasts; dry, hard; grading upward to brown (10YR 5/3) CLAYEY SAND; fine sand, with rare (5%) small pebbles of orange-brown and red-brown sandstone, subrounded to subangular; dry, very hard; upper part is soil A horizon developed on alluvium. In western part of site, basal part of unit grades to brown (10YR 5/3) SANDY SILT with clay and yellowish brown (10YR 3/4) CLAYEY SAND, trace gravel up to 1.5 cm, subrounded to subangular; massive; at basal contact common (20%), subangular to subrounded clasts up to 25 cm; directly adjacent to western fault strand, clasts include large angular clasts of locally derived Santa Clara Formation claystone, and subangular to subrounded clasts of sandstone and siltstone from Pleistocene alluvium; abrupt basal contact; soil developed on upper part of unit in western part of site is very dark grayish brown (10YR 3/2) SANDY CLAY, subangular blocky to coarse prismatic soil structure.

Unit 5: Latest Pleistocene to early Holocene alluvium. Mottled grayish brown (10YR 5/2) and yellowish brown (10YR 5/6) GRAVELLY SAND with silt and clay, grading upward to brown (10YR 5/3) GRAVELLY CLAY with silt and sand. Gravel (10%) up to 2 cm, subrounded to subangular, consists of orange-brown and red-brown sandstone clasts; poorly sorted, massive; dry, hard; upper 20 to 25 cm is soil A horizon developed on alluvial-fan or debris-flow deposits; clear smooth basal contact.

Unit 4: Late (?) Pleistocene colluvium. Brown (7.5YR 5/4) CLAY with sand. Trace gravel up to 7 cm, subrounded to subangular; fining upward, massive; soil Bt horizons with strong coarse angular blocky soil structure, clay films on ped faces; clear smooth basal contact.

Unit 3: Pleistocene (?) alluvium. Brown (7.5YR 5/4) GRAVELLY SAND WITH CLAY to dark yellowish brown (10YR 4/6) SANDY GRAVEL. Fine to coarse sand; subrounded to subangular gravel up to 30 cm; massive; dry, hard; clear smooth basal contact where in depositional contact with underlying units. Within western fault zone, pervasively deformed and containing gravel clasts that are rotated parallel to fault planes.

Unit 2: Pleistocene (?) alluvium. Dark brown (7.5 YR 4/4) CLAYEY SILT; well sorted, with trace fine sand; dense, massive; soil Bt horizon at top of unit contains coarse angular blocky soil structure, clay films on ped faces and pores, common tubular pores.

Unit 1: Plio-Pleistocene Santa Clara Formation. Light olive-brown (2.5 YR 5/4) to dark olive-brown (2.5YR 4/3) SILTSTONE and CLAYSTONE, and dark brown (7.5 YR 4/4) sandy gravel and gravelly sand CONGLOMERATE. Clasts within conglomerate beds are siltstone and claystone and are about 10% to 15% of unit; where discernible, bedding dips westerly. Commonly fractured and sheared, with calcium carbonate and clay gouge along fracture and shear planes.

Symbols

- Soil development
- Fracture
- Fault
- Radiocarbon sample location (see Table 1)

FURTADO RANCH SITE

Log of Trench 1 (South Wall)

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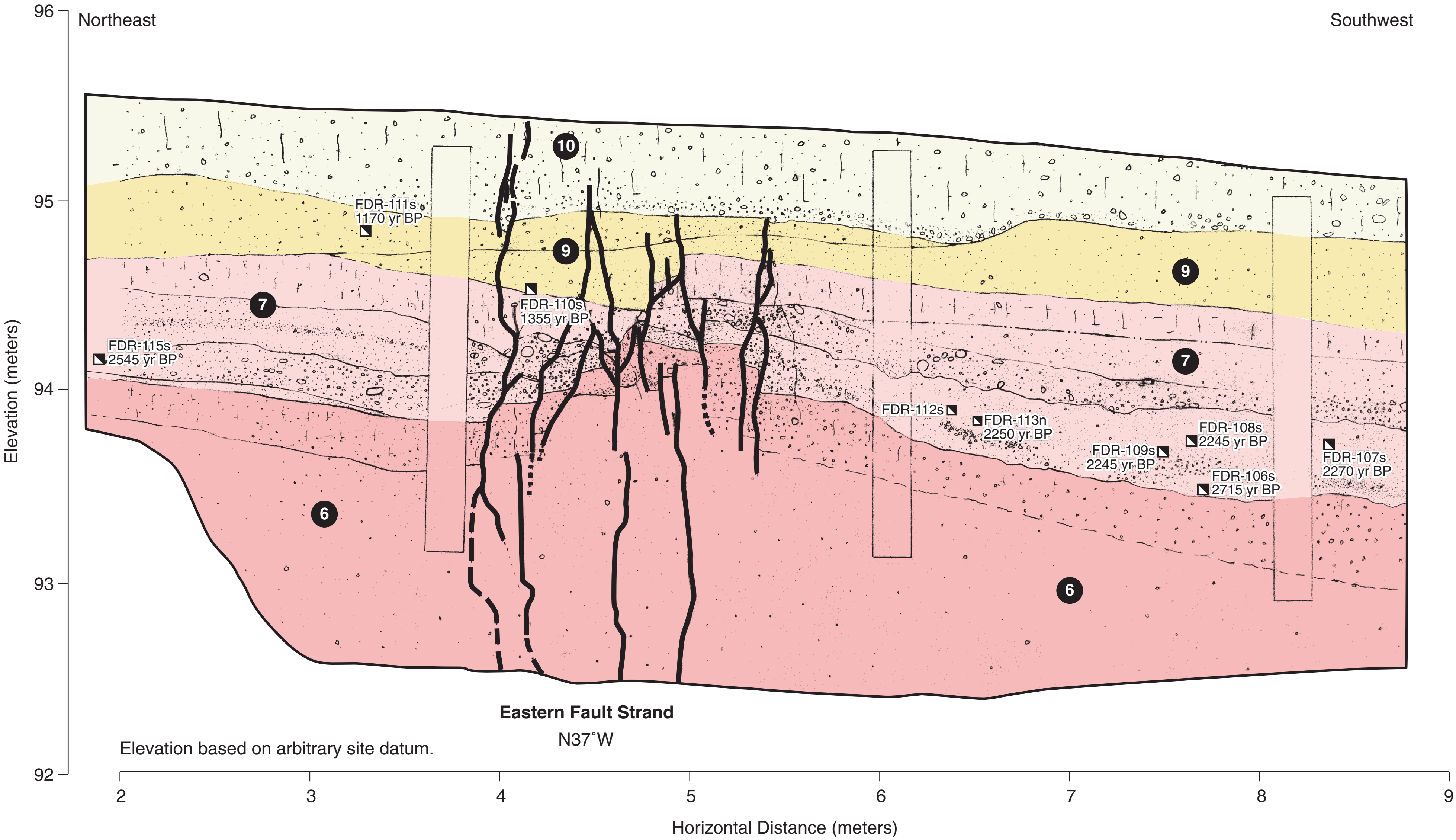
depression represent erosion of late Quaternary alluvium and Plio-Pleistocene Santa Clara Formation bedrock, which in this local area consists of interbedded sand, silt, and gravel deposited in a terrestrial alluvial setting. Based on exposures within the Pacheco Pass Landfill located directly west of the site, these semi-consolidated sediments are strongly deformed and consist of laterally discontinuous beds containing clasts of claystone, sandstone, siltstone and conglomerate (EMCON, 1992). The sediments derived from Windmill Creek and its alluvial fan primarily consist of sand, silt, and clay, with rare pebbles of sandstone and siltstone that were derived from Cretaceous Great Valley Sequence rocks in Windmill Creek watershed (EMCON, 1992). The stratigraphy exposed in the two trenches is shown on Figures 10 through 12 (trench T-1) and Figures 13 through 15 (trench T-2), and is summarized below.

