Final Technical Report

Paleoseismic Record Of Earthquakes on The Santa Cruz Mountains Segment of The San Andreas Fault - Testing The Influence of The Northern Transition Zone Using Earthquake Chronologies and Implications for Seismic Hazards on The San Andreas Fault:

Collaborative Research with William Lettis and Associates Inc. and the California Geological Survey

Prepared for:
U.S. Geological Survey
National Earthquake Hazards Reduction Program
Award No. 08HQGR0071 and 08HQGR0072

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September, 2009

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FINAL TECHNICAL REPORT

PALEOSEISMIC RECORD OF EARTHQUAKES ON THE SANTA CRUZ MOUNTAINS SEGMENT OF THE SAN ANDREAS FAULT – TESTING THE INFLUENCE OF THE NORTHERN TRANSITION ZONE USING EARTHQUAKE CHRONOLOGIES AND IMPLICATIONS FOR SEISMIC HAZARDS ON THE SAN ANDREAS FAULT: COLLABORATIVE RESEARCH WITH WILLIAM LETTIS & ASSOCIATES INC. AND THE CALIFORNIA GEOLOGICAL SURVEY

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Keywords:

San Andreas fault, research on paleoearthquake chronologies, and recurrence

Program Element III

U. S. Geological Survey
National Earthquake Hazards Reduction Program
Award Numbers 08-HQ-GR-0071 and 08-HQ-GR-0072

September 2009

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 08-HQ-GR-0071 and 08-HQ-GR-0072. 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.

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ABSTRACT

The Santa Cruz Mountains section of the San Andreas fault is poorly understood in terms of fundamental information such as earthquake chronology and geologic slip rate data. These data are fundamental inputs in fault rupture models, calculations of earthquake rates, and estimates of earthquake probabilities used in studies such as those conducted by the 2002 and 2007 Working Group on California Earthquake Probabilities (WG02 and WG07). This report presents preliminary findings for the Hazel Dell Road paleoseismic investigation site on the Santa Cruz Mountains section (SAS) of the San Andreas fault (SAF), located near the town of Corralitos, Santa Cruz County, California (Figure1). The primary goal of the Hazel Dell paleoseismic investigation is to obtain information on the timing of past Holocene surface rupturing earthquakes along the central portion of the SAS.

The Santa Cruz Mountains segment last ruptured during the 1906 earthquake, an event that produced continuous surface rupture across several northern San Andreas fault segments from Point Arena to San Juan Bautista. Paleoseismic studies on the Santa Cruz Mountains segment at the Grizzly Flat and Arano Flat sites provide evidence of 1906 surface deformation, but have yielded differing records of prehistoric surface-fault ruptures. Grizzly Flat is located 14 km northwest of the Arano Flat site and records one prehistoric earthquake between AD 1632-1659 (Schwartz and others, 1996). The Arano Flat – Mill Canyon sites suggest nine earthquakes in the past ~1000 years (Fumal and others, 2003). The average recurrence interval over the past 1,000 years at the Arano Flat site is 105 years (Fumal and others, 2003). The Hazel Dell paleoseismic site is located approximately 9.5 km north of Arano Flat, near the mid-point between the Arano Flat and Grizzly Flat sites (Figure 1). Results from this study have revealed a history of 3 – 4 events, including 1906 since A.D. 674. Preliminary age results have begun to constrain the age of the penultimate event, however a longer record of earthquakes and additional age constraints are needed to make meaningful comparisons at this site with the other sites on this section of the fault.

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1.0 INTRODUCTION

This report presents preliminary findings for the Hazel Dell Road paleoseismic investigation site on the Santa Cruz Mountains section of the San Andreas fault, located near the town of Corralitos, Santa Cruz County, California (Figure 1). The primary goal of the Hazel Dell paleoseismic investigation is to obtain information on the timing of past Holocene surface rupturing earthquakes along the central portion of the Santa Cruz Mountains section (abbreviated SAS by WG02 and used herein) of the San Andreas fault (SAF).

The San Andreas fault accommodates a significant fraction (40-50%) of the plate boundary motion within the San Francisco Bay Region (SFBR), making it one of the principal contributors to the total seismic hazard within the region (WG02). The SAS of the San Andreas fault is a 62-km long zone between Los Gatos and San Juan Bautista (WG02, WG90), and is associated with a broad restraining bend within the Santa Cruz Mountains (Figure 1). Deformation is more broadly distributed through this section than along the adjacent Peninsula and creeping sections to the north and south, respectively, as indicated by the M 6.9 1989 Loma Prieta earthquake and the active Sargent fault (Figure 1).

