FINAL TECHNICAL REPORT

EARTHQUAKE RECORD OF THE GREEN VALLEY FAULT LOPES RANCH, SOLANO COUNTY, CALIFORNIA

Collaborative Research Proposal

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ABSTRACT

Understanding the timing of the most recent surface faulting event, and earlier prehistoric events of the Green Valley fault is important for assessing seismic hazard and calculating probabilities of large earthquakes in the populated San Francisco Bay area. At the Lopes Ranch site, we have documented a geologic record of at least three surface-rupturing earthquakes on the Green Valley fault within the last approximately 2,000 years. Although this fault exhibits aseismic creep of several millimeters per year, making recognition of surface ruptures difficult, we interpret several stratigraphic horizons disrupted by upward-flowering ruptures, steeply tilted alluvial and debris fan deposits, fissure fills, and upward fault termination features that would not have formed singly by creep. The age of the most recent earthquake (MRE), critical to seismic hazard evaluation, is moderately well constrained at A.D.1573-1799 (95% confidence). The age of the poorly constrained penultimate event is A.D.147-1539 (95% confidence). The oldest rupture recognized at the site is an event that occurred between B.C.156–A.D.115 (95% confidence). By developing stratigraphic and event chronology sequences using an OxCal model, the event timing information provide a poorly constrained recurrence interval of approximately 865 years for surface-rupturing events on the Green Valley fault. The MRE and earlier events derived from the Lopes Ranch site can be evaluated and combined with the earthquake chronology developed from Mason Road to establish a more robust seismic characterization of the Green Valley fault.

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1.0 INTRODUCTION

This report presents the findings of a paleoseismic investigation of the Green Valley fault at Lopes Ranch, southwest of Fairfield, in Solano County, California (Figure 1). The primary objective of this research is to develop information on the timing of past surface rupturing earthquakes, including the most-recent earthquake (MRE), on the Green Valley fault. Currently only sparse data on earthquake timing are available for the Green Valley fault (Working Group California Earthquake Probabilities, 2003). Earthquake timing data are essential input parameters for probabilistic earthquake hazard estimates for future earthquake occurrence in the San Francisco Bay region (WGCEP, 2003). This study revisits the former BAPEX trench site of Baldwin and Lienkaemper (1999), where initial findings suggested that the site contains stratigraphic and structural conditions favorable for assessing the late Holocene paleoseismic record of the Green Valley fault.

Understanding the timing of the most recent surface faulting event, and earlier prehistoric events of the Green Valley fault, is important for assessing seismic hazard and calculating probabilities of large earthquakes in the populated San Francisco Bay area. The Green Valley fault is located in the eastern San Francisco Bay area and is part of the Concord-Green Valley fault system (CGVF). The CGVF is composed of at least two major fault segments from south to north: the Concord fault (16-to 24-km long) and the Green Valley fault (29-to 43-km-long). The Green Valley fault is comprised of a 14 ± 4 km long and a 23 ± 3 km long northern and southern section, respectively. The site is located on the southern section of the fault.

There have been few recent studies that have obtained well-constrained earthquake timing data on the Green Valley fault. Sims (1993) excavated seven trenches at the Lopes Ranch BAPEX site and concluded that the fault has experienced Holocene surface rupture. Baldwin and Lienkaemper (1999) revisited the same site, and excavated a new trench (BAPEX trench T-1) and preliminarily correlated stratigraphy with re-interpreted trench logs of Sims (1993). The initial results of the BAPEX study were that three to, possibly as many as, seven paleoearthquakes had occurred on the GVF between 2,720 cal yrs BP and 310 cal yrs BP. The latest trenching at Mason Road located 12 km to the northwest, reveals four earthquakes in the last millennium and yielded a mean recurrence time of 210 ± 160 yr, and a poorly constrained most recent event dated between A.D.1600 ± 130 yrs (Lienkaemper et al., 2008). The earthquake timing information of Baldwin and Lienkaemper (1999) was considered preliminary and based on a single trench; therefore the intent of revisiting the Lopes Ranch BAPEX site is to improve the documentation of the timing of the MRE and paleoearthquakes on the Green Valley fault.

2.0 REGIONAL SETTING

The Green Valley fault is an active, 29- to 43-km-long, dextral strike-slip fault that extends from north of Suisun Bay, near the northern termination of the Concord fault, to Wooden Valley in eastern Napa County (Figures 1 and 2). At Suisun Bay, the Concord fault steps right or bends about 5° to 10° more northerly, where it merges with the Green Valley fault beneath Suisun Bay. Geometrical differences along the Green Valley fault define a 14 ± 4-km-long northern segment and a 22 ± 3-km-long southern segment (WGCEP, 2003). The southern segment of the Green Valley fault extends northwest from Suisun Bay to near the Green Valley Golf Course (Figure 2). The northern Green Valley fault extends from near the Green Valley Golf Course to Wooden Valley (Figure 2). Along its entire length, the Green Valley fault is delineated by prominent tectonic geomorphology (e.g., right-laterally offset drainages, closed depressions, scarps, and tonal and vegetation lineaments) and is expressed as a complex anastomozing fault zone of at least two to four active fault strands. There is an inferred down-to-the-east vertical component across the fault zone as suggested by stratigraphy, topography and trench exposures at Reservoir Lane and Lopes Ranch (Baldwin and Lienkaemper, 1999; Baldwin and Koehler, 2002; Baldwin et al., 2004), as well as numerous consultant trenches excavated along the southern segment of the Green Valley fault. Near the Interstate 80/680 intersection some complexities in the fault zone suggest localized uplift between various fault strands. At Wooden Valley, the tectonic geomorphology abruptly terminates and is obscured by the Sonoma Volcanics and large bedrock landslides. The northward projection of the fault is less certain. Regional geomorphic mapping and aerial reconnaissance (Baldwin and Unruh, 1997) suggest that geologic slip is transferred, in part, to the northwest toward Napa Valley across a series of west-vergent folds and thrust faults that are part of the Atlas Peak-Foss Valley and Snow Flat-Lake Hennessey lineaments (Figure 1). Others interpret geologic slip being transferred to the north-northeast toward Lake Berryessa.

Most of the dextral shear component of distributed Pacific-Sierra Nevada plate motion in the northern San Francisco Bay area is accommodated by three major right-lateral strike-slip faults or fault systems, that include the San Andreas fault, Rodgers Creek-Healdsburg fault system, and Concord-Green Valley-Cordelia fault system (CGVF) (Figure 1). At this latitude, plate motion is partitioned between these three major right-lateral strike-slip fault systems. The San Andreas fault has a slip rate of about 23 ± 2 mm/yr (Niemi and Hall, 1992; Prentice, 1989) and the Hayward-Rodgers Creek fault system has a slip rate of about 8 ± 2 mm/yr (Lienkaemper and Borchardt, 1996; Schwartz and others, 1992). The remaining plate motion is distributed across the CGVF and other faults, although the rates and distribution of slip are poorly understood (Figure 1).

Current estimates of the geologic slip rate of the Green Valley fault are based on geologic data, aseismic creep rates and partly on the interpretation of slip transfer between either the northern Calaveras fault and Concord fault, or the Greenville fault and the Concord fault. It is generally agreed that aseismic creep rates along the CGVF are about 4 mm/yr for both the Concord and Green Valley faults (McFarland et al., 2007; Galehouse, 1998; Galehouse and Lienkaemper, 2003) (Figure 1). Slip rates used in earlier regional strain-rate studies (8 ± 2 mm/yr; Kelson and others, 1992), probabilistic seismic hazard maps (6 ± 3 mm/yr; Petersen et al., 1996) and earthquake probability models (6 ± 2 mm/yr; WGNCEP, 1996; WGCEP, 1999) usually assumed that the slip rate on the CGVF exceeded the aseismic creep rate. Paleoseismic studies suggest a slip rate of 3.4 ± 0.3 mm/yr over the past 6,000 years at Galindo Creek along the Concord fault (Borchardt et al., 1999) and a minimum slip rate of 3.9 to 4.8 mm/yr over the past 310 years on the Green Valley fault at Lopes Ranch (Baldwin and Lienkaemper, 1999). A more recent investigation at Lopes Ranch used several offset buried paleochannels to yield a preliminary slip rate of 2 to 4 mm/yr (Baldwin et al., 2004). These rates are consistent with WGCEP (2003) slip rate estimate of 5 ± 3 mm/yr for the GVF.

2.1 Geology and Geomorphology of the Lopes Ranch Site

The Lopes Ranch trench site is located along the southern part of the southern GVF, approximately 10 kilometers south-southwest of Cordelia, and 0.5 km northwest from the Lopes Ranch Creek slip rate site of Baldwin et al. (2004). In this area, the Green Valley fault juxtaposes Jurassic, Cretaceous and Tertiary sedimentary and metamorphic rocks of the Great Valley Sequence and Franciscan Complex on the west against Pliocene Sonoma volcanics to the east (Fox, 1983; Crane, 1988). Bedrock west of the fault consists of siltstone, sandstone and chert.

At Lopes Ranch, the Green Valley fault is mapped as a narrow well defined fault zone located along the western margin of an unnamed north-flowing creek (herein named as Lopes Ranch Creek) (Figure 3). The primary fault trace is associated with a subtle east-facing scarp, an alignment of moist zones and vegetation contrasts, and deflected drainages. An undocumented eastern secondary trace has been mapped east of Lopes Ranch Creek traversing across a steep west-facing bedrock ridge comprised of Pliocene Sonoma Volcanics. The eastern trace is associated with a prominent photo-lineament and a linear sidehill bench and may be associated with landsliding, bedding, or compositional differences within the Sonoma

Volcanics (Figure 3). Based on geomorphic relations, the primary fault zone strikes about N25°W to N30°W across the site (Baldwin and Lienkaemper, 1999) (Figure 3). South of the Lopes Ranch Creek site, the Green Valley fault projects across a low drainage divide at the base of a steep southeast-facing slope and becomes obscured by numerous large complex landslides as it traverses a set of hills mapped as Tertiary and Cretaceous sedimentary deposits.

The Lopes Ranch site is located on a late Holocene alluvial fan (Qf_3) that dips gently towards the northeast. The fan is bordered to the east by the north flowing Lopes Ranch Creek and to the northwest by an eastward flowing unnamed ephemeral creek (Figure 3). This east-flowing creek is a tributary to the larger north-flowing drainage and is the primary source of the alluvial fan material deposited at the site. Prominent tectonic geomorphology present north and south of the site includes springs, east and west facing scarps, tonal and vegetation lineaments, deflected and linear drainages and topographic saddles. Geomorphic evidence of recent surface faulting at the site consists of a right-laterally offset 300-yr-old gully that was previously investigated by Sims (1991) and Baldwin and Lienkaemper (1999), and a subtle east-facing scarp southeast of the site (Figures 3 and 4).

2.2 Previous Investigations along the Southern Green Valley Fault

Geologic slip rate and earthquake timing data are essential for evaluating the seismic potential of the Green Valley fault and for assessing its contribution to seismic hazards in the San Francisco Bay area. Direct paleoseismic information on slip rate and the timing of large-magnitude earthquakes along the Green Valley fault is limited to several recent preliminary studies at Lopes Ranch (Sims, 1993; Baldwin and Lienkaemper, 1999; Baldwin and Koehler, 2002; Baldwin et al., 2004), Dittmer Ranch (described in Baldwin et al., 2004), and Mason Road (Lienkaemper et al., 2008) located approximately 12 km northwest of Lopes Ranch. A summary of the results of each study is provided below.

Lopes Ranch Site of Sims (1991 and 1993)

As a part of an earlier paleoseismic study at Lopes Ranch, two fault normal and five fault parallel trenches were excavated across the Green Valley fault (Sims 1991) (Figure 4). These trenches revealed warped and faulted bedded, fine to coarse-grained alluvial fan and fluvial deposits with abundant detrital charcoal and an east-trending, right laterally offset late Holocene paleochannel (outline of paleochannels shown as blue dots in Figure 4; Sims, 1991; herein referred to as paleochannel Ch3 in this latest study). Sims (1991) never finished a final technical report documenting the study findings. Re-interpretation of Sims (1991) logs and ^{14}C dates by Baldwin and Lienkaemper (1999) provided a poorly constrained late

Holocene slip rate of 3.9 to 4.8 mm/yr. The Lopes Ranch site was considered a viable paleo-earthquake site based on the presence of bedded stratigraphy, abundant detrital charcoal, faulted late Holocene sedimentary deposits and abundant detrital charcoal.