In general, the trenches exposed a sequence of interbedded sandy and silty strata on the eastern side of, and within, the linear depression, as well as gravelly clay and clayey gravel on the western side of the depression (Figures 11 and 14). Soil development has occurred within several of these strata, and some of the soil horizons extend across the depression whereas some horizons are laterally discontinuous. These soil horizons provide evidence of intermittent surface stability, and also help indicate where erosion and subsequent deposition have affected the stratigraphic record within the closed depression. The trenches also exposed Plio-Pleistocene Santa Clara Formation beneath the western side of the depression. For simplicity, we herein group strata exposed in the trenches into 10 stratigraphic packages, some of which are associated with soil development within their upper strata. In the summary below, these packages are numbered from oldest to youngest, with Unit ❶ consisting of "bedrock", including siltstone and other lithologies within the Santa Clara Formation. Stratigraphic Units ❷, ❸, ❹, and ❺ consist of probable Pleistocene alluvium, and Units ❻ through ❿ consist of Holocene alluvium deposited within or near the present-day depression.

Unit ❶ is exposed only in the lower parts of the western ends of trenches T-1 and T-2 (Figures 11 and 14). Unit ❶ includes several semi-consolidated strata of the Plio-Pleistocene Santa Clara Formation that are fractured, sheared and folded, and are present only on the western side of the western fault strand in both trenches T-1 and T-2. These sediments include olive brown (2.5 YR) fractured siltstone and claystone, and dark brown (7.5 YR) sandy gravel and gravelly sand conglomerate. Most of the clasts within the conglomeratic beds are siltstone, and orientations of these beds suggest a westerly dip. Unit ❶ contains many shears associated with calcium carbonate accumulations, and some shears containing clay gouge (Figures 14 and 16).

Unit ❷ is a dense, massive clayey silt that is present only in the western part of trench T-1, adjacent to the western fault strand (Figures 11 and 13). This dark brown (7.5 YR) silt is at least 1 meter thick, and is in fault contact with sheared gravel (Unit ❸) along the western fault strand (Figure 13). A moderately well developed, clay-rich soil has formed in the uppermost part of this unit, and may be the same soil as that developed on Unit ❹ (see below). We interpret that Unit ❷ is a massive, overbank deposit laid down within the fault zone, although it may also be part of the Santa Clara Formation. The absence of Unit ❷ elsewhere in the trenches precludes further interpretation of its stratigraphic position or origin.



Note: Refer to Figure 10 for unit descriptions.

◪ Radiocarbon sample location, age in calibrated yr BP (see Table 1)

F U R T A D O   R A N C H   S I T E

Detailed Log of Trench 1
(South Wall, East Portion)

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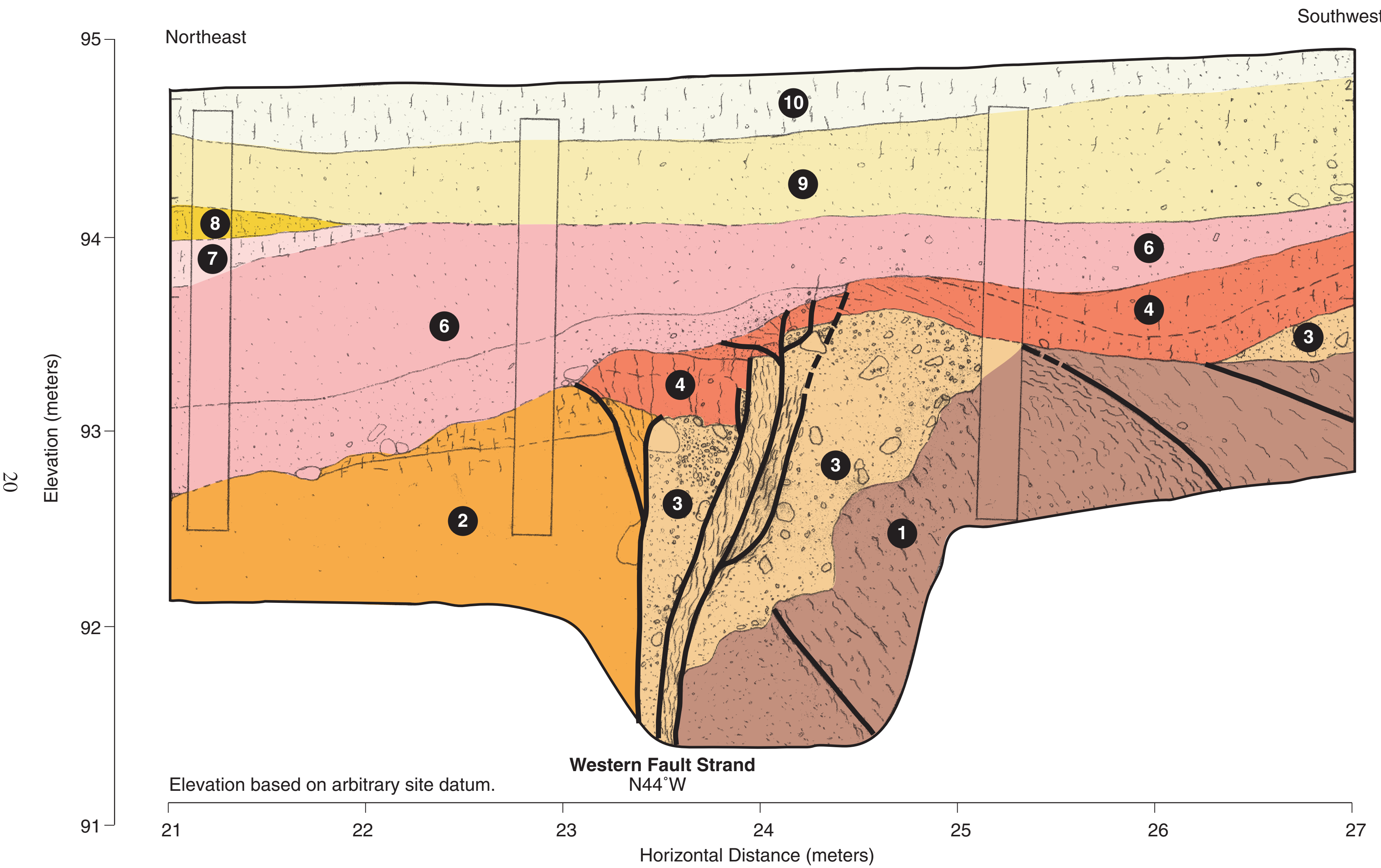

Note: Refer to Figure 10 for unit descriptions.

F U R T A D O R A N C H S I T E

Detailed Log of Trench 1 (South Wall, West Portion)

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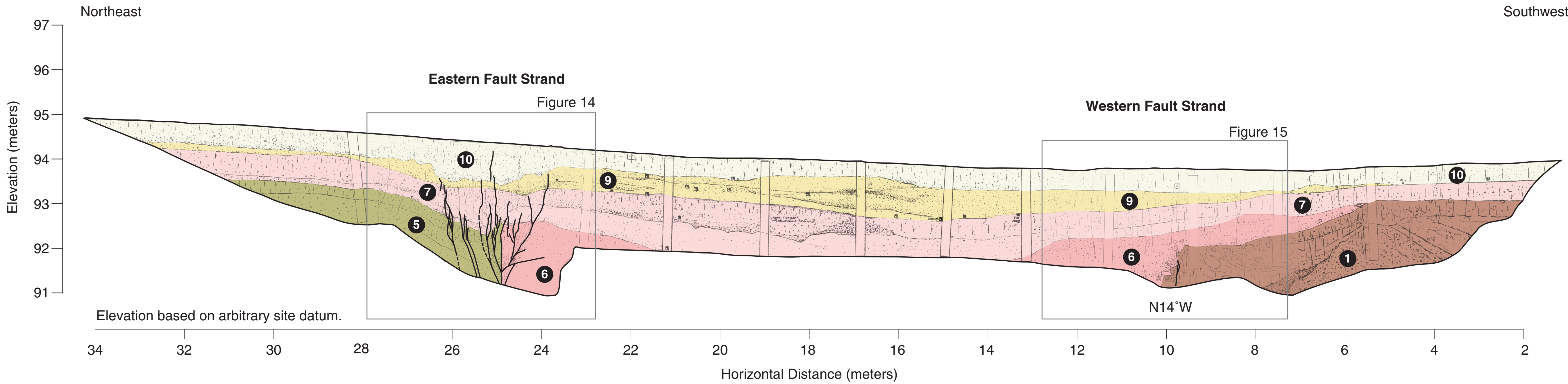