Historically, the SAS last ruptured during the **M** 7.9 1906 earthquake that produced over 430 km of surface rupture from Point Arena to San Juan Bautista. The **M** 6.9 1989 Loma Prieta earthquake, considered to be located off of the San Andreas fault (WG02), caused widespread damage and loss of life throughout the SFBR, particularly in nearby communities such as Santa Cruz and Watsonville. The WG02 estimated a mean model probability of 11% that the SAS could produce a M≥6.7 earthquake in the 30-year period between 2002-2031. The most recent WG (2007) essentially adopted the model parameters of WG 2002 for the SAS, and concluded that the northern San Andreas fault, which includes the SAS, has a 21% chance of a M ≥ 6.7 earthquake in the next 30 years. The historic observations as well as the relatively high probability assigned by past Working Groups underscores the danger that large, damaging earthquakes pose to this rapidly urbanizing area. Earthquake timing, geologic slip rate data and understanding how large earthquakes are associated with adjacent sections are essential for evaluating the seismic potential of Characterizing SAS behavior in terms of the frequency of large earthquakes, geologic slip rate, and how large earthquakes are associated with adjacent sections is critical to guide how seismic potential should be modeled for this section and the San Andreas fault as a whole for the next Working Group effort.

Paleoseismic studies on the Santa Cruz Mountains segment at the Grizzly Flat and Arano Flat sites have yielded different records of prehistoric surface-fault ruptures. Grizzly Flat is located 14 km northwest of the Arano Flat site and records one prehistoric earthquake between AD 1632-1659 (Schwartz and others, 1996). The record at the Arano Flat – Mill Canyon sites suggest nine earthquakes in the past ~1000 years (Fumal and others, 2003). Findings from the Arano Flat – Mill Canyon (AF-MC) (Figure 1) paleoseismic site of Fumal and others (2003) and Heingartner and Schwartz (1996) suggest that the rate of

large earthquakes may be much higher than estimated by WG02, with a reported average recurrence of 105 years (Fumal and others, 2003). There is considerable uncertainty as to the size of the earthquakes seen in the paleoseismic record at AF-MC as there are no other sites with comparable long records and well-constrained age control on the SAS. GPS and InSAR modeling by Johanson and Bürgmann (2005) suggest that the southern part of this segment is a zone where the fault transitions from fully creeping to fully locked. This "northern transition zone" may, in part, explain the differing paleoseismic records along this segment. The Arano Flat – Mill Canyon sites may record more frequent, but smaller earthquakes, while the earthquake record along the northern parts of this section may record fewer, but larger, ruptures similar to 1906.

This study presents preliminary results from a newly developed paleoseismic site, which is located near the midpoint between the two previous investigations along the SAS, and has begun to refine the understanding of the timing of past large earthquakes on this section of the San Andreas fault. The focus of the study is to develop a longer record of earthquakes at a site that is located along part of the fault that is fully locked and, presumably, out of the influence of the northern transition zone. We have excavated trenches at a promising new site located at the intersection of Hazel Dell and Green Valley Roads in the Santa Cruz Mountains and have begun to develop a paleoseismic record that will allow us to compare the local earthquake record to the other two sites along this segment of the fault and examine which record best represents the behavior of the segment as a whole.

2.0 HAZEL DELL ROAD PALEOSEISMIC INVESTIGATION SITE

2.1 Surface Fault Expression

In the Hazel Dell area the SAF trends northwesterly and bounds the western edge of the valley. Locally, the fault juxtaposes sandstone and shale of the Purisma Formation on the west against Shale of the Mt. Pajaro area on the east (Brabb, 1989). Previous workers mapped the SAF as several complex splays, the main trace is characterized by a linear valley, aligned topographic lineaments, offset drainages, linear drainages and sag ponds (Sarna-Wojcicki and others, 1975). Two prominent fault traces are mapped in the vicinity of the Hazel Dell site, the westernmost trace is located roughly 200 meters west of the site, is highly discontinuous and segmented (Figure 2). The central trace is located along the western edge of Hazel Dell Valley, has a relatively continuous surface trace marked by well defined linear base of slope along east-facing hillslopes bounding the valley, and aligned linear drainages and topographic escarpments south of Old Mt. Madonna Road and north of Green Valley Road respectively (Figure 2).