BAPEX Lopes Ranch Site (Baldwin and Lienkaemper, 1999)

As part of a BAPEX investigation, Baldwin and Lienkaemper (1999) revisited the Lopes Ranch site of Sims (1991) and performed an initial paleoseismic investigation that contributed valuable new data on the late Holocene behavior of the Green Valley fault. Baldwin and Lienkaemper (1999) used stratigraphic and structural relations in trench exposures as indirect evidence of coseismic surface-fault rupture. The relations included: (1) truncated units, (2) upward fault terminations, and (3) tilted and/or offset stratigraphic deposits. On the basis of trench exposures, radiometric analysis of charcoal samples collected from faulted deposits, and re-interpretation of unpublished logs from trenches previously excavated at the site (Sims, 1993), they inferred that multiple surface-rupturing earthquakes have occurred on the Green Valley fault in the past 2,700 years and that the most recent earthquake (MRE) may have occurred between 310 and 220 cal yr BP (Figure 5; Baldwin and Lienkaemper, 1999). Additionally, the buried paleochannel deposit of Sims (1991) was estimated to be right-laterally offset 1.2 to 1.5 m across the fault, from which the authors inferred a poorly constrained minimum slip rate of 3.9 to 4.8 mm/yr over a 310-yr time period. Due to the short time period considered, the timing of the most recent event and next future event significantly influences this rate. We note that Baldwin and Lienkaemper (1999) were unable to conclude unequivocally that the structural and stratigraphic relations observed in their trench and re-interpreted from previous trenches (Sims, 1993) were a result of coseismic surface-fault rupture and not a product of aseismic creep.

Lopes Ranch Creek Site (Baldwin et al., 2004)

At the Lopes Ranch Creek site, an ephemeral creek preserves the cumulative dextral separation of an abandoned north-trending paleochannel located east of the main Green Valley fault (Baldwin et al., 2004). The scope of work included generating a detailed topographic map of the Lopes Ranch Creek site and excavation of four fault-normal trenches. Trenches T-1, T-2, and T-4 were excavated across a linear swale (inferred paleo-stream valley) southeast of the mouth of Lopes Ranch Creek, and trench T-3 was excavated across the fault on a broad alluvial fan northwest of the creek (Figure 4). The initial slip rate yielded by the Lopes Ranch Creek site is close to the historical slip and creep rates for the Green Valley fault. Preliminary estimates of cumulative right-lateral displacement of a prominent paleochannel deposit range from 31 to 58 meters. Radiocarbon analyses of charcoal collected from a burn horizon directly above the offset channels provide a minimum age for the offset channel deposits of 14,080 to 15,380 cal yr BP. Based on the estimated cumulative displacement and minimum age of the offset paleochannel deposits, a preliminary long-term slip rate for the southern Green Valley fault is 2 to 4 mm/yr.

Dittmer Ranch Pre-1862 Rock Wall

At the Dittmer Ranch, located directly north of I-80, a pre-1862 rock wall interests the entire Green Valley fault zone (Figure 2). This information was presented previously in Baldwin et al. (2004). In this area, the fault is mapped as consisting of three to four fault traces (Bryant, 1982; Bryant, 1992). A survey of the pre-1862 rock walls was performed by Larry Anderson of the U.S. Bureau of Reclamation in 2004 (personal communication) to assess the width of the creeping fault zone and obtain a historical creep rate of the fault as part of a study for Terminal Reservoir. Preliminary survey results provide direct evidence for aseismic creep across one strand (central), and possibly a second strand (western) of the Green Valley fault (Larry Anderson, 2004, personal communication). Across the central fault strand, the survey indicates that the rock wall is right-laterally offset between 0.2 and 0.5 m, with possible reverse drag. In addition, it is permissible to interpret as much as 0.5 m of dextral displacement of the rock wall across the western strand, although this is less definitive than measurements of slip on the central strand. Uncertainty associated with the western strand stems from the wall's location within a deep swale where it appears the wall is undergoing downslope creep consistent with an apparent right-lateral displacement. Between the western and central fault strands, the preliminary survey results suggest a poorly constrained creep rate ranging from 1.4 to 7 mm/yr over a 142-year interval. Assuming that only the central fault strand is creeping, the creep rate may be refined to 1.4 to 3.5 mm/yr.

Mason Road Site (Lienkaemper et al., 2008)

A paleoseismic investigation at the Mason Road trench site located about 12 km northwest of Lopes Ranch provides geologic evidence of at least four surface-rupturing earthquakes in the past millennium. The MRE is poorly constrained between A.D.1623±112 (1SD). Based on an OxCal model that represents the earthquake sequence and radiocarbon data, the mean recurrence time (RI) is 200 ± 148 yr (1 SD).

3.0 RESULTS

Our objectives at the former Lopes Ranch BAPEX site were to characterize the late Holocene event stratigraphy interpreted previously by Baldwin and Lienkaemper (1999) and to refine the timing of Holocene paleoearthquakes on the southern Green Valley fault. In this latest study at the former Lopes Ranch site of Sims (1991; 1993) and Baldwin and Lienkaemper (1999), we present evidence for several late Holocene paleoearthquakes and their timing based on the re-excavation of portions of BAPEX trench T-1 (Baldwin and Lienkaemper, 1999), and Sims (1991) trenches GV-1 to GV-3, as well as the excavation of one new fault normal trench T-2 (Figure 4). In particular, trench GV-1 was completely re-excavated and logged to evaluate the near-surface structural relations associated with the inferred MRE and to correlate stratigraphy between new and former trenches. A short-test pit (TP-1) was excavated south of BAPEX trench T-1 to evaluate the lateral continuity of an offset and buried north-northwest-trending paleochannel. The paleochannel is interpreted to be an offset and abandoned thalweg of the unnamed creek located north of the site (shown as black circles in Figure 4). The western end of the BAPEX trench T-1 was connected with the southeastern end of trench GV-2 also to correlate stratigraphy between the previous trenches, and to provide a stratigraphic framework for interpreting deformation in re-excavated trench GV-1 (2007). Lastly, trench GV-1 was connected with previous trench GV-3 to permit stratigraphic correlations with trench T-2 (see black colored trenches of Figure 4 showing new excavation locations). The near-surface stratigraphy and structural features encountered in all the trenches were re-examined, photo-logged and surveyed. The photologs of trenches GV-1 and T-2 are presented as Figures (6a and 6b, 7a and 7b). Photo-logs of the other trenches were not reproduced for this report. Additional charcoal samples were collected and radiometrically dated to provide further age constraint on the age of the deposits and interpreted events. The radiocarbon analyses were performed by Beta Analytic, in Miami, by accelerator mass spectrometry. The results are presented in Table 1.

3.1 Near Surface Stratigraphy

The site geologic conditions exposed in the trenches at the Lopes Ranch site are consistent with episodic deposition of coarse-grained debris flow deposits overlain by fine-grained alluvial fan material as noted by multiple buried incipient soil horizons. These depositional events are interrupted by relatively stable periods of soil development followed by paleochannel incision and debris flow deposition. The deposits are further disrupted by faulting and warping within a 2-to 4-m-wide fault zone comprised of two to three fault strands (described herein as the western, central and eastern fault strands). Radiometrically dated charcoal samples provide constraints on depositional ages and interpreted paleoearthquakes.

The trenches at the Lopes Ranch study site (Figure 4) exposed two distinct sequences of latest Holocene deposits. Trench locations are shown in Figure 4. West of the fault zone, the stratigraphy consists of bedded alluvial fan and debris flow deposits that are slightly to heavily over-printed by pedogenic processes (i.e. presence of clay films and buried Bt horizons). East of the fault zone, the stratigraphy consists primarily of well-developed soil horizons developed within fluvial and fine-grained alluvial fan deposits that unconformably overlie Pliocene Sonoma volcanics (Sims, 1993). A thin veneer of fill and spoil material from previous trenching investigations mantles all of these deposits. Age estimates of the surficial deposits are based on cross-cutting stratigraphic relationships, and a total of 25 radiocarbon analyses of charcoal fragments collected from the surficial deposits exposed in the recent trenches (this study) and previous BAPEX trench T-1 (Baldwin and Lienkaemper, 1998). Overall, the recent radiocarbon analyses provide a suite of stratigraphically consistent age-estimates for the alluvial, fluvial and debris flow deposits (Table 1). A generalized stratigraphic column of the deposits is presented in Figure 8.

3.1.1 Deposits West of Green Valley Fault

The sequence of late Holocene alluvial fan and debris flow deposits exposed in trenches T-2, GV-1 to GV-3 and BAPEX T-1 include: (a) six distinct fine grained fan deposits, some with paleosol development, and (b) six distinct gravelly debris flow layers. The debris flow deposits are both interfingering and occasionally laterally discontinuous in a north-south direction, and may not be present in all trenches. The alluvial fan deposits are designated from oldest to youngest as units Af_1 to Af_{6a}, respectively. Similarly, the debris flow deposits are designated from oldest (Df_1) to youngest (Df_6). The oldest exposed strata have the numerical suffix 1 and the youngest have the numerical suffix 6 (i.e. Af_1 to Af_6).

In general, the alluvial fan deposits consist of massive, well sorted, brown silty to clayey fine-grained sand with a trace to less than 20% gravel; in comparison, the debris flow deposits consist of poorly sorted, yellowish-brown to orange-brown sandy gravel to gravely sand. The gravel lithology typically consists of fine- to medium-grained sandstone. The estimated ages of the alluvial fan/debris flow deposits range from about 2720 (Af_1) to about 300 cal yrs BP (Af_{6a}). A significant hiatus in deposition, likely related to erosion, followed by continuous fine-grained deposition of alluvial fan material exists between units Af_6 and Df_5. See Table 1 for a summary of the estimated ages of the alluvial fan and debris flow deposits exposed at the site. The estimated age of the deposit is based on the youngest radiocarbon age derived from the samples collected from each unit. We assume the anomalous older ages represent recycled charcoal. The generalized site stratigraphy is presented from oldest to youngest.

Alluvial fan unit Af_1 is a very dark, mottled grayish brown, organic, silty clay with 10-40% subangular yellowish-brown arkosic gravel clasts and exhibits a weakly formed blocky structure. The deposit is exposed in both trenches GV-1 and T-2, as well as previous trenches, and forms a distinct basal marker horizon that can be tracked across much of the site. Charcoal samples collected from this layer indicate that this unit was deposited between 2,720 and 2,340 cal yr BP (Table 1). Unit Af_1 is conformably overlain by a poorly sorted dark brown to dark yellowish brown, matrix-supported gravelly debris flow deposit (unit Df_1). This deposit has as much as 60 to 80% gravel near its base and is locally clast supported. In trench GV-1, unit Df_1 is laterally continuous from station ~0+8m to at least the central fault strand at 0+3.5m, where it is truncated. In trench T-2, unit Df_1 appears to interfinger and merge with unit Af_2 east of the central fault strand. Ages of charcoal samples collected from this unit range from 2840 to 1900 cal yr BP (Table 1). Based on the youngest age derived from the charcoal samples collected from this deposit, we estimate an age of 2120 to 1900 cal yrs BP for units Af_2 and Df_1. Units Af_2 and Df_2 also are close in age with paleochannel located east of the fault zone (see unit descriptions for east of the fault).

The next youngest deposits include alluvial fan and debris flow units Af_3/Df_3 and Af_4/Df_4 that conformably overlie unit Df_2 and consist of massive silty, sandy clay with 10-30% orange sandstone gravel clasts. These deposits comprise a massive homogenous deposit 0.6 to 0.8m thick with a prismatic structure. They locally show evidence of fining upwards sequences and at least two paleosol horizons in trench GV-1. The presence of these horizons suggests that deposition of these units was separated by hiatuses lasting long enough to allow formation of weak soils. The age of unit Af_3 in trench T-1 is estimated to range from 2290 to 1820 cal yr BP. Charcoal collected from unit Af_4 in trenches T-1 and GV-1 indicate an age as young as 1810 to 1540 cal yr BP for this overlying fan deposit.