Explanation

Lithologic Descriptions

Unit **10**: Holocene alluvium (associated with present-day ground surface). Dark grayish brown (10YR 4/2) GRAVELLY SAND. In eastern part of site, dark grayish brown (10YR 4/2) GRAVELLY SAND with 10 to 30% clasts, some silt, clasts are subrounded, up to 8 cm; Near the east-central partof site, grades to dark grayish brown (10YR 4/2) SANDY SILT with fewer small pebbles and granules (5%), and in the center of the depression grades to very dark grayish brown (10YR 3/2) CLAYEY SILT with little or no gravel. In the western part of site, grades back to dark grayish brown (10YR 4/2) GRAVELLY SAND, and is a thin colluvial mantle on underlying units. Abundant bioturbation throughout unit, and clear smooth basal contact. May have been affected by cultural modifications such as local cut-fill operations or agricultural soil mixing. Soil characteristics throughout unit include: many vesicular pores, common fine roots, medium to coarse subangular blocky to platy soil structure (present-day soil A horizon).

Unit **9**: Holocene alluvium. Dark brown (10YR 4/3) to dark grayish brown (10YR 5/4) GRAVELLY SAND to brown (10YR 5/3) SILTY SAND with gravel; fine to coarse sand, 20% to 30% silt; 2 to 5 cm thick laminae; gravel up to 5 cm, subrounded to subangular; fine subangular blocky soil structure; dry, hard; abrupt basal contact; overall, consists of multiple interfingering alluvial strata in the eastern and central parts of the site, grading into colluvium in the western part of the site.

Unit **8**: Holocene alluvium. Pale brown (10YR 6/3) SILTY SAND grading upward to brown (10YR 5/3) CLAYEY SILT with fine sand; trace granules; mottled 15% yellowish brown (10YR 5/6), many vesicular and tubular pores; dry, hard; abrupt smooth basal contact; uppermost part represents weakly developed soil A horizon.

Unit **7**: Holocene alluvium. Yellowish brown (10YR 5/6 to 10YR 5/4) SILTY SAND; fine to coarse sand, moderately well sorted; coarse sandy to pebbly interbeds, with subrounded clasts up to 7 cm; dry, hard; rare charcoal fragments; many beds fine upward from GRAVELLY SAND to SILTY SAND or GRAVELLY CLAY; in center of depression, finer-grained sand, no gravel, some clay; abrupt smoot contact; uppermost part is a dark grayish brown (10YR 4/2) GRAVELLY CLAY with subangular blocky soil structure.

Unit **6**: Holocene alluvium. The eastern and central part of unit is dark yellowish brown (10YR 4/4) SAND with clay and gravel; fine to medium sand; gravel (10% to 15%), subangular clasts up to 1.5 cm, orange-brown and red-brown sandstone clasts; dry, hard; grading upward to brown (10YR 5/3) CLAYEY SAND; fine sand, with rare (5%) small pebbles of orange-brown and red-brown sandstone, subrounded to subangular; dry, very hard; upper part is soil A horizon developed on alluvium. In western part of site, basal part of unit grades to brown (10YR 5/3) SANDY SILT with clay and yellowish brown (10YR 3/4) CLAYEY SAND, trace gravel up to 1.5 cm, subrounded to subangular; massive; at basal contact common (20%), subangular to subrounded clasts up to 25 cm; directly adjacent to western fault strand, clasts include large angular clasts of locally derived Santa Clara Formation claystone, and subangular to subrounded clasts of sandstone and siltstone from Pleistocene alluvium; abrupt basal contact; soil developed on upper part of unit in western part of site is very dark grayish brown (10YR 3/2) SANDY CLAY, subangular blocky to coarse prismatic soil structure.

Unit **5**: Latest Pleistocene to early Holocene alluvium. Mottled grayish brown (10YR 5/2) and yellowish brown (10YR 5/6) GRAVELLY SAND with silt and clay, grading upward to brown (10YR 5/3) GRAVELLY CLAY with silt and sand. Gravel (10%) up to 2 cm, subrounded to subangular, consists of orange-brown and red-brown sandstone clasts; poorly sorted, massive; dry, hard; upper 20 to 25 cm is soil A horizon developed on alluvial-fan or debris-flow deposits; clear smooth basal contact.

Unit **4**: Late (?) Pleistocene colluvium. Brown (7.5YR 5/4) CLAY with sand. Trace gravel up to 7 cm, subrounded to subangular; fining upward, massive; soil Bt horizons with strong coarse angular blocky soil structure, clay films on ped faces; clear smooth basal contact.

Unit **3**: Pleistocene (?) alluvium. Brown (7.5YR 5/4) GRAVELLY SAND WITH CLAY to dark yellowish brown (10YR 4/6) SANDY GRAVEL. Fine to coarse sand; subrounded to subangular gravel up to 30 cm; massive; dry, hard; clear smooth basal contact where in depositional contact with underlying units. Within western fault zone, pervasively deformed and containing gravel clasts that are rotated parallel to fault planes.

Unit **2**: Pleistocene (?) alluvium. Dark brown (7.5 YR 4/4) CLAYEY SILT; well sorted, with trace fine sand; dense, massive; soil Bt horizon at top of unit contains coarse angular blocky soil structure, clay films on ped faces and pores, common tubular pores.

Unit **1**: Plio-Pleistocene Santa Clara Formation. Light olive-brown (2.5 YR 5/4) to dark olive-brown (2.5YR 4/3) SILTSTONE and CLAYSTONE, and dark brown (7.5 YR 4/4) sandy gravel and gravelly sand CONGLOMERATE. Clasts within conglomerate beds are siltstone and claystone and are about 10% to 15% of unit; where discernible, bedding dips westerly. Commonly fractured and sheared, with calcium carbonate and clay gouge along fracture and shear planes.

Symbols

- Soil development
- Fracture
- Fault

FURTADO RANCH SITE

Log of Trench 2 (South Wall)

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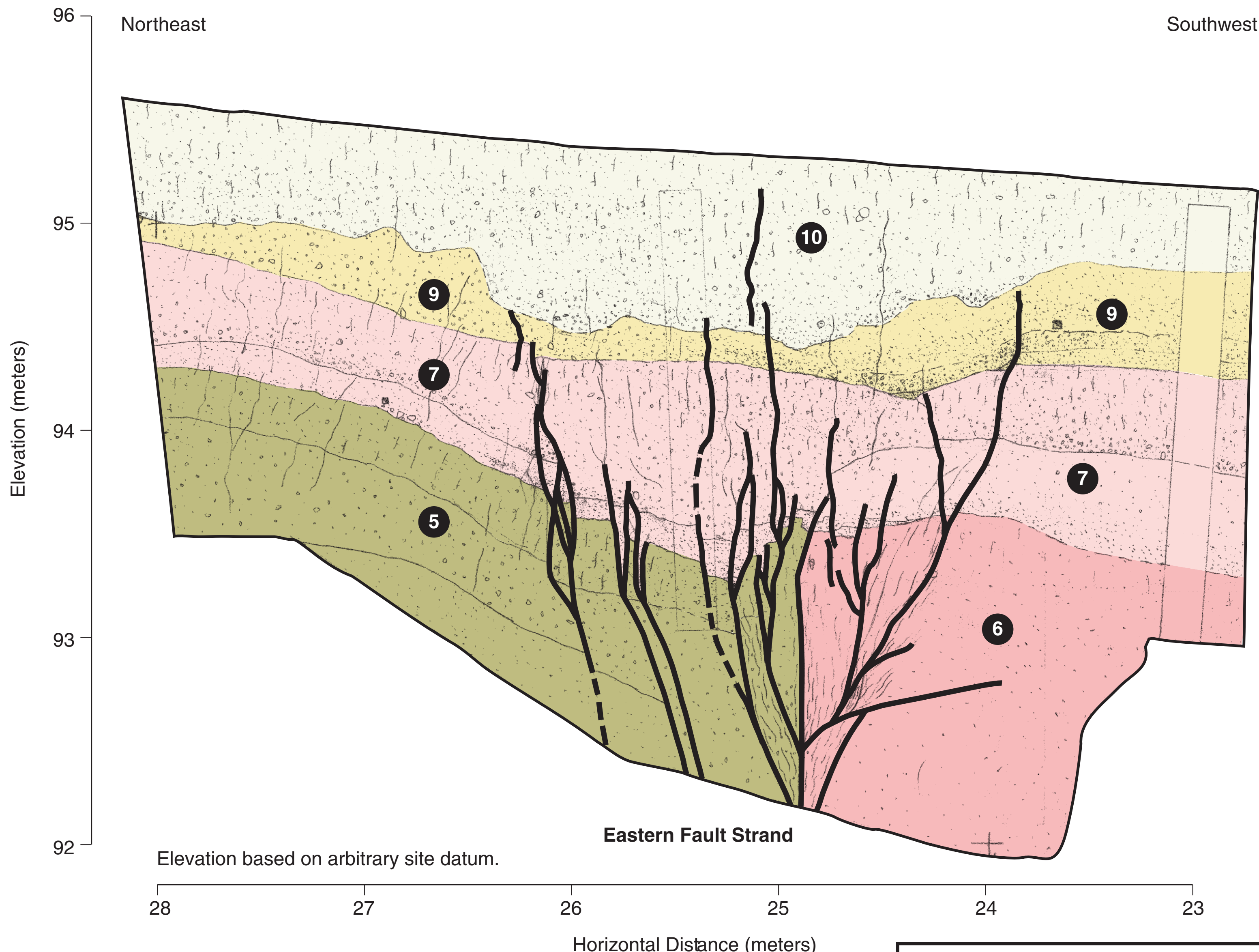