We created a detailed fault strip map of the Hazel Dell area with shaded relief, contour and slope maps generated from 0.5 meter resolution LiDAR data. We identify a series of aligned linear drainages, linear range fronts, aligned topographic escarpments and a sharp base of slope along the east-facing hillslopes (Figure 3). We found the central trace identified by previous mappers, bounds the western edge of the valley, and has the strongest geomorphic expression on this high resolution data. Using these data we were able to map small scale (<1m relief) fault features projecting toward the paleoseismic investigation site. Immediately north-northwest of the investigation site located within a stand of redwoods, LiDAR data reveals the SAF is expressed as a subtle west-facing break-in-slope and less well expressed set of *en echelon* linear closed depressions. South of the site at the northern extent of Simas Lake, near the fault's intersection with Green Valley road, the fault is expressed as an abrupt, linear break in slope (Figure 3). We projected these features across the investigation site in order to refine exploratory fault trench locations.

2.2 Geomorphology of the Hazel Dell area

The Hazel Dell paleoseismic study site is located southwest of the intersection of Hazel Dell and Green Valley Roads near Corralitos, CA. A series of large sag ponds, known collectively as Simas Lake, lie along the western edge of the valley. These ponds dry to the north and transition to a seasonal marsh, this transition coincides with a slight rise in elevation along the valley floor, just before Green Valley Road. The marsh surface at the Hazel Dell site is located at approximately 400 feet elevation, and is approximately 10 feet higher in elevation than the Simas Lake sag ponds. Modern aerial imagery reveals that the Simas Lake sag ponds are wet throughout the summer, while the investigation site north of Green Valley road is dry seasonally (Google Earth imagery, June 2007) (Figure 4).

The Hazel Dell trench site traverses the low marsh area on the north side of Green Valley Road, is bound by Green Valley Creek to the south and west and is flanked by a sandstone sequence of Mt. Pajaro area formation hillslopes to the northeast. Green Valley Creek flows from the northwest, making an abrupt ~90° turn paralleling Green Valley Road, flowing due southwest and out of Hazel Dell valley and crossing the fault in the vicinity of our project site (Figure 3). Green Valley Creek continues westward where it eventually flows into Corralitos Creek. The Hazel Dell Road site is within the floodplain and has been inundated by flood waters on the creek in recent high rainfall years (personal communication, property owner, D. Dent, 2008). In these flood events the site is blanked by fine-grained alluvial overbank deposits. The investigation site was occupied by an apple orchard between roughly 1950 and 1980 (personal communication property owner, D. Dent, 2008) (Figure 5). Roots from apple trees extended to a depth of roughly 75 cm below the ground surface, the ground surface has also been tilled, disturbing 20 to 50 cm below the ground surface. These farming activities combined with historic overbank sediment deposits sourced by the Green Valley Creek likely obscured surface expression of 1906 surface rupture across the investigation site.

3.0 RESULTS

Our primary objective at the Hazel Dell Road site was to obtain information on the timing of Holocene paleoearthquakes along the central portion of the SAS. Trenches across the site revealed structural and stratigraphic relationships across the fault which enabled detailed analysis and interpretation of evidence for pre-historic surface rupturing events at the study site. We excavated a total of eight fault normal trenches within the marsh area on the north side of Green Valley Road (Figure 5). Of the eight trenches, three trenches, T4, T7 and T8, crossed the projected fault trace, and the other five revealed no clear evidence of fault deformation (Figure 6). Trenches T7 and T8 revealed multiple fault strands and good stratigraphic evidence for multiple event histories. Trench T4 revealed a single fault strand and complex stratigraphy that is not continuous across the fault zone, as a result this trench did not have distinguishable event horizons. Event evidence is expressed as upward terminations, fissure fills, and possible folding of units that are overlain by less deformed stratigraphic units. Trenches were excavated between August and September, 2008, following a dry winter and spring (Figure 7). We were able to excavate to depths of 2 to 2.5 meters below the ground surface before encountering ground water.

The site revealed fine-grained stratigraphy, and an abundance of datable material, detrital charcoal was identified in all stratigraphic units, and an organic/peaty unit was identified and is shown here as unit 400, the dark gray-brown unit on Plate 1, and Plate 2. Detrital charcoal samples were reviewed during field sampling, and, based on sample size, samples were prioritized for further inspection in the office. In the office, samples were ranked based on the sample size and the location within the stratigraphic unit from which they were recovered, and were prioritized for ^{14}C analysis. Five detrital charcoal samples from key stratigraphic units were submitted for radiocarbon analysis (Table 1). Probability distribution functions for radiocarbon ages are shown in stratigraphic order in Figure 8. Of these samples, four were in good stratigraphic order, and one sample was inconsistent with ages determined from both overlying and underlying samples.