Debris flow deposit Df_3 separates Af_3 and Af_4 near the west end of trench GV-1 and in trenches GV-2 and T-1. Deposit Df_3 is a laterally discontinuous gravely debris flow deposit, and there are no charcoal samples from this unit for estimating an age.

Several distinct debris flow deposits (Df_4, Df_{4a}, Df_5 and Df_6) overlie unit Af_4. These deposits consist of poorly sorted subangular matrix to clast supported sandstone and siltstone gravels that are the most distinct near station 0+10 m. The gravel content decreases towards the east and these units cannot be reliably traced past the easternmost fault strands. These debris flow packages are distinguished based on upward fining sequences and the presence of discontinuous prismatic sandy silt lenses. Charcoal collected from unit Df4 in trench GV-1S has an estimated age of 1820 to 1600 cal yr BP which overlaps with the underlying alluvial fan unit Af_4.

The shallowest units exposed are alluvial fan deposits with modern soil forming processes heavily overprinting them. Unit Af_6 is a sandy, clayey silt with a trace of gravel and contains moderately developed prismatic ped structures, clay films, roots and root casts. We interpret this unit to be overprinted with the modern Bt soil horizon. The Bt horizon grades upward into unit Af_{6a}, which exhibits progressively less soil horizon formation-having a moderately well developed prismatic to blocky structure and very thin clay films. Unit Af_{6a}, interpreted as the modern A horizon, is a sandy silt with poorly developed blocky to massive structure, numerous roots and root casts and no clay films. The range of ages for units Af_{6b} and Af_{6a} is 430 to 0 cal yr BP (Table 1). There is very little bedding in Af_6 deposits with the exception of a thinly bedded sand inset into this deposit in trench T-2 that is possibly associated with the 300-yr-old gulley (Ch3; formerly Ch4 of Baldwin and Lienkaemper, 1999).

3.1.2 Deposits East of Green Valley fault

Sandy fluvial deposits, including a north trending infilled paleochannel (Ch2), well developed soil horizons and alluvial fan units Af_6, Af_{6b} and Af_{6a} are present east of the Green Valley fault in trenches GV-1, GV-3 and T-2. The lowest units exposed east of the Green Valley fault are not directly correlative with units west of the fault zone and thus are designated as units A and B (this study; Figures 6b and 7b) and Fluv 1 (in Baldwin and Lienkaemper, 1999). Units A and B consist of a clayey sandy silt with traces of siltstone and sandstone clasts (unit A) overlain by a buried paleosol (Unit B) having well-developed prismatic structure, clay films, and few roots. Unit B is unconformity overlain by paleochannel Ch2.

Paleochannel Ch2 contains poorly sorted sandstone and siltstone lag gravels at its base, and faint bedding and laminae within a clayey sand upsection. The unit fines upward to a massive olive brown sandy clayey silt with gravel. The faint bedding laminations are observed in the upper part of these deposits, and the presence of a weak blocky structure suggests overprinting by soil forming processes. Based on orientation and the inconspicuous alignment with the unnamed drainage to the north, paleochannel Ch2 is interpreted as being displaced southeast along the fault zone, or alternatively is an abandoned paleochannel of the north flowing Lopes Ranch Creek. Two charcoal samples collected from unit Ch2 in trenches GV-1 and T-2 yield an age of 2140 to 1940 cal yr BP. This age overlaps with the estimated ages of units Df_1 and Af_3. Paleochannel Ch2 appears to be overlain by deposits Af_4 and Af_3 across much of the site. Units Af_6, Af_{6b} and Af_{6a} overlie the entire sequence. The test pit TP-1 did not encounter the paleochannel Ch2 deposit suggesting that this unit terminates south of BAPEX T-1 (Figure 4).

3.2 Near Surface Structural Relationships

The location of the southern Green Valley fault zone is constrained at the study site on the basis of multiple exposures within several fault normal trenches (GV-1, T-2, and BAPEX T-1) and prominent tectonic geomorphology. These trenches expose a complex 2- to 4-m-wide fault zone aligned with prominent vegetation lineaments, seeps, and east-facing escarpments southeast and northwest of the site. The exposures reveal several fault strands with strikes ranging between N2°E to N14°W and dips ranging from near vertical to 60° to 80° to the northeast. Creep-related features are most prevalent along the western and central fault strands.

The faults strands broaden and flower up section as they splay into multiple fractures and shears (Figures 6a and 7a). This is most apparent in the fault strands mapped between 0+3m to 0+4m in trench GV-1 and between 0+5.5m and 0+6m in trench GV-1. Previous studies (Baldwin and Lienkaemper, 1999) found that slickensides preserved along clay seams developed in units Fluv 1 and Df_1 in BAPEX T-1 plunge about 15° northwest; and 27° southeast in trench GV-1 where measured in unit Af_1. The well-defined slickensides show that slip during at least one or more earthquakes (or from aseismic surface creep) was principally lateral with a lesser vertical component. This is supported by exposures in trenches T-2 and GV-1 showing 0.1m to 0.3m of apparent east-side down vertical separation of alluvial fan and debris flow deposits across the fault zone (Figures 6b and 7b). Variable fault orientations between trenches GV-1 and T-2 also demonstrate the complexity of the fault zone and suggest a right extensional step in the fault zone, consistent with the east-side down displacement observed.

Fault-normal exposures in trenches T-2 and GV-1 expose three main fault strands (western, central and eastern), all of which are discussed briefly below. Each fault strand is composed of multiple, closely spaced subparallel to upward splaying subsidiary strands.

- The western fault strand strikes between N7°W to N9°W and dips 61°NE to subvertical. Across the fault strand alluvial and debris flow deposits Af_4/Af_3, Df_2, Af_1 and Df_1 show between 0.1 to 0.15 m of apparent east-side down vertical separation. The fault strand extends to within about 1.75 m of the ground surface, where the upward extent of the faulting becomes obscured in unit Af_4/Af_3 by pedogenic fractures and truncation against the basal contact of a buried soil horizon. The western fault strand appears to die up upsection as discontinuous fractures or merges with the central fault strand at or near trench T-2.

- The central fault strand strikes N10°W to N14°W, and dips 78°NE to sub-vertical. The fault splays upward into several sub-vertical fractures that show minor vertical offset (less than 0.1m) of alluvial fan and debris flow deposits within trench GV-1. In trench T-2, apparent east-side down vertical separation from 0.17 m to 0.23 m of alluvial fan and debris flow deposits is present. The central fault strand comes within about 0.5 to 0.75 meters of the ground surface and offsets unit Af_{6b}.

- The eastern fault strand truncates units Af_4/Af_3, Df_4 and Af_6. The fault strand is oriented between N2°W to N8°W and dips 78°NE to sub-vertical. The eastern fault strand extends to within 0.7 m of the ground surface where the upward terminations become obscured by pedogenic fractures within the modern Bt horizon of unit Af_6. This fault strand appears to have had significant displacement relative to the other fault strands based on the lateral juxtaposition of different units across the fault at depth.

In trenches GV-1 and T-2, the highest upward-terminating fault traces extend to at least the base of the modern Bt horizon (Af_{6b}). In both trenches, apparent down-to-the-east vertical offset is observed at the base of the Bt horizon across the central fault strand. Faulting likely extends further up section based on prominent fractures within the clayey Bt horizon; however, the presence of well-developed prismatic pedogenic fractures at about 0.70 m below the ground surface, as well as the absence of well-defined bedded stratigraphy (minor exception in trench T-2) in these upper deposits make the determination of upward fault terminations problematic. Many of these fractures extend close to the ground surface, and thus may be associated with either aseismic fault creep or shrink/swell soil processes.

3.3 Radiocarbon Age Analyses

Radiometric ^{14}C dates obtained during a previous trench investigation (Baldwin and Lienkaemper, 1999) were augmented with additional dates obtained from charcoal samples collected during this study to provide timing constraints for interpreted events. During Baldwin and Lienkaemper's (1999) investigation, a total of 17 detrital charcoal samples were collected from selected units in trench T-1, and submitted for radiocarbon analysis at Lawrence Livermore National Laboratory. The radiometric dates were dendrochronologically corrected to calibrated years (cal yrs BP) according to the procedure of Stuiver and Reimer (1993). From the present study, eight additional samples collected from trenches T-2 and GV-1 were sent to Beta Analytic in Miami, Florida, for radiometric dating by accelerator mass spectrometry. Results for all of these samples are presented in Table 1. Note that samples with designations LR98 denote the Baldwin and Lienkaemper (1999) study; and samples with designations LR07 denote this recent study.

We also use the OxCal calibration and analysis program (Ramsey, 2007) to help interpret the ages of surficial deposits and the timing of earthquake ruptures at the Lopes Ranch site. This program uses stratigraphic relations among deposits and Bayesian statistics applied to deposit ages to develop probability density functions for ages of inter-deposit “events”. In our analysis, these “events” are surface ruptures that resulted in specific deposits at the site. From the suite of analyzed samples, we selected ten radiocarbon dates that are assumed to best represent the ages of deposits. The laboratory ages of these deposits were calibrated to the dendrochronologic record by the OxCal program (v 4.0.3; Ramsey, 2007), and then used to construct an appropriate analytical model that consists of eight separate depositional phases encompassing three surface-rupture “events.” The dates between and within each phase were sequenced in the model based on stratigraphic position (Table 2), and analysis of dates from the phases bracketing each event provides estimates of the timing of the surface ruptures. The results of this OxCal model are presented in Table 2 and in Figure 9, and are discussed in section 4.0.

Table 1 Summary of Radiocarbon Ages from Lopes Ranch Site

Sample No.	Trench	Lab No.	Conventional ^{14}C Age (yr BP ± 1σ)	^{13}C / ^{12}C ‰	Calibrated Age (cal. yr BP) (95% probability)
Af6a					
LR07-16	GV1S	Beta 239532	1280 ± 40	-25.4	1290 to 1140
LR98-19	T1N	LLNL 51009	260± 40	-25.0	430 to 0
LR98-25	T1N	LLNL 51311	90 ± 70	-25.0	290 to 0
LR98-37	T1S	LLNL 51756	210± 40	-25.0	310 to 0
Af6b					
LR98-34	T1N	LLNL 51755	260 ± 40	-25.0	430 to 0
Af6					
LR07-07	GV1S	Beta 239528	2480 ± 50	-25.4	2740 to 2350
Df4					
LR07-05	GV1S	Beta 240564	1780 ± 40	-25.7	1820 to 1600
LR07-21	GV1S	Beta 239533	2470 ± 40	-23.8	2730 to 2360
Af4					
LR07-09	GV1S	Beta 239529	3120 ± 40	-25.2	3410 to 3260
LR98-02	T1S	LLNL 51010	1890 ± 30	-25.0	1920 to 1720
LR98-30	T1S	LLNL 51753	1760 ± 40	-25.0	1810 to 1540
LR98-32	T1S	LLNL 57154	1780 ± 50	-25.0	1820 to 1540
LR98-40	T1N	LLNL 51757	1980 ± 60	-25.0	2110 to 1730
LR98-42	T1S	LLNL 51758	1990 ± 40	-25.0	2000 to 1824
Af3					
LR98-20	T1S	LLNL 51011	2180 ± 60	-25.0	2340 to 1950
LR98-26	T1S	LLNL 51313	2040 ± 70	-25.0	2290 to 1820
Df2					
LR98-21	T1S	LLNL 51013	2270 ± 50	-25.0	2350 to 2120
LR98-28	T1S	LLNL 51312	2470 ± 40	-25.0	2720 to 2350
Ch2					
LR07-28	GV1S	Beta 239530	2070 ± 40	-26.0	2300 to 2240 and 2170 to 2000
LR07-12	T2N	Beta 239535	2070 ± 40	-22.8	2140 to 1940
Df1 / Ch1					
LR07-08	GV1S	Beta 240565	3540 ± 60	-24.7	3980 to 3690
LR98-03	T1S	LLNL 51015	2060 ± 40	-25.0	2120 to 1900
LR98-05	T1S	LLNL 51012	2610 ± 60	-25.0	2840 to 2150
LR98-22	T1S	LLNL 51014	2320 ± 60	-25.0	2640 to 2150
Af1					
LR98-23	T1S	LLNL 51016	2430 ± 60	-25.0	2720 to 2340

Notes:
(1) LR07 represents detrital charcoal from the 2007 trenches (this study); whereas LR98 refers to a sample collected from a 1998 BAPEX study of Baldwin and Lienkaemper (1998).
(2) Beta: Denotes samples analyzed by Beta Analytic, Inc.
(3) LBNL: Denotes samples analyzed by Lawrence Livermore National Laboratory.
(4) See Baldwin and Lienkaemper (1999) for location of the LR98 sample locations.