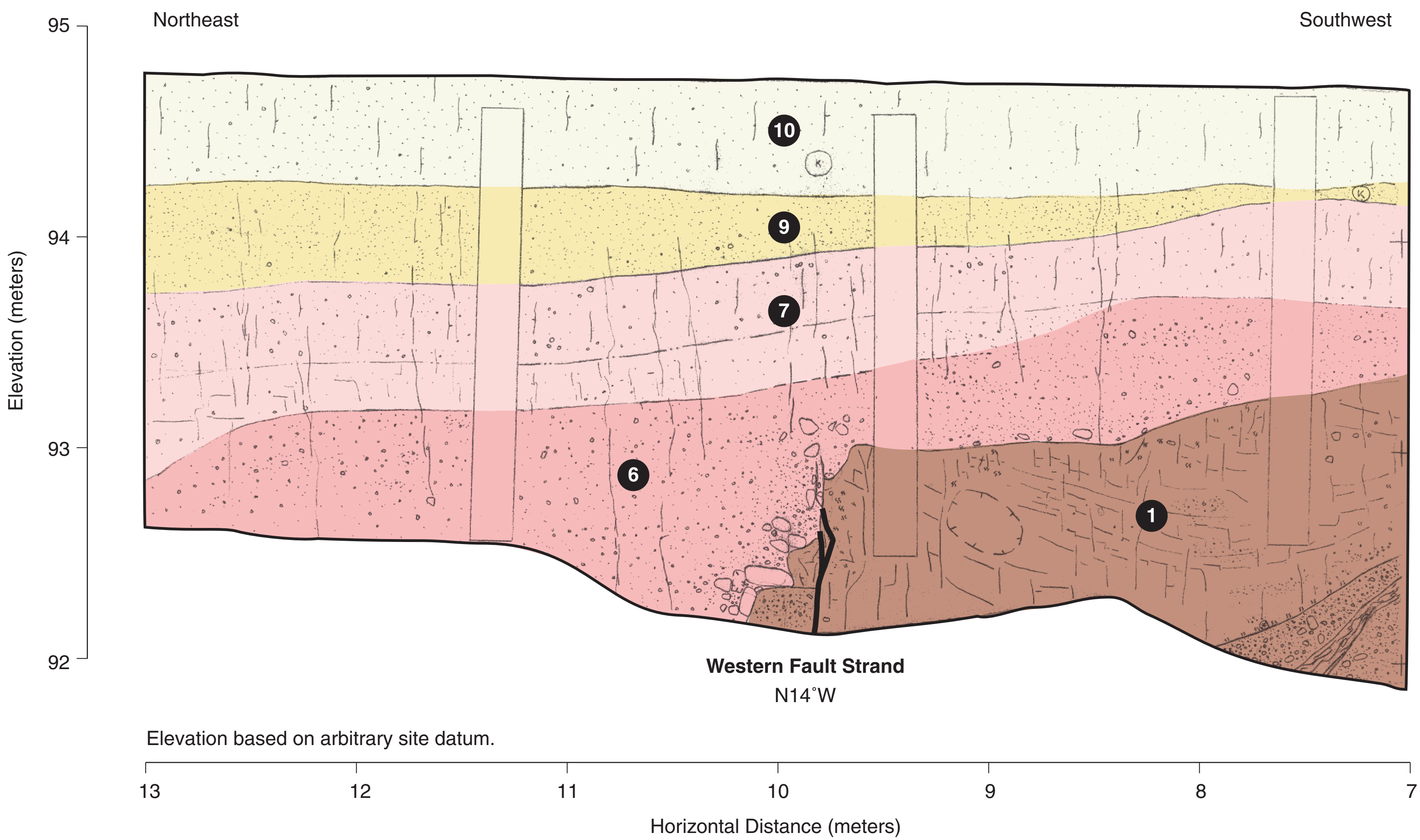
Note: Refer to Figure 13 for unit descriptions.

FURTADO RANCH SITE

Detailed Log of Trench 2 (South Wall, East Portion)

WLA William Lettis & Associates, Inc. | Figure 14

1450 Furtado



Note: Refer to Figure 13 for unit descriptions.

FURTADO RANCH SITE

Detailed Log of Trench 2 (South Wall, West Portion)

WLA William Lettis & Associates, Inc. | Figure 15

1450 Furtado

Unit ❸ is an oxidized, gravelly sand that unconformably overlies the conglomerate of the Santa Clara Formation in the western part of trench T-1 (Figure 11). The gravel has a hue of 7.5YR but no accumulation of secondary carbonate. This massive gravel has a clear, smooth basal contact that, west of station 28 m (Figure 11), is essentially horizontal and suggests that the gravel is a strath terrace deposit cut onto the underlying Santa Clara Formation bedrock. However, close to the western strand of the fault, the deposit dips eastward, and appears to be folded. Unit ❸ also includes a large body of deformed gravel along the western fault strand exposed in trench T-1 (Figure 12). The characteristics of this unit are similar to those of Unit ❸ in the western part of the trench, and the sandstone clasts are of comparable size, rounding, and lithology. The gravel is sheared and deformed within the fault zone, and contains clasts that are oriented parallel to the fault planes. A 10- to 20-cm-thick vertical sliver of pervasively sheared sandy gravel is within Unit ❸ and marks the primary western fault strand (Figure 12). Although this gouge consists mostly of silty and sandy material similar to the local rocks of the Santa Clara Formation, occasional rounded sandstone clasts are within the gouge and likely were incorporated from the surrounding parts of Unit ❸ (Figure 12).

Unit ❹ is a clay associated with a well-developed argillic (Bt) soil horizon in the western part of trench T-1 (Figures 10 and 12). The soil characteristics include prominent clay films on ped faces, strong coarse soil structure, and a 7.5YR hue, which suggest a Pleistocene age for the soil (and thus the deposit). This deposit unconformably overlies the Unit ❸ gravelly sand adjacent to the western fault strand (Figure 12), and likely is either a sandy alluvium laid down by Windmill Creek, or colluvium derived from the Unit ❸ alluvium. The soil formed on Unit ❹ has similar amounts of development as the soil formed on Unit ❷ adjacent to the western fault strand in trench T-1 (Figure 12). Unit ❹ is faulted by the western fault strand, and is folded into a syncline-anticline pair, indicating that deposition of this unit precedes the last episode of movement along the western fault strand.