Table 1. Radiocarbon Analysis: Hazel Dell Road site

Sample Number	Laboratory Name	Stratigraphic Unit	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age *	2-sigma Calibrated Date (95.4%)
HDT7-7	Beta - 254277	200b	330 ± 40 BP	-23.8 o/oo	350 ± 40 BP	Cal AD 1450 1650
HDT7-3	Beta - 254274	300a	1160 ± 40 BP	-25.5 o/oo	1150 ± 40 BP	Cal AD 780 to 980
HDT7-4	Beta - 254275	400	630 ± 40 BP	-23.9 o/oo	650 ± 40 BP	Cal AD 1280 to 1400
HDT7-6	Beta - 254276	400	670 ± 40 BP	-26/7 o/oo	640 ± 40 BP	Cal AD 1280 to 1400
HDT8-31	Beta - 254278	600b	1200 ± 40 BP	-21.9 o/oo	1250 ± 40 BP	Cal AD 670 to 880

* Reported in radiocarbon years at 1 standard deviation measurement precision (68.2%), corrected for δ13C

In addition to radiocarbon analysis we collected samples for pollen analysis of non-native *Erodium cicutarium*. We employed non-native pollen analysis as a preliminary age constraint for the deposits to test the relative age of the deposits. Initial results from the pollen analysis reveal an absence of non-native pollen in the units sampled, which suggest that all units sampled predate the year 1770, the approximate timing in which non-native pollen from the *erodium cicutarium* (Common Stork's-bill) appears regionally in the stratigraphic record (Table 2). Radiocarbon and pollen sample locations are shown on trench logs (Plates 1 and 2).

Table 2. Pollen Analysis: Hazel Dell Road site**

Sample Number	Stratigraphic Unit	Results
HD7-2P	200a	Absence of Non-native pollen
HD7-3P	200b	Absence of Non-native pollen
HDT8-3P	300a	Absence of Non-native pollen
HDT8-4P	400	Absence of Non-native pollen
HD7-4P	400	Absence of Non-native pollen

** Pollen Analysis performed by Liam Reidy, UC Berkeley Pollen Lab, Dept. of Geography

3.1 Near Surface Stratigraphy

Trenches across the site exposed alluvial deposits sourced by Green Valley Creek, organic marsh deposits, and colluvium that originated from the bedrock escarpment to the north and east. Coarse-grained alluvial deposits, medium to fine-grained alluvial stream deposits and a fine-grained alluvial marsh sequence are deposited against and interfinger with slope derived colluvium proximal to hillslopes bounding the site. Coarse-grained alluvial deposits and fine-grained alluvial overbank deposits are sourced by Green Valley creek which bounds the site to the south and west (Figure 6). Alluvial deposits were encountered in trenches; T1, T2, T3, T4, T5 and T7. Moderately coarse-grained slope derived colluvium was only encountered in one trench, T6, where the trench traversed the west facing bedrock hillslope. Slope derived colluvium was observed to interfinger with fine-grained overbank alluvial deposits. For simplicity, we describe here the characteristics of the major geologic units observed in the trenches to cross the fault.

Description of Stratigraphic Units:

Unit 500 is a sandy gravel, composed primarily of sand and pebbles, with occasional cobbles and is the deepest and oldest stratigraphic unit observed both east and west of the fault (Trench 8, Plate 2). A detrital charcoal sample HDT8-31 was submitted from the unit (Unit 600b) below this gravel and yielded a two sigma calibrated age of 670 to 880 calendar years AD. (Table 1, Figure 8).

Unit 400 is a massive gray to black clayey silt with abundant detrital charcoal fragments, massive to weakly laminated in areas with parted organic layers. The basal contact of the

unit is slightly wavy and gradational over 5 to 10 cm. The upper horizon (20-30 cm) is defined by a distinct dark gray to black color that grades downward to medium grey. This unit represents fine-grained overbank alluvial deposits with strong organic development in the upper 20 to 30 cm, which suggests a period of marsh stability prior to deposition of the overlying sandy alluvial unit 300. Two detrital charcoal samples, HDT7-4 and HDT7-6, from unit 400 yielded nearly identical radiocarbon ages (Table 1). Both samples have a two sigma calibrated age range of 1280 to 1400 calendar years AD (Figure 8).