Table 2. Summary of OxCal modeled Sample and Event Ages

Sample / Event	Modeled Range (1σ) (BC/AD)		Modeled Range (2σ) (BC/AD)		Mean (σ)	Standard Deviation (σ)	Median
	From	To	From	To			
LR98-37	1750	1803	1649	1809	1762	42	1778
LR98-25	1719	1810	1680	1820	1758	39	1767
LR98-19	1651	1800	1631	1806	1753	58	1784
Event 1	**1630**	**1796**	**1573**	**1799**	**1707**	**69**	**1728**
LR98-34	1522	1666	1485	1679	1590	60	1577
Event 2	**245**	**535**	**147**	**1539**	**503**	**283**	**405**
LR98-32	220	331	160	380	269	56	270
LR98-30	235	331	171	385	280	51	283
LR07-05	134	247	125	303	196	47	191
LR98-26	-33	120	-105	208	32	62	32
Event 3	**-96**	**39**	**-156**	**115**	**95.4**	**68**	**-28**
LR98-03	-160	-46	-181	1	-97	49	-96
LR07-12	-346	-116	-357	-63	-201	78	-182
LR98-23	-528	-398	-744	-386	-492	94	-469

See Baldwin and Lienkaemper (1999) for location of the LR98 sample locations.

4.0 DISCUSSION

The latest stratigraphic and structural relationships exposed at the Lopes Ranch site provide evidence for a minimum of three paleoearthquakes. Of the three interpreted earthquakes, the most recent event (MRE) is the best constrained. To constrain the ages of the three events, we relied upon ten radiocarbon ages to construct the site-specific chronologic OxCal (version 4.0.3) model by which to develop mean and median ages, and probability density functions for the events, respectively. Output from the site-specific OxCal model is presented in Figure 9 and Table 2. Note that the earlier study by Baldwin and Lienkaemper (1999) used a single trench to hypothesize as many as seven poorly constrained surface rupture events.

4.1 Depositional History

The depositional history of the Lopes Ranch site has involved deposition via alluvial fan, debris flow and fluvial processes (Figure 8). Stratigraphy west of the Green Valley fault consists of alternating sequences of alluvial fan and debris flow deposits with sediment derived from the west and transported to the site by the unnamed east-flowing ephemeral creek directly north of the site. Evidence that all of these deposits are derived from the west is that the gravel clasts exposed within the trenches consist of orange sandstone and dark orange to brown siltstone derived from the Jurassic Great Valley sequence, as well as bedding dips that indicate an easterly-directed deposition. Stratigraphy east of the Green Valley fault consists of fluvial deposits derived from the north-flowing creek east of the site and an offset paleochannel of the unnamed creek north of the site, all of which are capped by alluvial fan deposits sourced from the west. The deposits include fining upward fluvial sequences, the presence of an infilled and buried north-trending paleochannel, fine-grained alluvial or fluvial deposits at depth and a prominent buried soil horizon. Gravels within these fluvial sequences include weathered sandstone, siltstone, and volcanic clasts.

4.2 Paleoearthquake Interpretation and Timing

Evidence for the oldest event (Event 3) interpreted at the site is defined by the truncation and offset of units Af_1, Df_1, Af_2, Df_2 and Af_4/Af_3 by the westernmost fault strand of the Green Valley fault, as well as the upward termination of this fault strand. In particular, a buried soil horizon developed in the upper to middle part of units Af_4/Af_3 is unfaulted in trenches GV-1 and T-2, and denotes the upward limit of faulting along this fault strand. Reexamination of the trench logs from BAPEX trench T-1 of Baldwin and Lienkaemper (1999) reveals a similar relationship and shows that it is permissible to interpret an upward fault termination within unit Af_3 (Figure 5). The latest logging of trench GV-1 provides the most compelling evidence for the presence of this event based on the several paleosols mapped within units Af_4/Af_3 (shown as dashed and dotted lines in Figure 6a and 6b). Note that the age of Event 3 is constrained by the OxCal modeled ages of units Af_1, Df_1, Af_4/Af_3 and Df_4, and is based entirely on the recent subsurface investigation. On the basis of the OxCal model this earthquake occurred between the time interval of B.C.156 to A.D.115 (95% probability) (Figure 9, Table 2).

Evidence for the penultimate event (Event 2) includes the juxtaposition of units Df_4 and Df_5 against Af_6 across the central fault strand in trench GV-1, and the upward termination of the eastern fault strand at or near the basal contact with unit Af_{6b}. This faulting is best expressed across the eastern strand on the southern wall of trench GV-1 and is inferred in trench T-2 (Figures 6a and 7a). The base of unit Af_{6b} does not appear to be displaced in trench T-2 across the eastern fault strand, however an inconspicuous fracture in unit Af_6 aligns upsection with this fault strand at depth. In addition, trench T-2 does not have a well defined demarcation between units Af_6 and Af_{6b} allowing for some uncertainty on the presence of this event. The penultimate event also is expressed in trench GV-1 and T-2 along the central fault strand, where faulting terminates upward against the base of unit Af_6 (Figures 6a and 7a). The age of Event 2 is constrained by the ages of Af_4/Af_3, Df_4, Df_5, Df_6 (lower stratigraphic boundary) and Af_{6b} (upper stratigraphic boundary). Given these stratigraphic, structural and age relations, the OxCal model interprets the penultimate event occurred between A.D.147-1539 (95% probability) (Figure 9, Table 2). Given that this event evidence appears at a surface that apparently went for many centuries without deposition, this evidence may actually represent surface ruptures from more than one earthquake.

The most recent event (Event 1) interpreted on the Green Valley fault is based on evidence of unit truncation and offset and tilting of deposits adjacent to the central fault strand observed in trenches GV-1, T-2 and on the log of BAPEX T-1 (Baldwin and Lienkaemper, 1999). In addition, we interpret the presence of a fissure fill across the central fault strand in trench GV-1. Trench GV-1 exposed two subparallel fault strands penetrating and offsetting all deposits with the exception of unit Af6a and the modern spoils. Units Af_4/Af_3, Df_4 and Df_5 are truncated and tilted between these two primary fault strands and show apparent down-to-the east vertical offset of 0.1 to 0.15m. Units Df_4 and Df_5 are juxtaposed against deposit Af_6 to the east and Df_4 and Af_4 to the west of the fault strand, respectively. In trench T-2, the central fault is exposed as a single primary strand with a minor splay, cutting and offsetting all units up to and including Af_{6b}. The central fault strand terminates upward against the basal contact of unit Af_{6a}. Deposits Df_2 and Af_4/Af_3 show an apparent vertical down-to-the-east offset of 0.2m, whereas unit Df_4 located higher upsection shows up to 0.25m of apparent vertical down-to-the-east offset across the fault strand. Units Af_4/Af_3 and Df_4 are tilted towards the east between the main strand and the minor splay in trench T-2. A fine-grained silty sand developed within unit Af_6/Af_{6b} shows a minor amount of east-side-down displacement across the central strand within 0.75m of the ground surface. The log of BAPEX T-1 from Baldwin and Lienkaemper (1999) shows the central fault strand cutting and truncating all units up to and including Af_6 and possibly continuing into Af_{6b}. Based on these observations, the age of Event 1 can be constrained by the ages of Af_{6b} (lower boundary) and Af_{6a} (upper boundary). We interpret the most recent event on the Green Valley fault to have occurred between A.D. 1573-1799 (Figure 9, Table 2). The upper limit of the event is constrained to the arrival of the missions and the written documentation of earthquakes beginning around this time.

5.0 CONCLUSIONS

We excavated three fault normal trenches across the Green Valley fault and two fault parallel trenches, thus connecting all excavations. All the trenches were photo-logged and stratigraphy correlated between the trenches. The fault normal trenches exposed a 2-to 4-m-wide fault zone containing three primary strands. These fault strands strike between N2°E to N14°W and have dips ranging from near-vertical to 60° to 80° degrees to the northeast. Stratigraphy exposed in the excavations included alternating sequences of alluvial fan and debris flow deposits west of the Green Valley fault and fluvial deposits capped with the youngest alluvial fan deposits east of the fault zone. Sediments comprising the deposits appear to be primarily derived from weathered Great Valley sequence sandstones and siltstones located west of the site.

Paleoseismic indicators including: (1) truncated and offset stratigraphic units, (2) upward terminations of fault strands, (3) tilted stratigraphic units, and (4) a fissure fill exposed within the fault normal trenches provide evidence for a minimum of three surface-rupturing earthquakes in the latest Holocene. Twenty-five charcoal samples were collected from stratigraphic units and dated using ^{14}C accelerator mass spectrometry. Ten of these dates were used to create an OxCal (Ramsey, 2007) model that constrained the ages of three interpreted paleoearthquakes at Lopes Ranch that from oldest to youngest include: (a) pre-penultimate that occurred between B.C.156-A.D.115 (2SD), (b) penultimate event estimated to have occurred between A.D.147-1539 (2SD), and (c) the most recent event estimated between A.D.1573-1799 (2SD). The age of the MRE is consistent with historical records beginning about 1799 that report no earthquakes on this fault since that time. Using the average ages of the events yields a recurrence interval of ~865 yrs. However, this recurrence interval is based on only 2 inter-event periods and likely is not representative of the long term recurrence interval of the Green Valley fault. Previously, no geologic data has existed for the recurrence interval for the Green Valley fault, although, based on a generic geophysical model of the fault, the Working Group on California Earthquake Probabilities (2003) estimated a shorter recurrence interval of 210 yr (112-665 yr, 95-percentile). The mean recurrence time from Mason Road is 200 ± 148 yr (1SD) and is poorly constrained. Data from this site can be combined with event chronology information from the Mason Road site for a more complete late Holocene record of the Green Valley fault.