Unit ❺ is identified only in trench T-2, east of the eastern fault strand (Figures 10 and 11). This unit is a sandy alluvial-fan or debris-flow deposit consisting of clayey sand and gravelly sand strata with clasts of red-brown and orange-brown sandstone. The soil formed on this unit is moderately developed, and exhibits evidence of less clay accumulation than in Unit ❹ in the western part of the site. Overall, we interpret that Unit ❺ was laid down as an alluvial-fan or debris flow deposit, which may have interfingered with Unit ❹ colluvium/alluvium in the western part of the site. The stratigraphic conditions and spatial distribution of Units ❸, ❹ and ❺ suggest that during the late Pleistocene, the Furtado Ranch site was characterized by coarse alluvial deposition throughout the site, followed by colluviation in the western part of the site and soil formation on the colluvial and alluvial deposits.

Units ❻ through ❿ are primarily a stacked sequence of fine-grained alluvial deposits laid down within or adjacent to the linear depression along the Calaveras Fault (Figures 10 and 13). Unit ❻ is a brown clayey sand with about 10% to 15% gravel. Within trench T-1, this unit contains a moderately developed soil horizon that is about 20 to 35 cm thick and extends across the entire depression (Figure 10). The absence of a similar soil in trench T-2 suggests that later erosion related to Unit ❼ removed this soil in the southern part of the depression. The moderate amount of soil development in the upper part of Unit ❻ suggests that the site was free of substantial erosion or deposition for a moderate length of time following deposition of Unit ❻. The eastern part of Unit ❻, which appears to be an alluvial-fan or debris flow deposit probably derived from Windmill Creek, locally contains slightly greater concentrations of gravel clasts. For example, relatively more gravel is present within the eastern fault zone, which may be related to tectonic mixing with overlying units. From east to west (Figures 10 and 13), Unit ❻ grades from an alluvial-fan/debris-flow deposit into a colluvial deposit derived from the east-facing hillslope bordering the closed depression.

The western part of Unit ❻ contains more clasts at its base, particularly directly adjacent to the western fault strand (Figures 12 and 15). In trench T-1, between stations 21 and 24 (Figure 12), the lowermost part of Unit ❻ contains clasts as large as 12 cm in diameter that likely were derived from uphill exposures of Units ❸ or ❹. This concentration of clasts is present only downhill (east of) the western fault strand, and appears to be a coarser facies of the Unit ❻ colluvium. Similarly, in trench T-2 at station10 (Figure 15), the lowermost part of Unit ❻ contains clasts as large as 25 cm that are adjacent to the sub-vertical fault plane. These clasts also probably were derived from sandstone-rich alluvium that was present uphill of the western fault strand. In trench T-2, Unit ❻ buries a steep, fractured face in Unit ❶ that developed along the western fault strand (Figure 15, station 10). In addition, trench T-2 exposed blocks of poorly resistant claystone bedrock within this near-fault colluvium, which likely would not survive transport over distances more than a couple of meters. We interpret the scarp-derived colluvium to reflect possible surface fault rupture along the western fault strand of the Calaveras Fault at the Furtado Ranch site, and subsequent eastward colluviation into the linear depression. This is consistent with evidence of faulting, folding, and relative uplift of strata directly underlying this unit (i.e., Units ❷, ❸, and ❹; Figure 12).

Unit ❼ is a series of sandy strata that erosionally overlie older deposits. This deposit consists mostly of silty sand and gravelly sand that grades upward into gravelly clay. The lower and middle parts of this unit contain laterally discontinous, interfingering strata typical of alluvial deposits. This unit contains rare charcoal fragments that provide stratigraphically consistent age estimates (see *Age Estimates*, below). The uppermost part of Unit ❼ is a dark grayish brown (10YR) gravelly clay with subangular blocky soil structure and moderate ped development, suggesting a moderate level of soil formation. As noted above, Unit ❼ eroded into Unit ❻ in the southern part of the depression, and probably removed the soil horizon and uppermost deposits of Unit ❻. There was little or no erosion of underlying Unit ❻ in the area of trench T-1 (Figure 10). The elevation of the base of Unit ❼ based on the two trench exposures suggests that the overall flow direction of this unit was from northwest to southeast. In trench T-1, the base of Unit ❼ is about 92.7 m (arbitrary site datum; Figure 10), whereas the elevation of the base of Unit ❼ in trench T-2 is below the trench floor and thus is lower than 92.7 m (Figure 13). These data are consistent with the stratigraphic evidence of erosion of Unit ❻ in the southern part of the site.

Unit ❽ is exposed only in the central part of trench T-1, and consists of a thin, pale brown silty sand that grades upward into a clayey silt (Figure 10). The uppermost part of Unit ❽ represents a weakly developed soil A horizon. This laterally discontinuous deposit probably was laid down only within the linear depression, perhaps derived from either a sandy debris-flow deposit from the adjacent hill slope or from an overbank flood event along Windmill Creek. Considering the southeasterly gradients on both Units ❼ and ❾ (see below), the depositional flow direction for Unit ❽ probably also was to the southeast.

Unit ❾ is a sandy alluvium consisting of multiple interfingering strata in the central part of the site, and a sandy colluvium in the western part of the site (Figures 10 and 13). The unit extends across the eastern fault strand as a fine-grained sand that likely was derived from sheetfloods on the Windmill Creek alluvial fan, and perhaps as broad channel alluvium within the linear depression. Based on topographic surveying of both trenches, the base of Unit ❾ is at an elevation of 94.0 m in trench T-1 and 93.6 m in trench T-2 (Figures 10 and 13), suggesting that the overall gradient of this unit is also southeasterly, toward the lowest part of the present-day closed depression (Figure 7). In trench T-1, the bedded alluvial silty sand grades westward into colluvium containing progressively greater amounts of gravel clasts. At about station 23, the unit has about 5% gravel clasts (all orange-brown and red-brown sandstone), whereas at about station 27 the unit has about 15% clasts up to 7 cm in diameter (Figure 12). There are progressively more clasts upslope to the west (Figure 10). In addition, the soil developed at the present-day surface (through Unit ❿) extends into Unit ❾, and represents the modern soil A horizon.

Unit ❿ is the deposit and associated soil at the present-day ground surface (Figures 10 through 15). In the eastern parts of both trenches T-1 and T-2, this deposit is a gravelly sand with 10 to 30% gravel clasts. Near the central part of the linear depression, this deposit grades to a sandy silt with fewer clasts, and in the center of the depression is a clayey silt with little or no gravel. In the western parts of both trenches, Unit ❿ then grades to a gravelly sand again, and is a thin colluvial mantle on Unit ❾. The soil development within this dark grayish brown (10YR 4/2) deposit includes subangular blocky soil structure and coarse to medium peds. Unit ❿ is characterized by abundant bioturbation, and may have been affected by cultural modifications such as local cut-fill operations or agricultural soil mixing. We interpret that the eastern part of the unit is an alluvial-fan deposit, which grades to a finer-grained alluvium in the linear depression, which then grades into hillslope colluvium derived from the hillslope bordering the western margin of the depression.