Unit 300 is a light tan to grayish-orange alluvial silty sand to sandy silt and consists of three distinct sandy alluvial deposits, subunits 300a, 300b and 300c. Subunit 300c is a massive to finely laminated light grayish yellow silty sand. Subunit 300b is a massive to locally laminated and crossbedded tan to light orange silty sand. This is overlain by unit 300a, a massive sandy silt to silty sand with some fine laminations. Unit 300a has a sharp to diffuse and planar basal contact. One detrital charcoal sample was submitted for age dating from unit 300a, sample HDT7-3 (Table 1). This sample yielded a two sigma calibrated age of 780 to 980 calendar years AD. We interpret this age to be stratigraphically out of order, yielding an age older than the underlying unit 400 radiocarbon ages (Figure 8). The radiocarbon age from unit 300a could potentially be a reworked piece of charcoal, or could reflect a long lag time between the burn that formed the charcoal and deposition of the fragment.

Unit 200 is a light gray to grayish brown massive clayey silt with sand and consists of subunits 200a and 200b. Subunit 200b is massive, contained abundant roots and rootlets and has a relatively planar basal contact that is gradational over roughly 5cm. Subunit 200a conformably overlies subunit 200b and grades upward from sandy silt to clayey silt with sand, the basal contact is gradual over ~5 cm. Radiocarbon analysis of a detrital charcoal sample from unit 200b yielded a two sigma calibrated age range of 1450 to 1650 calendar years A.D. (Figure 8, Table 1).

Unit 100 represents agriculturally modified stratigraphy immediately below the ground surface including the depth of the till-zone and roots from former apple trees.

3.2 Structural Relations and Event Evidence

The Hazel Dell trenches revealed evidence of at least three to four events including; 1906 and two to three pre-historic surface fault ruptures. Event horizons are labeled E1-1906, E2, E3 and E4, and ascend in age (Plate 1, Plate 2). Evidence for each event is discussed below.

We observe evidence of apparent vertical displacement, with an east-side-down sense of motion, based on trench exposures. In trench T7 and T8 alluvial units 200, 300, 400 and 500 infill a graben bound by a splay of the fault on the west (Plate 1 and 2). In trench T-7 these younger alluvial units appear to on-lap older alluvial units (Plate 1), in trench T8 the fault is expressed as a buttress unconformity where younger alluvial units are in roughly vertical fault contact with older alluvial units (Plate 2).

Evidence of Event E1 – 1906

Evidence for the most recent event, interpreted as 1906 is expressed as one to two fault strands that extend upward toward the basal contact of unit 100. Unit 100 is heavily bioturbated and is interpreted as an unconformable, agricultural contact.

Evidence of Event E2

Evidence for the penultimate event is expressed as a fault that terminates upward within unit 300b, and is capped by unit 300a (Plate 1), The primary strand vertically displaces unit 300c, dropping it roughly 16 cm down on the west, and is also expressed as a roughly 10 cm wide zone of distributed shear within subunit 300b. The penultimate event occurred after deposition of unit 300b and 300c, and prior to deposition of 300a. We interpret that unit 300a, composed of bedded fine sands and silts, was deposited within a depression formed by Event 2.

Evidence of Event E3

Evidence of the antepenultimate event, E3, includes a small fissure filled with sediment from unit 400 (Plate 1, Cutback 1). We interpret this exposure to represent gravity driven material falling or sloughing from unstable fissure walls near the ground surface and infilling the fissure. E1-1906 later ruptured along the same fault, extending displacements upward into unit 200b. Although this in itself is weak evidence for E3, E3 is also expressed in Trench 8 as warping of unit 400, with unit 300b and 300c apparently deposited against this fold scarp.

Evidence of Event E4

Evidence for the oldest event, E4 was identified in trench T8. This event is expressed as upward fault terminations within the oldest gravel unit 500, and as a gravel filled fissure which incorporated gravels from the overlying unit, 500, in the fissure fill. The gravel filled fissure was observed on the south wall of trench T8 near station 3 (Plate 2). These observations reveal event E4 occurred after deposition of unit 500, and prior to deposition of overlying unit 400.

3.3 Event Timing

Pollen analysis of the stratigraphic unit overlying the penultimate event horizon revealed that the penultimate event predated the regional occurrence of a non-native species *erodium cicutarium* (Common Stork's-bill) and roughly predates the year 1770 AD (Table 2). Thus, the penultimate event at the Hazel Dell Road is prehistorical and not the elusive 1838 earthquake as has been suggested by Toppozada and Borchardt (1998).

Preliminary radiocarbon dating suggests that the penultimate earthquake, E2, occurred after A.D. 1280 – 1637, and 1 to 2 paleoearthquakes (events E3 and E4) have occurred after A.D. 674- 874 (Table 1, Figure 8).