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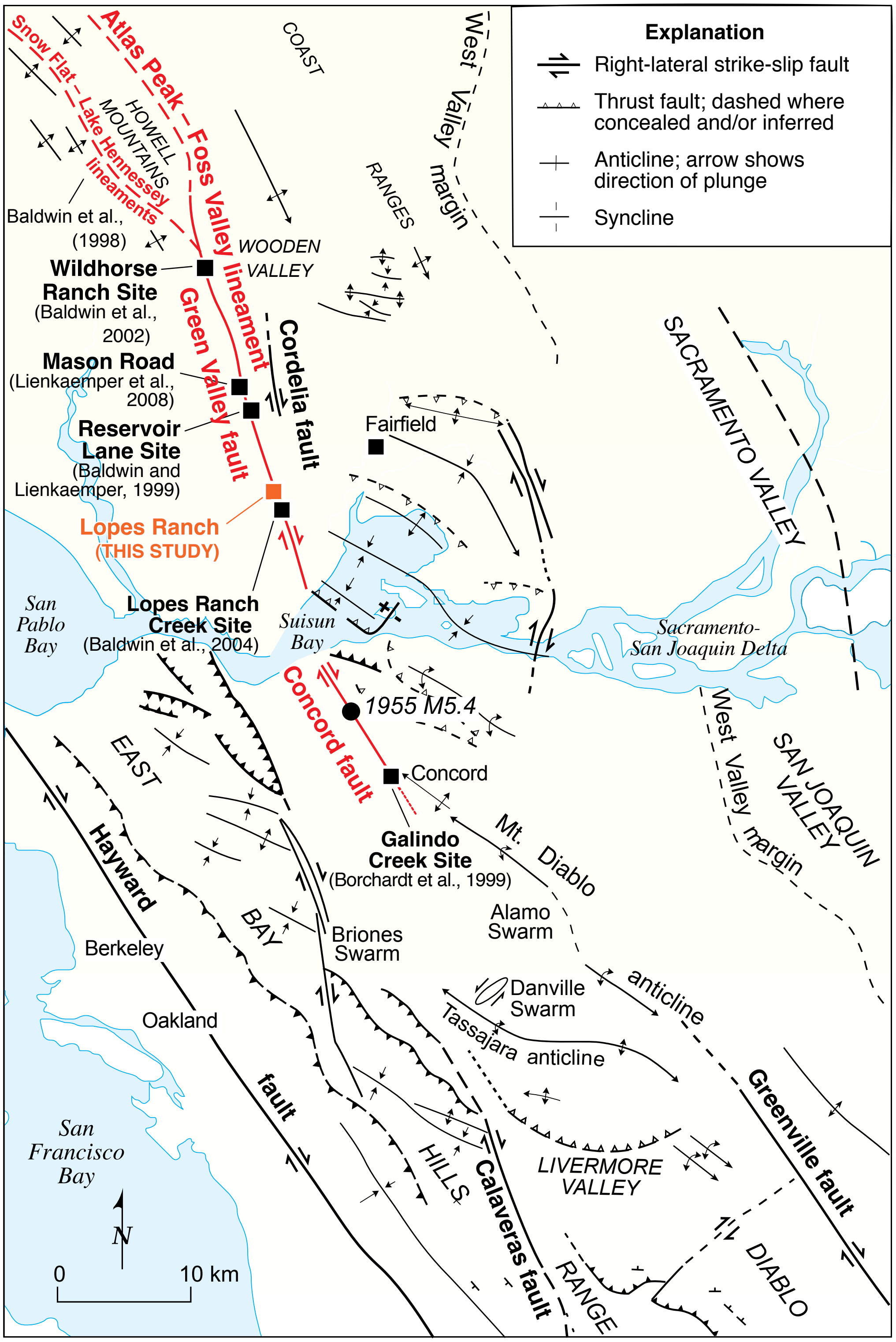
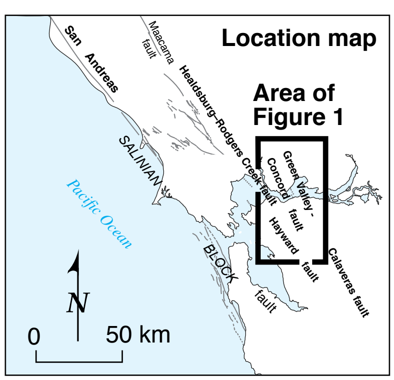


Concord-Green Valley fault system, and other faults in the eastern San Francisco Bay area.



G R E E N V A L L E Y

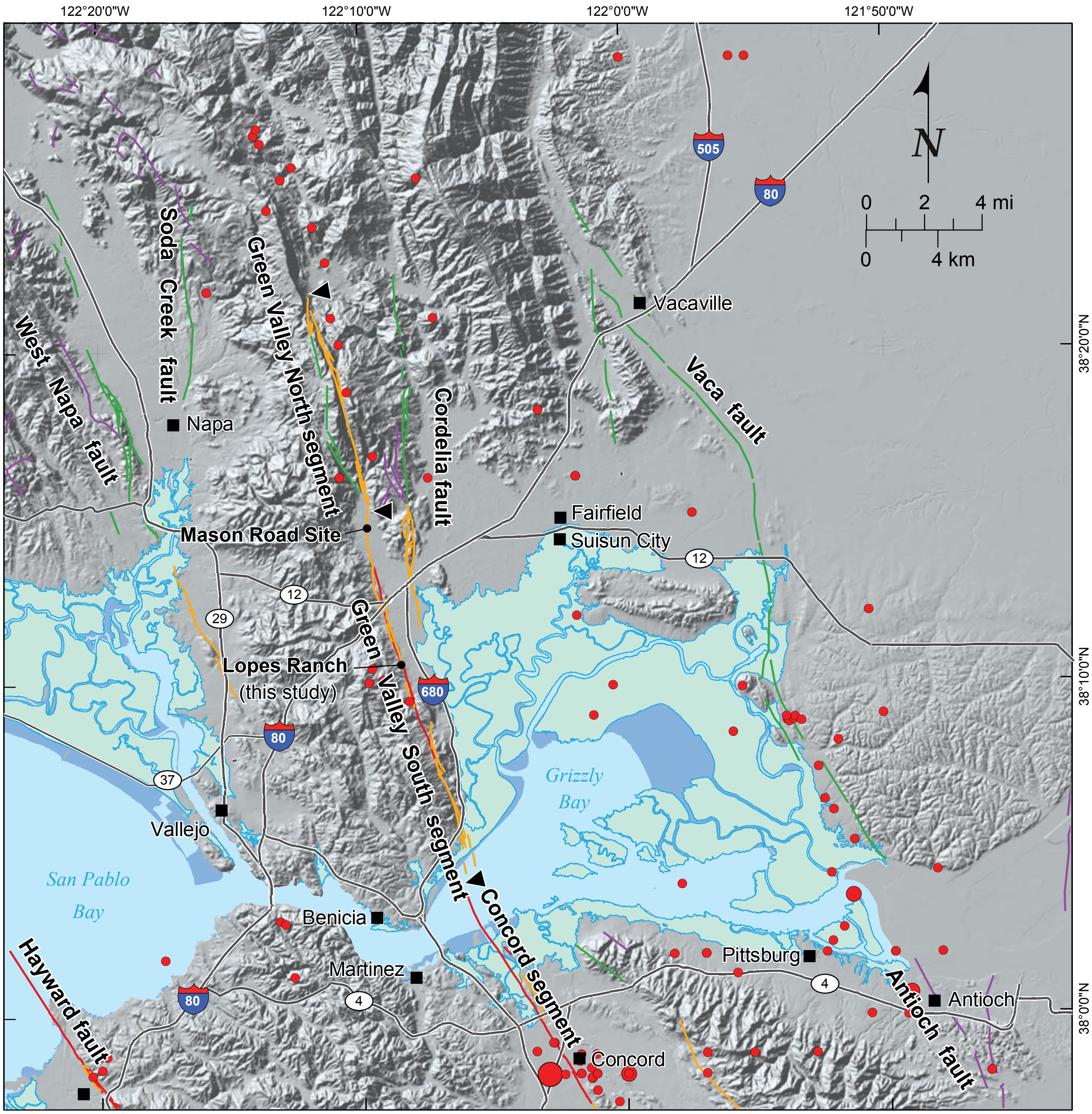
Concord-Green Valley Fault System

WLA William Lettis & Associates, Inc.

Figure 1

November 26, 2008 9:36 AM

1791 Lopes Ranch FTR



Explanation

▼ ▼ Fault segment boundaries

Eco Atlas Marshes

Historic marsh | Modern marsh

Fault Type (CGS, 2005)	*Seismicity (magnitude)*
Historic	3.0 - 3.99
Holocene	4.0 - 4.99
Late Quaternary	5.0 - 5.4
Quaternary	

Notes: 1. Digital Database of Quaternary and Younger Faults from the Fault Activity Map of California, Version 2.0, Bryant, W. A. (compiler), 2005.

2. Seismicity from Advanced National Seismic System Catalog, 1898 through 2007.

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Regional Tectonic Setting

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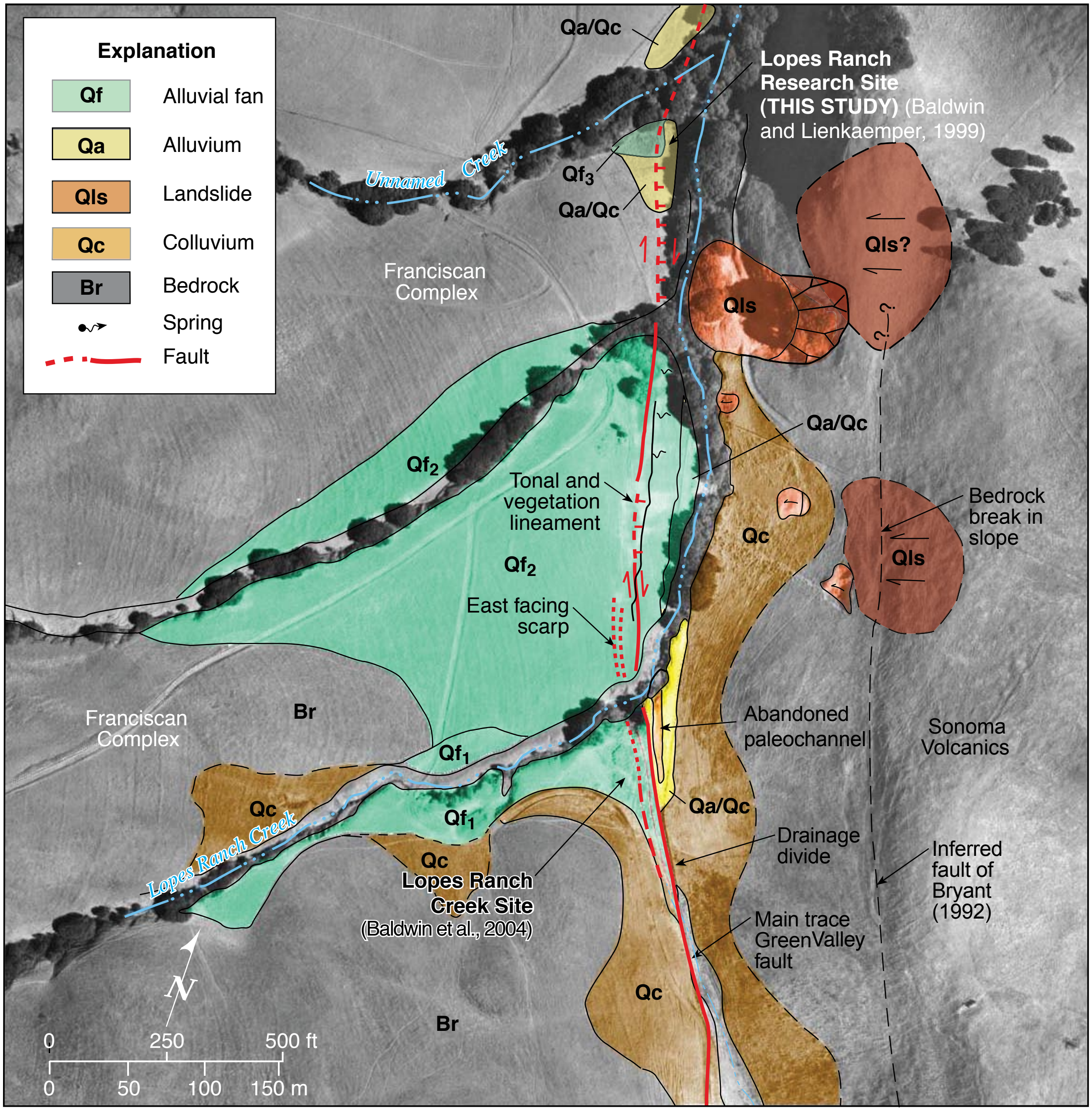
1791 Lopes Ranch FTR



Aerial photograph interpretation of the southern Green Valley fault at Lopes Ranch and Quaternary geologic map units and fault traces. Photograph from 1996.