Age Estimates

Charcoal fragments were fairly abundant within the sag-pond stratigraphy, and a total of 30 samples were collected from various stratigraphic units exposed in trenches T-1 and T-2. We sampled only angular charcoal fragments that appeared to have not been reworked or altered. Of the 30 fragments, 11 samples were analyzed for radiocarbon age determination by the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore Laboratories (Table 1). Nine of these samples were taken from the lower part of Unit ❼, which is a sandy alluvium containing multiple interfingering sand and silt beds. Based on stratigraphic position, we interpret that two of the nine samples from Unit ❼ are reworked (samples 112s and 114s, Table 1). Therefore, analyses available at this point in time yield seven valid radiocarbon dates from Unit ❼. The average calibrated age of these seven samples is 2340 $\pm$ 10 cal. yr BP (2σ probability). Five samples from the central part of the unit yielded extremely consistent ages, ranging from 2245 $\pm$ 95 to 2270 $\pm$ 90 cal. yr BP. However, the lowermost stratigraphically consistent age estimate is from the base of Unit ❼ (sample 106s, Table 1), which yielded a calibrated age-estimate of 2715 $\pm$ 35 cal. yr BP. From these data, we interpret that the base of Unit ❼ is about 2,700 years old,

Table 1. Summary of Radiocarbon Ages, Furtado Ranch Site

Sample No.	Lab No. [1]	Conventional ^{14}C Age (yr BP ± 1σ)	Calibrated Age Range (cal. yr BP) [2] (2σ, 95% probability)	Interpreted Age-estimate [3]
Alluvial Deposit 9				
FDR-111s	80357	1255 ± 50	1060 to 1280	1170 ± 90
FDR-110s	80356	1470 ± 40	1290 to 1420	1355 ± 65
Average:		*1380 ± 30*	*1260 to 1350*	*1305 ± 45*
Alluvial Deposit 7				
FDR-105s	80351	2230 ± 40	2150 to 2340	2245 ± 95
FDR-107s	80353	2315 ± 40	2180 to 2360	2270 ± 90
FDR-108s	80354	2235 ± 40	2150 to 2340	2245 ± 95
FDR-109s	80355	2230 ± 40	2150 to 2340	2245 ± 90
FDR-112s	80358	(2910 ± 140)	(2770 to 3050)	
FDR-113n	80359	2265 ± 40	2150 to 2350	2250 ± 100
FDR-114s	80360	(6390 ± 60)	(6330 to 6450)	
FDR-115s	80361	2480 ± 50	2360 to 2730	2545 ± 185
FDR-106s	80352	2545 ± 40	2680 to 2750	2715 ± 35
Average:		*2320 ± 20*	*2330 to 2350*	*2340 ± 10*

Samples are listed in stratigraphic order, with stratigraphically highest samples at the top.
Parentheses indicate stratigraphically inconsistent samples (not included in average).
1 All samples analyzed by CAMS, Livermore, California
2 Calibrated based on Stuiver and Becker (1993), using CALIB v 4.3 (2000).
3 Interpreted based on 2-sigma ranges.

and the middle of the unit is about 2,250 years old. Notably, Unit ❻ is at least as old as 2,700 yr BP, on the basis of its stratigraphic position below Unit ❼, and is probably middle Holocene in age.

The two charcoal samples analyzed from Unit ❾ yielded an average calibrated age of 1305 ± 45 cal. yr BP (samples 110s and 11s, Table 1). The lower of these two samples yielded a calibrated age of 1355 ± 65 cal. yr BP, and the higher of the two samples yielded a calibrated age of 1170 ± 90 cal. yr BP. These data are consistent with their depositional relationships in the trench exposures. From these data, we interpret that the base of Unit ❾ is about 1,350 years old, and the top is about 1,150 years old. Thus, the middle and upper part of the sandy alluvium beneath the linear depression at the Furtado Ranch site is late Holocene in age, which is consistent with the cumulative amount of soil development throughout the exposed depositional sequence.

In addition, the degree of relative soil development allows rough age estimates of units ❹ and ❺ to be made. Unit ❹ consists of a well-developed argillic Bt horizon that exhibits prominent evidence of secondary clay accumulation, and we interpret that this unit is most likely late Pleistocene in age. Similarly, soil development in Unit ❺ is moderate, consisting of moderate secondary clay accumulation (although not as much as in Unit ❹). We interpret that Unit ❺ probably is latest Pleistocene to early Holocene in age. Additional age-dating is required to further refine or improve these rough age estimates.

Stratigraphic Interpretation

On the basis of our logging and stratigraphic descriptions provided above, we interpret that the late Quaternary depositional setting of the Furtado Ranch site has been dominated by deposition from Windmill Creek and the east-facing hillslope along the western margin of the closed depression. The stratigraphic and soil characteristics of Units ❷ and ❸ suggest that these units probably were deposited in a fluvial setting. The coarseness of Unit ❸ suggests a fairly large stream system, perhaps as a large channel draining westerly out of the Diablo Range. It appears that this terrace gravel is associated with a strath surface cut onto the Santa Clara Formation. The distinct difference between Units ❷ and ❸ suggests a fairly large fluvial system with several diverse facies, including overbank (Unit ❷) and channel facies (Unit ❸). However, we do not know the absolute or relative ages of these two deposits, and alternatively they could represent a major change in the depositional setting of the site through time. In general, however, we interpret that these units are late Pleistocene or older in age, on the basis of the well-developed soil on Unit ❹, which is a fluvial or colluvial deposit laid down on Unit ❸.

Unit ❺ represents the oldest exposed alluvial-fan or debris-flow deposits from Windmill Creek. This unit may mark the initial development of the Windmill Creek alluvial fan, and may have interfingered with Unit ❹ colluvium/alluvium in the western part of the site. The moderate amount of soil development on Unit ❺ suggest local landform stability prior to burial of the site by Unit ❻. Units ❻ through ❿ are a stacked sequence of fine-grained alluvial deposits laid down within or adjacent to the linear depression along the Calaveras Fault. The eastern parts of these deposits likely were derived from Windmill Creek, as alluvial-fan or debris-flow deposits on the distal part of the Windmill Creek alluvial fan. The central parts of these units were deposited in the linear depression as distal alluvial-fan deposits or fluvial deposits by intermittent flooding events that flowed to the southeast from the site toward the lowest part of the closed depression

(Figure 7). The western parts of Units ❻ through ❿ represent colluviation into the closed depression from the east-facing hillslope bordering the site. As noted above, Unit ❼ is approximately 2,700 to 2,250 years old, and Unit ❾ is approximately 1,350 to 1,200 years old (Table 1). Thus, we speculate that the development of the linear depression as a substantial landform at the Furtado Ranch site probably occurred approximately during the middle and late Holocene.

3.2.3 Trench Geologic Structure

Trenches T-1 and T-2 exposed two prominent fault strands associated with the linear depression at the Furtado Ranch site (Figure 7). The eastern fault strand exhibits evidence of substantial aseismic creep, whereas the western fault strand does not (Figure 8). In addition, the trenches show that the eastern fault strand extends to the ground surface as a series of fractures, whereas the western fault strand does not (Figures 10 and 13). The two fault strands are described briefly below.

Eastern Fault Strand

The eastern fault is exposed in both trenches T-1 and T-2, and coincides with the creeping trace of the Calaveras Fault as defined by the offset alignment array (Figure 7). The eastern fault strand crosses the upper part of the broad, 0.5-m-high scarp along the eastern margin of the linear depression. Based on the exposures in both trenches, the eastern fault strand is subvertical and has an average strike of about N36˚W. In trench T-1, the eastern strand is about 1.5 to 2 m wide (stations 3.5 to 5.5; Figures 10 and 11), and is oriented N37ºW. The eastern fault strand consists of numerous subvertical, slightly anastomosing and interconnecting fractures that offset stratigraphy across the zone. In lower clayey strata (i.e., Unit ❻), the fault is distinguished on the basis of contrasting colors across the fault strand. In many cases, as the strata dried after excavation, vertical cracks developed along individual fault strands. In overlying bedded strata, vertical displacements of contacts demonstrate the presence of multiple fault planes that have small amounts of vertical separation. The number and development of these fractures is far less in the upper, younger strata than the deformation present in lower, older sediments. Overall, bedded strata in trench T-1 are bulged upward across the fault zone, and there is a net west-side-up vertical separation of Unit ❼ across the fault zone (Figure 11).

In trench T-2, the eastern fault strand also is composed of several strands that extend from the floor of the trench to near the ground surface (Figures 13 and 14). These strands have distinct, abrupt displacements of strata, and are associated with numerous subsidiary faults that branch upward. At the base of the trench, the main fault zone is about 1 m wide, but at the top of the trench the width of the fault zone is about 2 m (Figure 14). Overall, bedded strata in trench T-2 are lower within the fault zone, having a negative flower-structure configuration (Sylvester, 1988). This style of deformation is distinct from the positive flower-structure configuration shown in trench T-1, only 25 m to the northwest (Figure 11). There is a minor, net east-side-down vertical separation of beds within Unit ❼ across the eastern fault zone in trench T-2 (Figure 14). This sense of slip in both trenches T-1 and T-2 suggests that the closed tectonic depression may be related primarily to movement on the western fault strand rather than the eastern fault strand.