Based on this very preliminary data, we suggest that 1.) The penultimate earthquake observed at Arano Flat-Mill Canyon did not rupture as far north as Hazel Dell Road and 2.) The timing penultimate event observed at Hazel Dell Road permissively overlaps with the penultimate event at Grizzly Flat and the third event at AF-MC (Figure 9). However,

additional dating is necessary to adequately test these correlations. Fumal and others (2003) show that, due to age inheritance issues associated with detrital charcoal in similar environments, many (>10) samples *per unit* may need to be dated before the event age can be confidently determined.

4.0 SAS EVENT TIMING AND RUPTURE MODELS

A synthesis of previous studies on the Santa Cruz Mountains segment (SAS) of the San Andreas fault suggests that the SAS may be characterized by a multi-modal behavior in how strain is released through time along this segment. One mode of strain release, observed historically, is through large multi-segment earthquakes, with moderate seismicity and creep dominating the interseismic period between these large earthquakes within the northern transition zone between the locked portion of the SAS and the creeping section. The 1906 earthquake can be regarded as one of these large multi-segment earthquakes that dominates the moment budget of the fault. During the period prior to 1906, analysis of the historic record suggests that the SAS was characterized by moderate seismicity, with six M≥ 6 earthquakes between 1840 and 1899 (Toppozada and others, 2002), all located along the southern half of the segment. Additional observations of creep, and moderate and microseismicity have continued to the present, with the majority of this activity largely restricted to the southernmost part of the SAS.

Existing data from two sites, combined with preliminary results from this study, the Hazel Dell site suggest an additional mode of behavior in the paleoseismic record. Fumal and others (2003) document nine earthquakes (including 1906) during the past ~1000 years at the AF-MC sites. Preliminary age results for the Hazel Dell site reveal that the penultimate event occurred between A.D.1280-1637, and two to three earlier events occurred since A.D. 674 to 874 (2σ calibrated ages). Figure 9 summarizes the results of OxCal generated event ages and shows that the recurrence of surface rupturing earthquakes is about 105 years at the southern AF-MC sites. Of particular importance to this discussion is that the timing for the penultimate earthquake at the AF-MC sites is constrained to be between AD 1720-1790, with a third event between AD 1600-1680.

The Grizzly Flat site, located 14 km northwest of Arano Flat site, records two earthquakes: The 1906 earthquake and a prior earthquake constrained to have occurred AD 1632-1659 (Schwartz and others, 1996). Schwartz and others (1996) argue that the paleoseismic record at Grizzly Flat is complete for these past two earthquakes. Figure 9 is a time-space diagram that compares the ages of the earthquakes between the three sites. Although the record at Grizzly Flat is much shorter than that of AF-MC, there is a striking observation that can be made: The Grizzly Flat paleoseismic record does not record the penultimate earthquake observed at AF-MC. If this is correct, then the combined paleoseismic record for these two sites suggests an additional mode of behavior not seen in the historic record: *A moderate to large surface-rupturing earthquake that is restricted to the southern-most part of the SAS southeast of the Grizzly Flat site*. However, it is apparent that better event age control at the Hazel Dell site is needed in order to better constrain the penultimate event age and evaluate whether the penultimate event identified at this site agrees with the event at GF or AF-MC.

An additional observation that can be made between these sites if the age range for the penultimate event at Grizzly Flat and Hazel Dell does overlap with the third event at AF-MC. If these events are the same, then this would be similar to what occurred along the

SAS in 1906, for at least a larger part of the SAS, if not a repeat of 1906 itself, as argued by Schwartz and others (1996). These observations suggest that: 1.) The fault has failed in the past as large, multi-segment ruptures, such as 1906 and a possible mid-1600's event and 2.) The SAS also fails in smaller sub-segment ruptures, one of which occurred in the mid-1700's, with the northern termination of rupture somewhere to the southeast of the Hazel Dell site.

Recent geodetic modeling by Johanson and Bürgmann (2005) using GPS and InSAR has provided additional information that further characterizes the behavior of the SAS and suggest a possible reason that could explain the existing paleoseismic data and this apparent bi-modal behavior. They identify a 45 km-long northern transition zone between the creeping section of the San Andreas fault south of San Juan Bautista and the fully locked portion of the SAS. This section of the fault, named the San Juan Bautista (SJB) segment, includes a 12 km-long section at the northern end of the SJB characterized by a creeping section that was the source area for an observed slow earthquake in 1996. This creeping section of the fault is sandwiched between the fully locked SAS to the north and a locked asperity to the south, located north of San Juan Bautista. This asperity is suggested to be the source location for future moderate to large earthquakes and when combined with another asperity located south of San Juan Bautista, Johanson and Bürgmann (2005) estimate that the locked patches are currently running a moment deficit at the rate of one M 6.3 – 6.7 earthquake per century. This rate implied by the moment deficit is tantalizingly similar to the average recurrence interval at the Arano Flat - Mill Canyon sites and suggests that the AF-MC paleoseismic record may also record earthquakes along the northern transition zone.