GREEN VALLEY

Aerial Photograph Interpretation of Green Valley Fault

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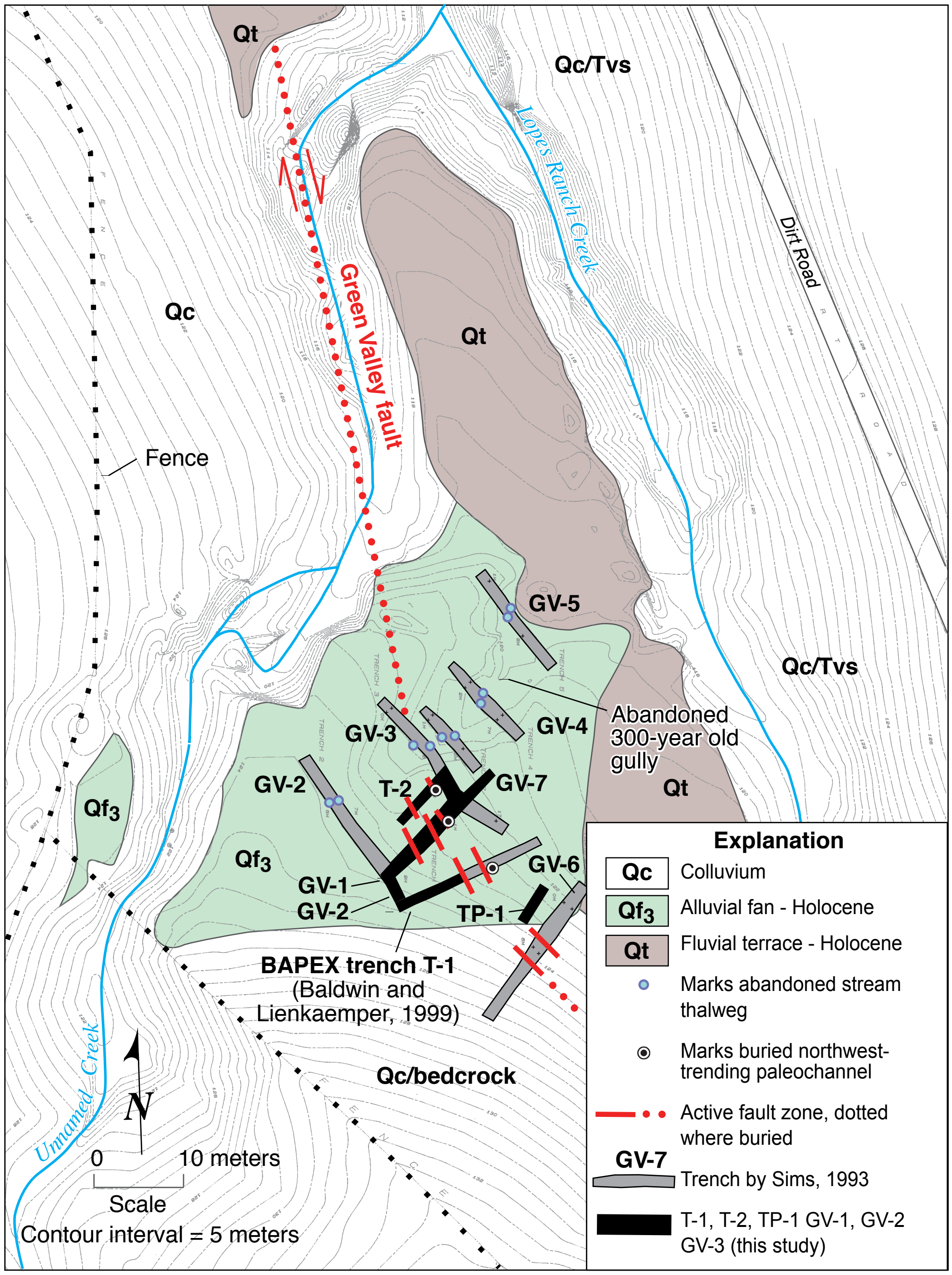

Detailed topographic map of Lopes Ranch trench site showing location of Sims (1993, unpublished) trenches (GV-1 to GV-7) and BAPEX trench T-1. Blue dots represent the approximate location of an offset buried paleochannel.

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Detailed Topographic Map of Lopes Ranch Trench Site

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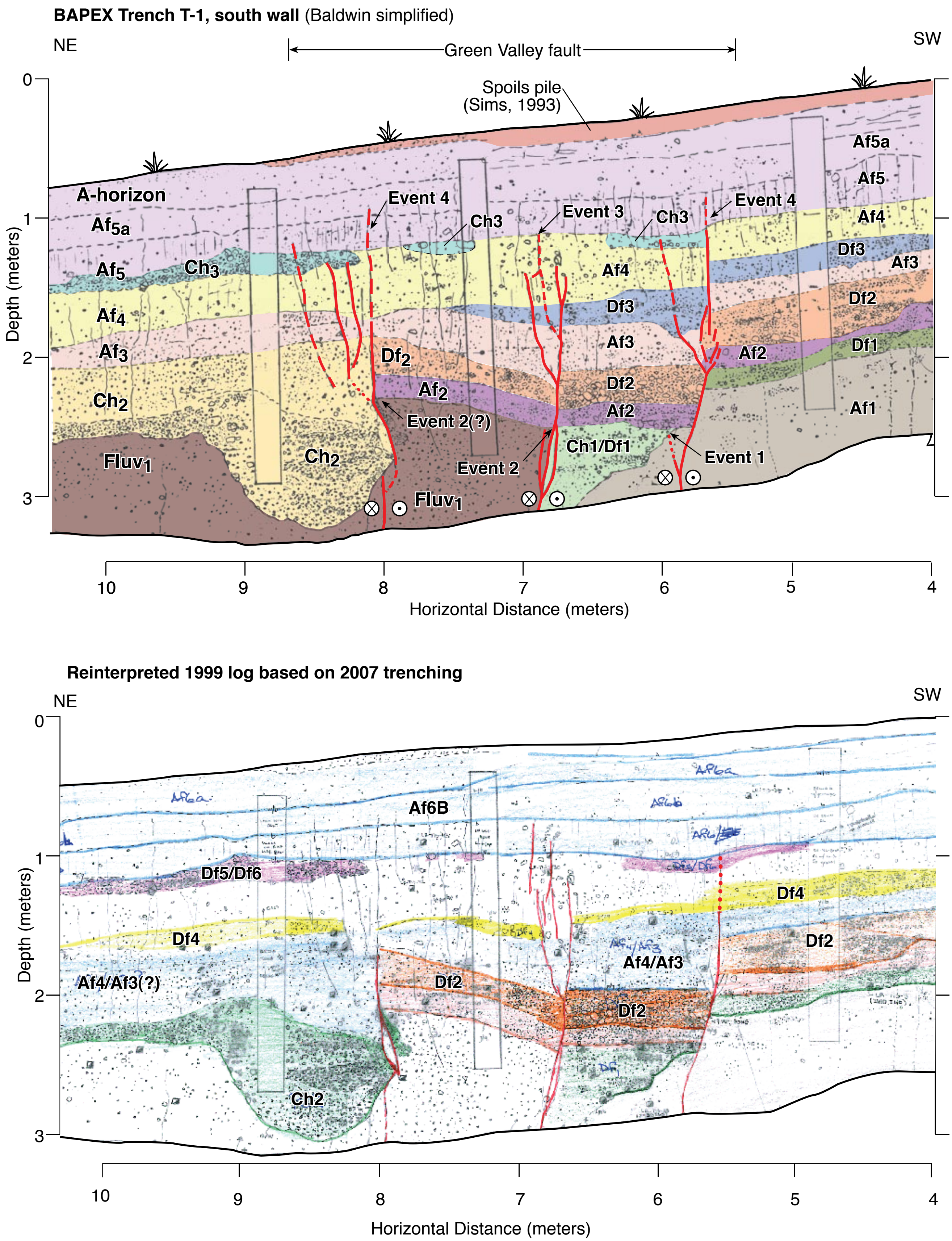

Logs of BAPEX trench T-1 (Baldwin and Lienkaemper, 1999) of the main Green Valley fault zone. The upper figure depicts hypothesized paleoearthquake events. See Baldwin and Lienkaemper (1999) for discussion on event chronology. Lower figure is revised stratigraphy based on this study.

GREEN VALLEY

Logs of BAPEX Trench T-1

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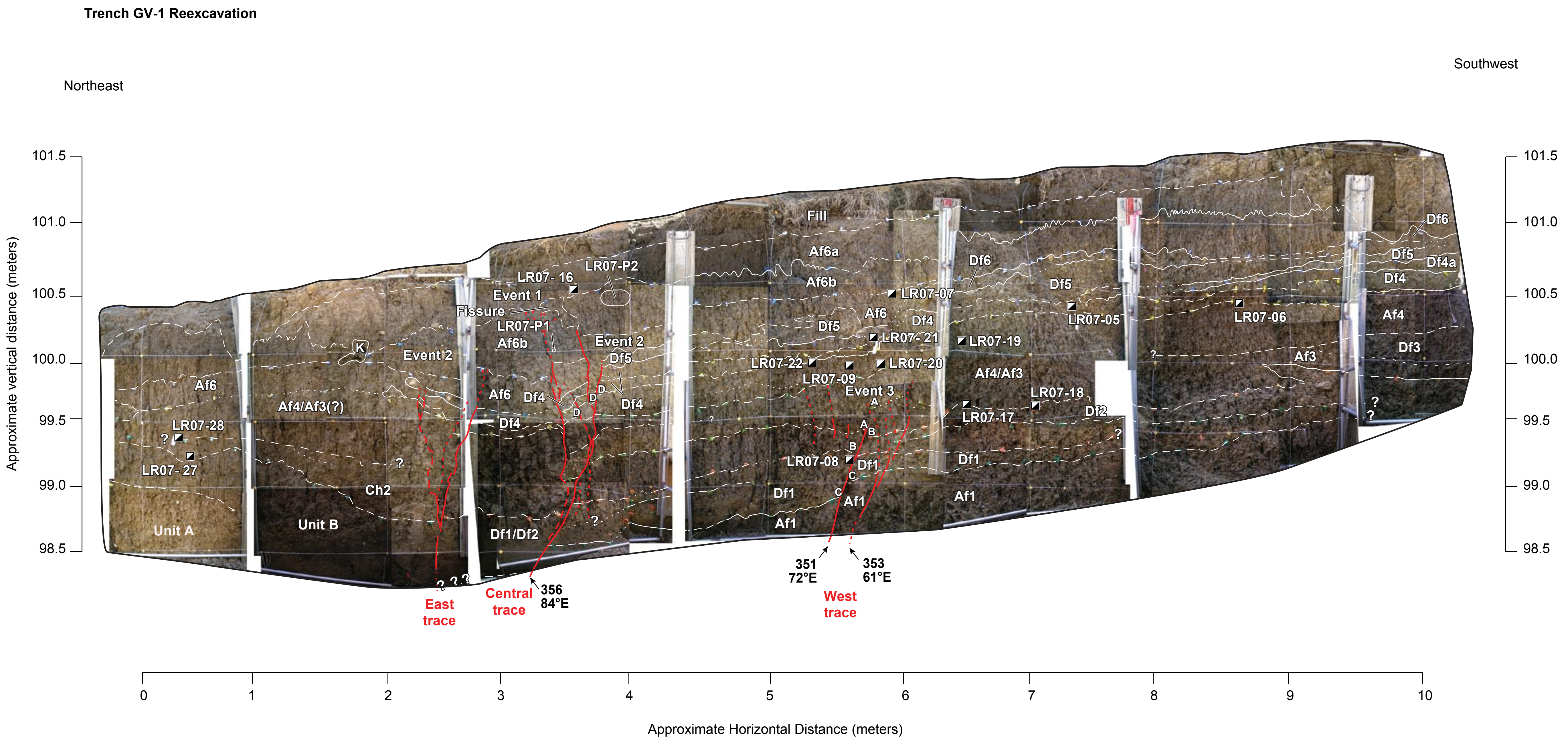

Explanation

LR07-32	Radiocarbon sample location and designation	(K)	Krotovina
LR07-P2	Pollen sample location and designation		Fault, dashed where uncertain
A	Stratigraphic marker horizon across fault		Sharp gradational inferred contact