In both trench exposures of the eastern fault strand, fault deformation extends to the ground surface as a series of thin fractures that branch upward from faults having distinct stratigraphic offset. In trench T-1, several fractures reach the ground surface near station 4 (Figure 11), and these correlate with the location of the creeping trace as seen in the offset alignment array. In trench T-2, two fractures extend to within 20 cm of the ground surface near station 25 (Figure 14), and probably are obscured by modern soil processes. The massive character of Unit ❿ may help mask evidence of fault offset. Alternatively, there may not be sufficient lateral offset along the fault zone to provide evidence of the juxtaposition of distinct strata within the upper, younger units. The subsidiary faults that branch upward change from exhibiting abrupt truncations of strata to warping and subtle brittle faulting of younger, overlying units. On the basis of apparent vertical separation and truncation of strata, we recognize that some of the fault strands show evidence of variable activity over time.

Notably, there is no evidence of deformation related to surface fault rupture along the eastern fault strand. Because this strand clearly is an actively creeping strand (Figure 8), the deformation exposed along this strand in trenches T-1 and T-2 is most likely related to aseismic creep. As summarized by Kelson and Baldwin (2001), several criteria may be used to interpret the possible occurrence of surface fault rupture, including: multiple upward fault terminations at the same stratigraphic horizon, sediment-filled fissures, and scarp-derived colluvium. Based on the trenches across the eastern fault strand at the Furtado Ranch site, none of these features are present. Thus, we interpret that the deformation exposed in trenches T-1 and T-2 across the eastern fault strand is primarily or entirely a result of aseismic creep, and that there is no strong evidence of coseismic surface fault rupture along this fault strand.

Western Fault Strand

The western fault strand is exposed in both trenches T-1 and T-2, and roughly coincides with the western margin of the linear depression (Figure 7). Overall, the western fault strand strikes about N40˚W between trenches T-1 and T-2, although we measured a strike of N44˚W in trench T-1 and a strike of N14˚W in trench T-2 (Figures 12 and 15). This fault strand shows no evidence of offset of the USGS alignment array (Figure 8), and therefore apparently has not experienced creep in at least the past 29 years. In the trench exposures, the western fault strand is a relatively narrow (less than 1.5 m) zone of deformation that offsets surficial deposits and bedrock with an east-side-down sense.

In trench T-1, the fault zone consists of three to four subvertical strands extending from the floor of the trench to the base of Unit ❻ (Figure 12). The central part of the fault zone is a fault gouge that consists of pulverized and tectonically mixed alluvium and Santa Clara Formation (Figure 12). The soil developed on Units ❷ and ❹ shows a net east-side-down vertical separation across the fault zone. In addition, Unit ❹ is strongly folded into a syncline and anticline pair in the area west of the primary fault (stations 24 to 27; Figure 12). However, the overlying Unit ❻ appears to be undeformed across the fault zone, suggesting that it post-dates the episode of deformation. The lower part of Unit ❻ is a coarse colluvial deposit that pinches out directly over the fault zone (Figure 12), and appears to onlap onto the folded soil of Units ❷ and ❹. Notably, large clasts within the lowermost part of Unit ❻ unconformably overlie Units ❷ and ❹, and these clasts are largest and most concentrated directly downhill from the fault zone. The size and concentration of the gravel clasts in basal Unit ❻ decrease abruptly to the west at about station 20 (Figures 10 and 12), at the western margin of the linear depression and where the topographic slope is shallow.

West of the fault strand at station 24 in trench T-1, the fault zone also includes several west-dipping, bedding-parallel strands that juxtapose different lithologies of the Santa Clara Formation (stations 24 to 27, Figure 12). These faults have shallow dips and form the contacts between west-dipping shale, siltstone, and conglomerate beds within the Santa Clara Formation. A strong, 10- to 20-cm-thick fault-parallel shear fabric is developed in the sediments adjacent to these faults, and several clasts within the bedrock conglomerate are parallel to the fault strands. These west-dipping faults are restricted to the Santa Clara Formation, and none of them extends into Unit ❸ or younger deposits. We interpret that these west-dipping fault strands were formed as a result of flexural slip during folding of the Santa Clara Formation.

In trench T-2, the western fault strand occurs as a single vertical feature with a strike of N14ºW (Figure 15). In this trench exposure, the fault is present only within the Santa Clara Formation, although Unit ❻ appears to have been deposited against a near-vertical bedrock face. Fractures extend upward into Unit ❻ gravelly sand, but no conclusive evidence of fault displacement was observed in this unit. Notably, Unit ❻ is considerably coarser above the fault strand, with large angular to subrounded clasts within the colluvium. These clasts appear to have been derived from the Santa Clara Formation directly west of the fault. Overlying stratigraphic units (i.e., Units ❼ and younger) are undeformed, and no fault strand extends upward to the ground surface.

4.0
INTERPRETATION AND DISCUSSION

This investigation provides information on the late Holocene characteristics of the Central Calaveras Fault, including data on the historic creep rate, the location of creeping and non-creeping fault strands, and recent history of fault behavior. Our geologic investigation at the Furtado Ranch site yields information on the location, width and rate of fault creep along the Central Calaveras Fault. In a general sense, the creeping strand of the fault is spatially associated with prominent geomorphic features along the fault, including a linear valley containing a series of closed, linear depressions, a gentle, west-facing fault escarpment, deflected drainages, and offset cultural features. In detail, the creeping fault strand is near the crest of a broad, 0.5-m-high topographic scarp along the eastern margin of a large, linear depression, and is clearly identified by the offset of a USGS alignment array. Data from our survey of the alignment array demonstrate that over the past 29 years, aseismic creep has occurred at a rate of 15 $\pm$ 1 mm/yr. The location of the offset in the alignment array correlates with the location of the eastern fault strand identified in the two trench excavations. The deformation of the alignment array occurs primarily within a zone that is 5 m wide, with perhaps only a few percent of the total deformation occurring outside of this 5-m-wide zone but within 10 m on both sides of the fault. The location of the actively creeping trace is near the crest of a broad topographic scarp that marks the eastern margin of the linear depression, but otherwise is not associated with distinct geomorphic features. The alignment array shows no evidence of offset across the western fault strand, indicating that active creep on this strand has not occurred since installation of the array about 29 years ago. In contrast to the creeping eastern fault strand, the non-creeping western fault strand is generally associated with the western margin of the linear depression and the base of the adjacent escarpment. The trenches at the Furtado Ranch site show an absence of other fault traces in the center of the linear depression. Thus, we interpret that all of the present-day creep along the Central Calaveras Fault at this site is occurring along the eastern fault strand.

Our trenches at the Furtado Ranch site provide insight into the near-surface character of an active fault that creeps at a relatively high rate. The creeping eastern fault strand shows characteristics that classically are associated with strike-slip faults, and are not necessarily restricted to faults that creep. For example, this strand has an upward-widening series of fault planes that deform surficial deposits (Figures 11 and 14), and juxtaposes dissimilar deposits on either side of the fault. As noted above, the eastern strand in trench T-1 is similar to a classic positive-flower structure along strike-slip faults (Sylvester, 1988), and in trench T-2 is similar to a negative-flower structure.

Several criteria may be used to interpret the possible occurrence of surface fault rupture, including: sediment-filled fissures, multiple upward fault terminations at the same chronostratigraphic horizon, and scarp-derived colluvium (Weldon et al., 1996; Kelson and Baldwin, 2001). In addition, certain sites may have geomorphic relations formed by fault movement that are more likely related to coseismic rupture rather than aseismic creep. For example, Kangming et al. (1995) interpret the ratio of coseismic slip to aseismic creep along the active Changma Fault in China through geomorphic analysis of deformed ridges and offset gullies. A promising line of investigation is the assessment of micro-textural shear fabric within active fault gouge zones, being pursued by Cashman et al., (in prep.), in which millimeter-scale characteristics of shearing along known creeping and non-creeping fault strands are being compared. Through the use of these criteria, differentiating between trench-scale features formed by creep and coseismic rupture may be possible in the near future. The absence of such features along the eastern fault strand at Furtado Ranch (Figures 11 and 14) strongly suggests that fault creep dominates the deformation along this strand. There is no evidence that the eastern fault strand has experienced surface rupture during the past several thousand years.