The observations from the GPS/InSAR inversions, the historical and paleoseismic records leads to several fundamental questions with implications to seismic hazards for both the Santa Cruz area as well as the San Francisco Bay Area. First, is this bi-modal behavior typical for the SAS? Additionally, for events prior to the mid-1600's, which of the events observed at AF-MC are restricted to the southern-most part of the SAS and which earthquakes represent larger, full segment or multi-segment ruptures? Given that the AF-MC site lies only 5 km northwest of the part of the SJB characterized as only being partially locked, is it possible that the record at AF-MC represents earthquakes restricted to the transitional zone and partially rupture into the locked portion of the SAS, but do not rupture as far as Hazel Dell?

5.0 CONCLUSIONS

Our preliminary results suggest that the rate of surface rupturing earthquakes at the Hazel Dell Road site is significantly less than what is recorded at the AF-MC site. However, the rate of earthquakes (3 intervals in 1032 to 1232 years or more) is somewhat more than past Working Groups model from assumptions about slip rate (RI = 224 yrs, WG02). Additional age dating of events and more extensive paleoseismic investigations at the Hazel Dell site will allow us to evaluate whether larger and more frequent events are produced with recurrence intervals of ~100 years as suggested by Fumal and others (2003), or if this section of the fault produces larger and less frequent earthquakes, as modeled by past Working Groups. This could significantly change the estimates of seismic hazard and earthquake probabilities than what is currently modeled for the SAS. Therefore, it is essential that additional data on the timing of earthquakes be developed at the Hazel Dell site in order to extrapolate the extent of surface-rupturing earthquakes on this segment of the San Andreas fault.

6.0 ACKNOWLEDGEMENTS

The authors would like to thank the property owner David Dent for allowing us to conduct this investigation and for his continued interest in our results. We thank Carol Prentice, David Schwartz, Suzanne Hecker and Stephen Thompson for their thoughtful field review and insightful discussion of event evidence. We are grateful to Chris Madden, Danielle Verdugo, Courtney Streig and Long-sheng Lee for their assistance in the field.