For explanation of geologic units see Figure 6c

GREEN VALLEY

Trench GV-1, South Wall

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Figure 6a

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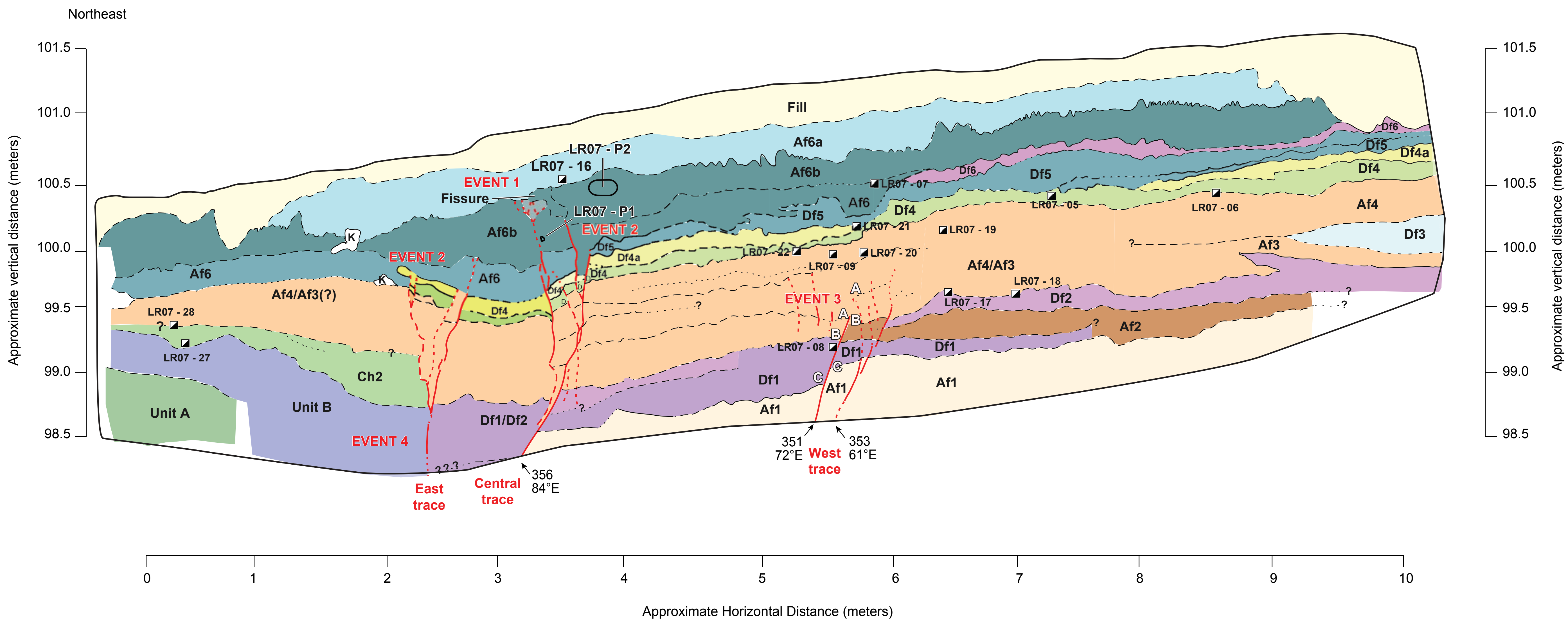
Trench GV-1 Reexcavation



Explanation

LR07-32	Radiocarbon sample location and designation	Ⓚ	Krotovina
LR07-P2	Pollen sample location and designation		Fault, dashed where uncertain
A	Stratigraphic marker horizon across fault		Sharp gradational inferred contact

For explanation of geologic units see Figure 6c

GREEN VALLEY

Trench GV-1, South Wall

WLA William Lettis & Associates, Inc. | Figure 6b

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1791 Lopes Ranch FTR

Geologic Units

Af6a	Sandy Silt; Dark Grayish Brown (2.5Y 4/2); massive to very weak blocky structure; 25-40% subangular to angular sand; <5% subangular to subrounded siltstone gravel clasts 4-6mm in size; many roots.
Af6b	Sandy Clayey Silt; Dark Grayish Brown (2.5Y 4/2); slender prismatic structure; 10-15% subangular to angular sand; <5% subangular to subrounded siltstone gravel clasts 3-13mm in size; roots and root casts.
Af6	Sandy Silt; Dark Grayish Brown (10YR 4/2); prismatic structure; 10-25% subangular to angular sand; <5% subangular to subrounded siltstone and sandstone gravel clasts 3-8mm in size.
Df6	Poorly Sorted Gravel; Light Olive Brown (2.5Y 5/3); massive structure; matrix supported near base of unit, clast supported near top; sandstone and siltstone gravel clasts 6-90mm; gravel coarsens upwards, matrix consists of sandy silt.
Df5	Poorly Sorted Gravel; Light Olive Brown (2.5Y 5/3); matrix supported; subrounded to subangular clasts, 5-115mm in size composed of oxide stained arkosic sandstone; sandy, silty clay matrix; slightly damp.
Df4	Poorly Sorted Gravel; Olive Brown (2.5Y 4/3); primarily clast supported, locally matrix supported; subrounded to angular clasts 5-50mm in size composed of weathered sandstone and siltstone; matrix consists of clay, silt and sand matrix.
Df4a	Silty Sandy Clay; Very Dark Grayish Brown (10YR 3/2); prismatic structure; high dry strength; slightly damp.
Af4	Gravelly Silt with Sand; Dark Grayish Brown (2.5Y 4/2); prismatic structure; 20-25% fine to medium subrounded sand, 15-30% gravel; subrounded to subangular sandstone 3-10mm in size, dominantly <5mm.
Df3	Poorly Sorted Gravel; Gravel: Brownish Yellow (10YR 6/8), Matrix: Olive Gray (5Y 4/2); massive structure; matrix supported; subrounded to subangular sandstone clasts 3-35mm in size, dominantly 3-6mm; matrix consists of silt and clay.
Af3	Silty Sandy Clay; Very Dark Brown (10YR 2/2); prismatic structure; fining upwards sequence; 5% gravel (localized lenses with 10-20% gravel composed of highly weathered orange sandstone;.
Df2	Poorly Sorted Gravel; Gravel: Yellowish Brown (10YR 5/6), Matrix: Very Dark Grayish Brown (10YR 3/2); matrix supported; 40-70% gravel; subangular to angular clasts of arkosic sandstone 4-8mm in size; matrix consists of sand, silt and clay.
Af2	Clayey Silt with Gravel; Matrix: Dark Grayish Brown (2.5Y 4/2), Gravel: Yellow to Olive Yellow (2.5Y 6/8 to 2.5Y 7/8); blocky to prismatic structure; 20-30% subangular sandstone gravel clasts 4-11mm in size evenly distributed through unit.
Df1	Poorly Sorted Gravel; Dark Yellowish Brown (10YR 4/4); massive structure; clast supported (locally matrix supported); subrounded to angular clasts of orange arkosic sandstone 4-35mm in size, dominantly 6-12mm; matrix consists of sand and silt.
Af1	Silty Clay with Gravel; Silty Clay: Very Dark Grayish Brown (10YR 3/2), Gravel: Yellowish Brown to Dark Yellowish Brown (10YR 3/4 to 10YR 5/6); weak blocky structure; 10-40% gravel (subangular arkosic sandstone).
Ch2	Sandy Silt with Gravel; Dark Grayish Brown (2.5Y 4/2); weak prismatic structure; 20-40% fine to coarse subrounded sand; 5-10% subrounded to subangular siltstone gravel clasts 3-12mm in size.

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Explanation of Geologic Units

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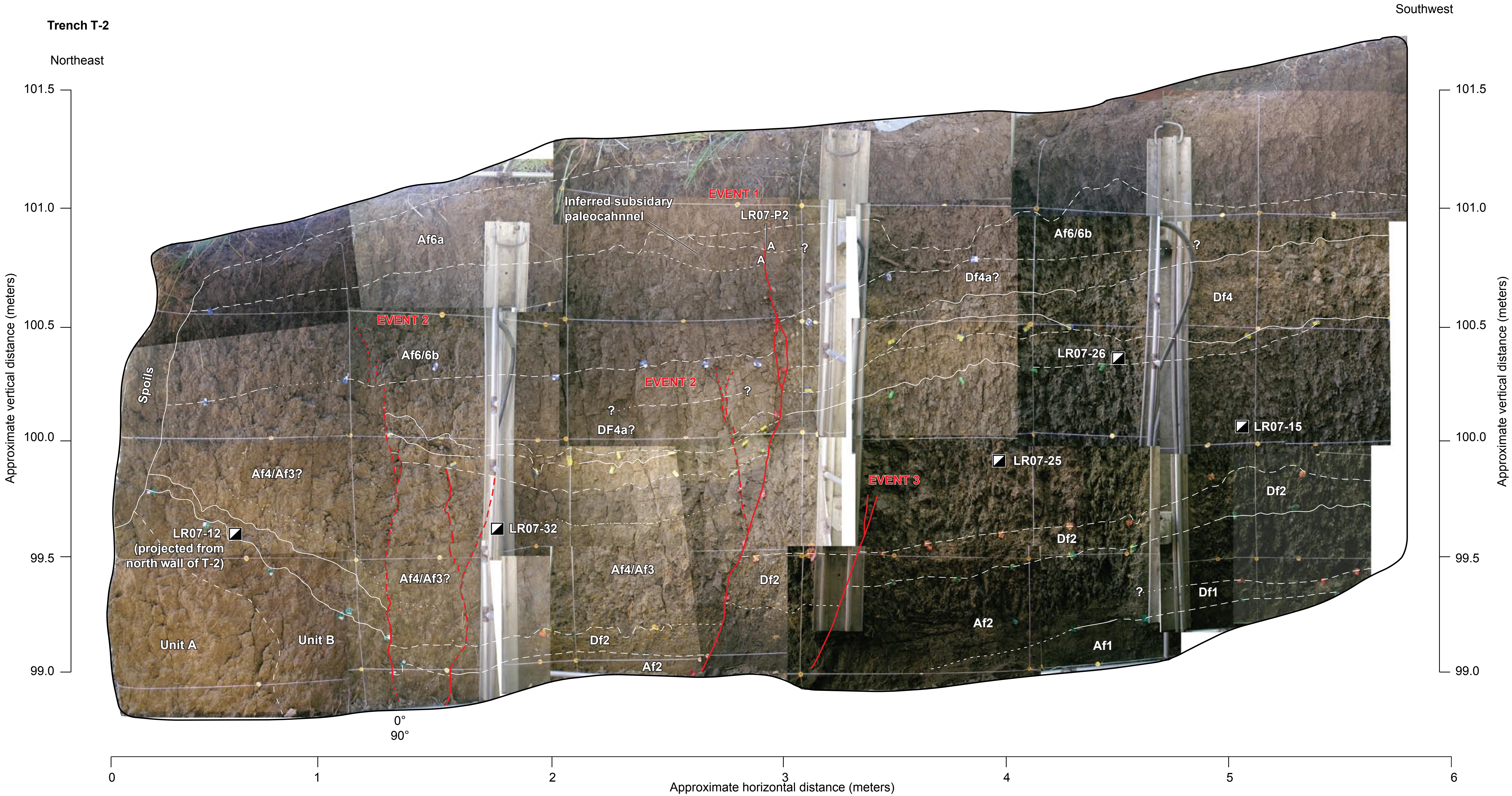

For explanation of geologic units see Figure 6c

Explanation

LR07-32 ◪	Radiocarbon sample location and designation
LR07-P2	Pollen sample location and designation
A	Stratigraphic marker horizon across fault
(K)	Krotovina
- - - —— (red)	Fault, dashed where uncertain
- - - —— (gray)	Sharp gradational inferred contact