Stratigraphic evidence along the western fault strand, however, allows for an interpretation of possible surface ruptures along this strand. In trench T-1, the western fault strand is associated with deformation of the Santa Clara Formation and overlying alluvial Units ❷ through ❹ (Figure 12). This deformation is fairly intense, involving extensive shearing of all these older units and a 20-cm-thick near-vertical zone of fault gouge within Unit ❸. Unit ❹ is folded and faulted, and shows relative uplift on the western side of the fault zone (Figure 12), which is consistent with a tectonic origin for the closed depression. Of particular note is the sedimentologic character of Unit ❻, which has a locally coarse basal section overlain by a relatively finer grained colluvium. Directly above and to the east of the western fault strand, the basal part of Unit ❻ contains gravel and pebbles in higher concentrations than elsewhere in this unit or in younger deposits within the linear depression. The basal part of this unit pinches out at station 24.5 (Figure 12), and thickens eastward toward the linear depression. The concentration of gravel and pebble clasts decreases eastward as well, suggesting that the source of the gravel clasts may be Unit ❸ in the vicinity of the fault zone. Because the exposure along the southern wall of trench T-1 (Figure 12) shows only a small amount of Unit ❸ available as a local source for basal Unit ❻, we speculate that the source of the gravel in Unit ❻ is higher up the slope or out of the plane of the trench wall. We interpret that the coarse, eastward-fining and eastward-thickening gravel at the base of Unit ❻ to be a scarp-derived colluvium possibly related to surface fault rupture and production of a scarp along the western fault strand.

Similar possible stratigraphic evidence of surface rupture can be interpreted from the trench T-2 exposure of the western fault strand (Figure 15). At station 10 in this trench, blocks of Santa Clara Formation on the eastern side of the single primary fault plane are tectonically mixed and displaced. In addition, the basal part of Unit ❻ at the fault strand is unusually coarse, and contains gravel and pebble clasts that were derived from the west (Figure 15). These large clasts are deposited on/against olive-brown claystone of the Santa Clara Formation directly west of the western fault strand, and do not appear to have been faulted against the bedrock. The buried, near-vertical face developed in the poorly resistant claystone of the Santa Clara Formation along the fault zone may be a buried fault scarp. It is unlikely that fault creep would produce a free face in erodible claystone that would be maintained as near vertical over the time period needed to form the scarp via aseismic creep. We hypothesize that movement on the western fault strand pre-dates deposition of Unit ❻, and that the Unit ❻ gravel clasts were deposited against a scarp face developed in the claystone. We interpret that the presence of the coarse basal colluvium adjacent to the claystone scarp face is suggestive of possible surface fault rupture along the western fault strand (Figure 15).

The stratigraphic relations summarized above may be interpreted as evidence for the occurrence of surface rupture along the western fault strand. Geomorphic evidence in support of this interpretation includes the presence of the linear depression directly east of the non-creeping fault strand, the initiation of alluvial deposition in the depression coincident with deposition of the unit ❻ colluvium, and a sense of vertical separation along the eastern fault strand that is inconsistent with formation of the depression. Although we acknowledge that the colluvium may have been derived via natural hillslope processes unrelated to surface fault rupture, the weight of geologic evidence from the Furtado Ranch site suggests that surface fault rupture occurred along the western fault strand.

Stratigraphic relations at the Furtado Ranch site provide important information on the timing of episodes of deformation along the eastern and western fault strands. Along the eastern fault strand, the (creeping) fault planes extend from the base of the trenches, where they exhibit shearing of Unit ❺, upward through Unit ❾ and nearly to the ground surface (Figures 11 and 14). We attribute all of this deformation to fault creep distributed onto the multiple fault planes, which clearly has occurred up to the present time. Along the western fault strand, however, all of the deformation occurred prior to the deposition of Unit ❻ (Figures 12 and 15), which is more than 2,700 years old. Thus, all of the deformation on the western fault strand occurred prior to about 2,700 yr BP, and the fault strand has not experienced movement (creep or otherwise) since this time.

Therefore, although the western fault strand is not presently creeping, interpretation of stratigraphic relations at the Furtado Ranch site raise the possibility that the fault may have experienced surface fault rupture prior to about 2,700 years ago. The basal part of Unit ❻ is more than about 2,700 years old, and, if related to a scarp-producing surface rupture suggests that this possible rupture occurred prior to 2,700 yr BP. In addition, the absence of deformation of overlying Unit ❼ above the western fault strand indicates that there has been no movement on this fault strand within the past approximately 2,700 years. Thus, we interpret that if surface rupture occurred on the western strand of the Central Calaveras Fault sometime prior to about 2,700 years ago, this fault strand has since been tectonically quiet.

We speculate that the Calaveras Fault may have experienced a change in behavior over the past few thousand years. The absence of scarp-derived colluvium, fissure fills, and multiple upward fault terminations along the eastern fault strand suggest that late Holocene (post-2,700 yr BP) deformation on this strand most likely occurred via aseismic creep. This is supported by presence of east-down vertical separation at the crest of the scarp along the eastern fault strand. Within the past 2,700 years, the eastern fault strand exhibits only evidence of aseismic creep, whereas the western fault strand shows no evidence of movement during this time period. The deformation along the western strand occurred only prior to about 2,700 years. If the deformation on the western fault strand is related to surface rupture, this rupture occurred prior to 2,700 years ago. Thus, we can speculate that strain on the Central Calaveras Fault likely has been accommodated by aseismic creep on the eastern fault strand at least within the past 2,700 years, but prior to that may have been accommodated by coseismic rupture along the western fault strand. Alternatively, it is possible that all of the deformation on both fault strands is related to surficial creep, and that the western fault strand merely has not experienced movement within the past few thousand years.

5.0
CONCLUSIONS

Our geologic investigation at the Furtado Ranch site provides information on the late Holocene characteristics of the Central Calaveras Fault, including data on the location of creeping and non-creeping fault strands, the historic creep rate, and the recent history of fault behavior. In a general sense, the fault is spatially associated with prominent geomorphic features along the fault, and the creeping strand is clearly identified by the offset of a USGS alignment array. Our survey of the alignment array demonstrates that over the past 29 years, creep has occurred at a rate of 15 $\pm$ 1 mm/yr. The location of the offset in the alignment array correlates with the location of the eastern fault strand identified in our two trench excavations. The deformation of the alignment array occurs primarily within a zone that is 5 m wide, with perhaps a few percent of the total deformation occurring outside of this 5-m-wide zone but within 10 m on both sides of the fault. An absence of offset elsewhere along the alignment array shows that the western fault strand, which lies along the western margin of the linear depression, is not creeping.

The trenches at the Furtado Ranch site exposed two primary strands of the Central Calaveras Fault. The eastern fault strand is a complex, upward-widening structure that is a positive flower structure in trench T-1 and a negative flower structure in trench T-2. We observed no characteristics of this fault that are similar to other strike-slip faults known to have had surface rupture, such as fissure fills, scarp-derived colluvium or multiple fault terminations. The displacement on the eastern fault strand extends as a series of faults and fractures from the trench floor to the ground surface, within a zone about 2 to 3 m wide. The western fault strand also is about 2 to 3 m wide, but does not extend to the ground surface. This strand is overlain by unfaulted deposits that are more than 2,700 years old. The absence of creep along this strand, and the lack of displacement of 2,700-year-old deposits, shows that this strand has had a different deformational history compared with the eastern fault strand. The timing of movement on the western strand is different than that on the eastern strand, which continues to deform near-surface sediments via fault creep. Stratigraphic relations near the western fault strand are suggestive of the deposition of a scarp-derived colluvium following an episode of surface deformation prior to about 2,700 years ago. If this colluvium is related to a surface rupture, then such a rupture occurred more than about 2,700 years ago. This may suggest that the behavior of the fault has changed within the late Holocene from one involving surface rupture to one characterized by aseismic creep. Although it is easiest to assume that the Central Calaveras Fault has been dominated by aseismic creep deformation over the past few thousand years, at this point we cannot preclude the occurrence of surface rupture along the fault.

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