GREEN VALLEY

Trench T-2, South Wall

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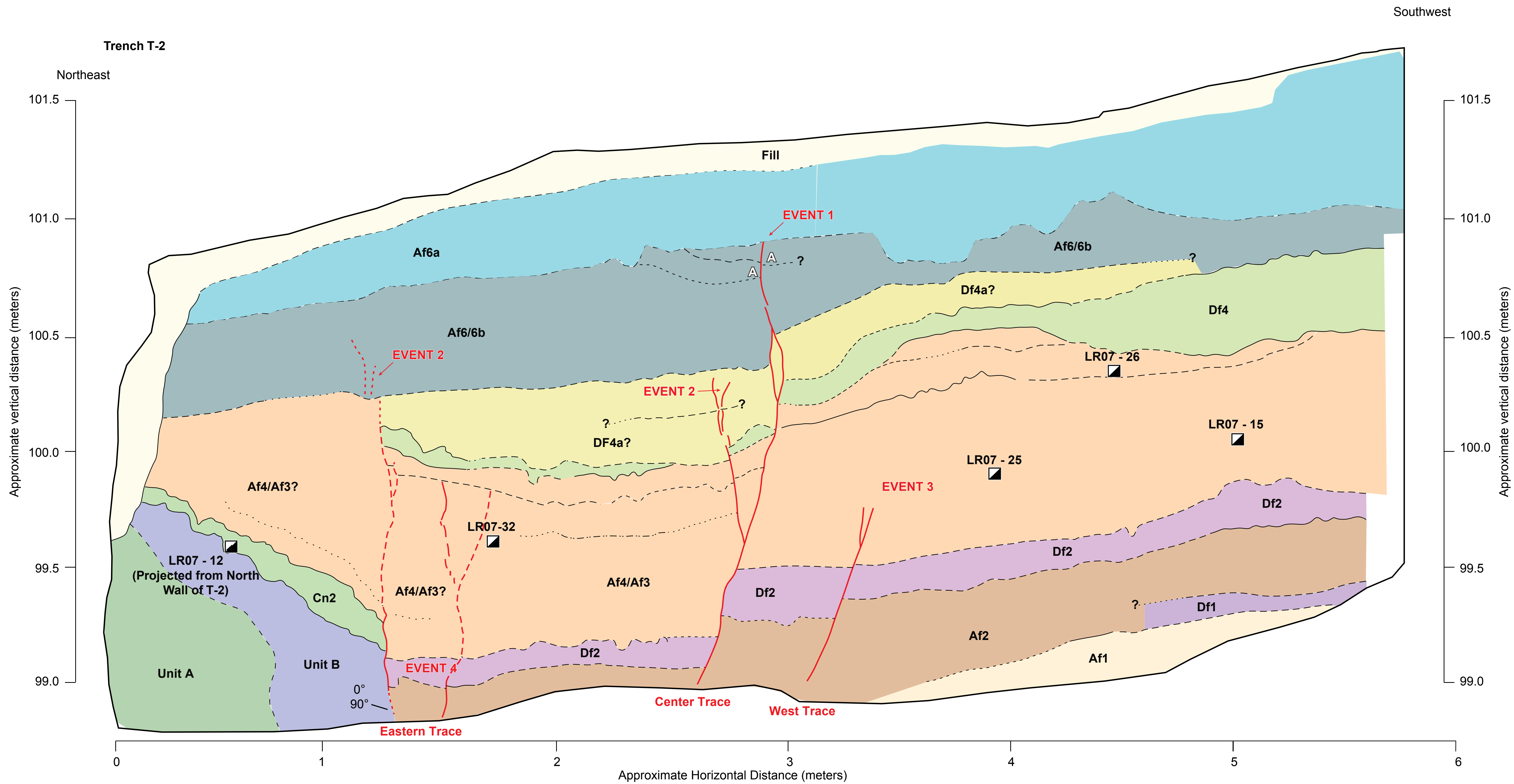


Explanation

LR07-32	Radiocarbon sample location and designation
LR07-P2	Pollen sample location and designation
A	Stratigraphic marker horizon across fault
K	Krotovina
	Fault, dashed where uncertain
	Sharp gradational inferred contact

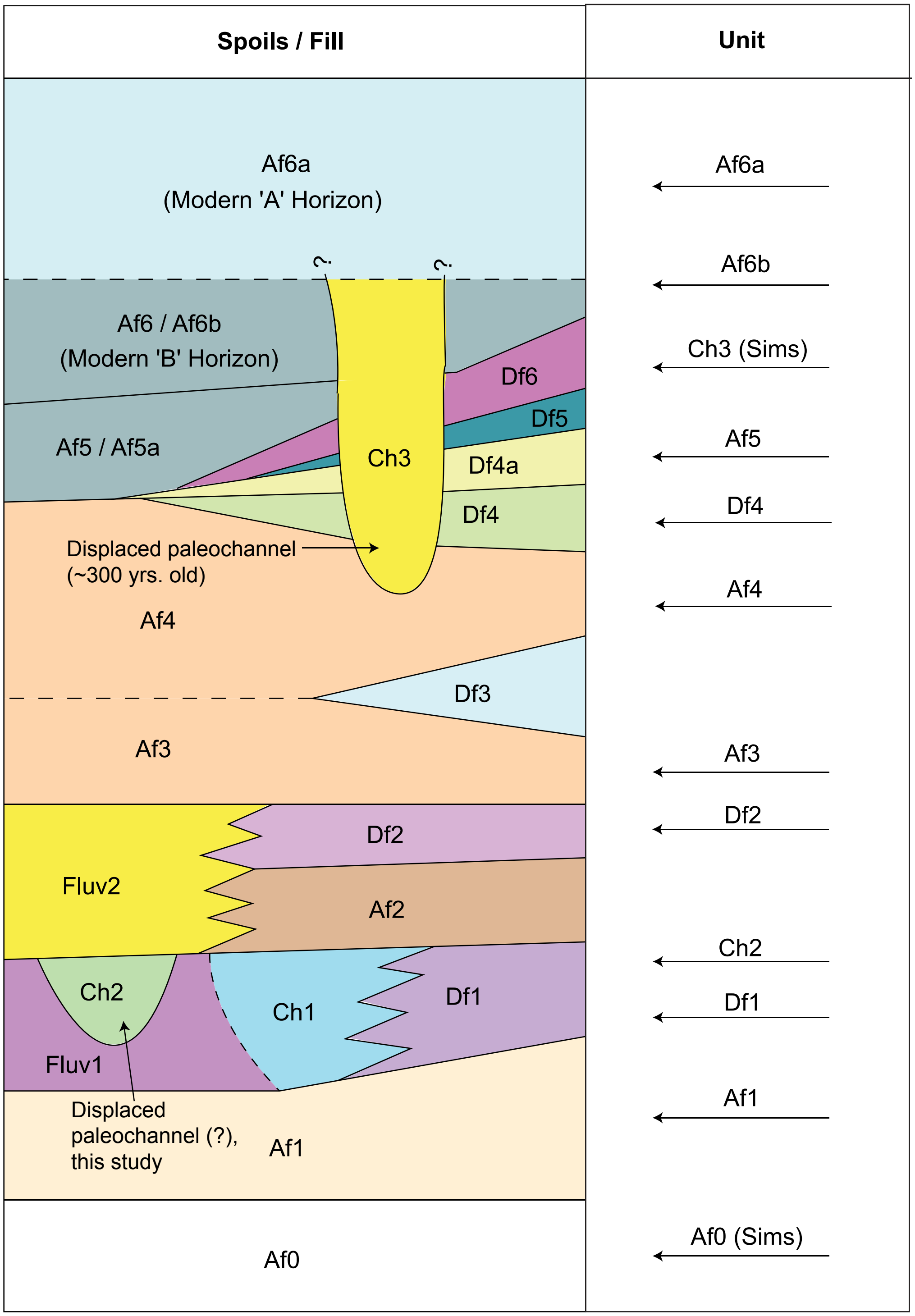
For explanation of geologic units see Figure 6c

G R E E N   V A L L E Y

Trench T-2, South Wall

WLA William Lettis & Associates, Inc.

Figure 7b



Generalized stratigraphic column for Lopes Ranch site combining data collected in trenches T-1 (Baldwin and Lienkaemper, 1999), T-2 (this study) and GV-1 to GV-7 (this study, Sims, 1991 unpublished). Not all units are discussed in this study.

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Generalized Stratigraphic Column for Lopes Ranch Site

WLA William Lettis & Associates, Inc. | Figure 8

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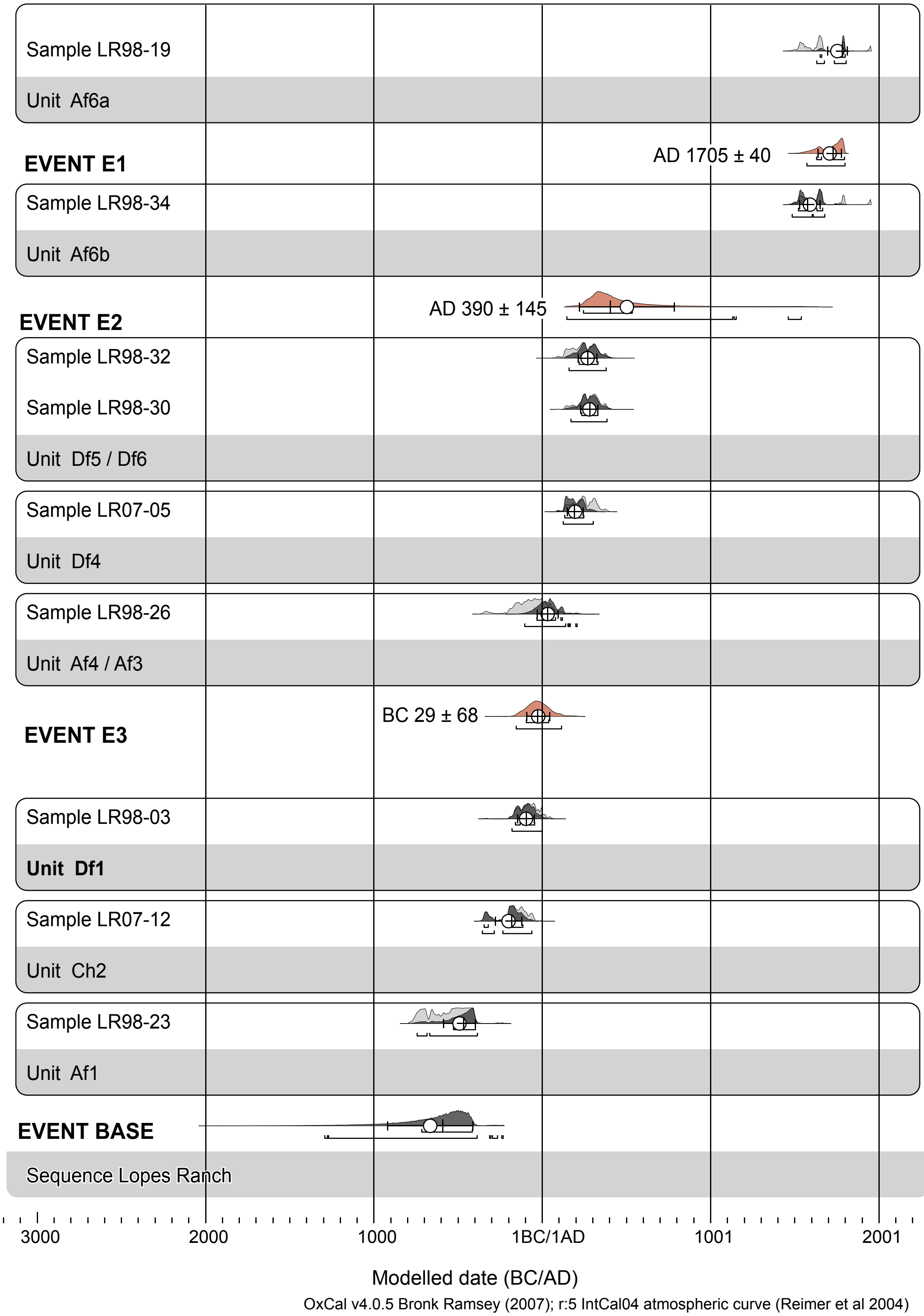
1791 Lopes Ranch FTR



Analytical output from Oxcal v.4.0 (Ramsey, 2007), showing radiocarbon sample numbers within each unit, with probability density functions of each sample and earthquake events. Circled event dates are 1σ ranges. Bracketed bars represent the 2σ range (ages described in report).

G R E E N V A L L E Y

Analytical Output from Oxcal

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