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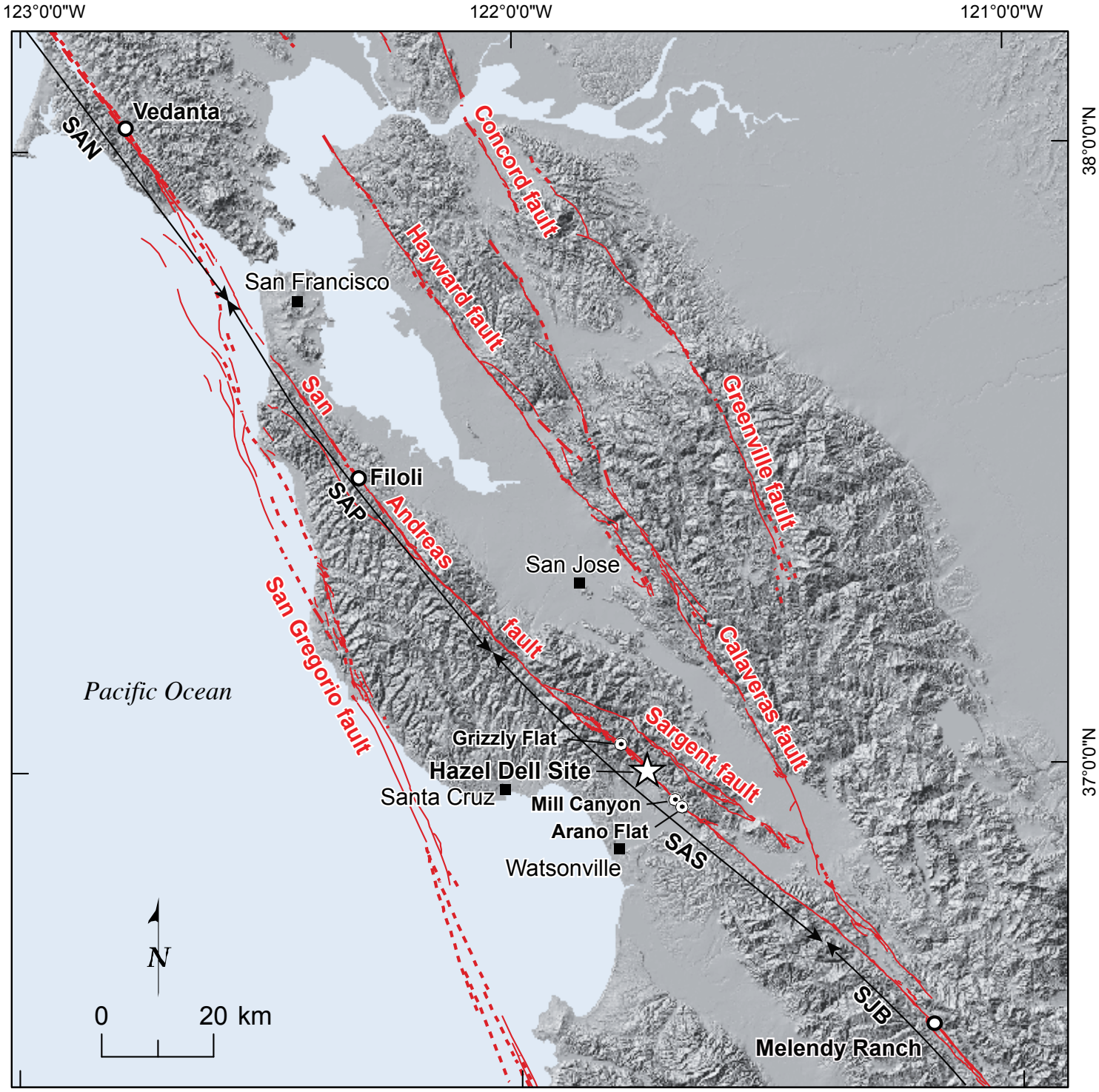
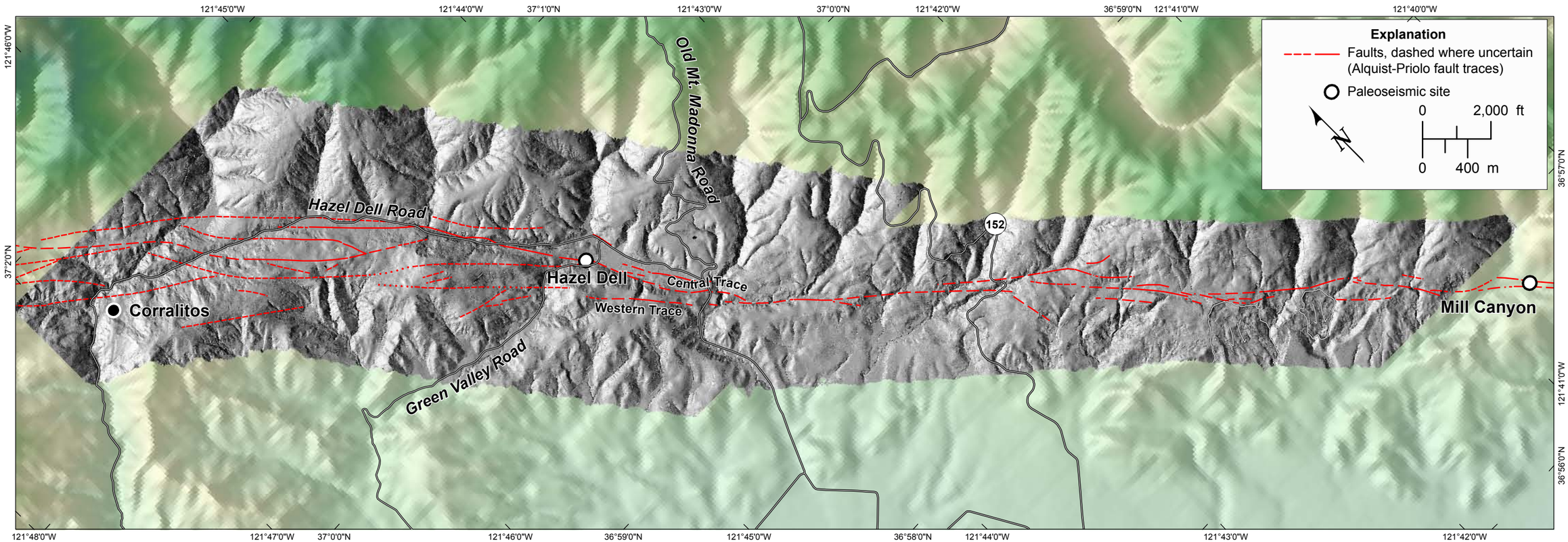
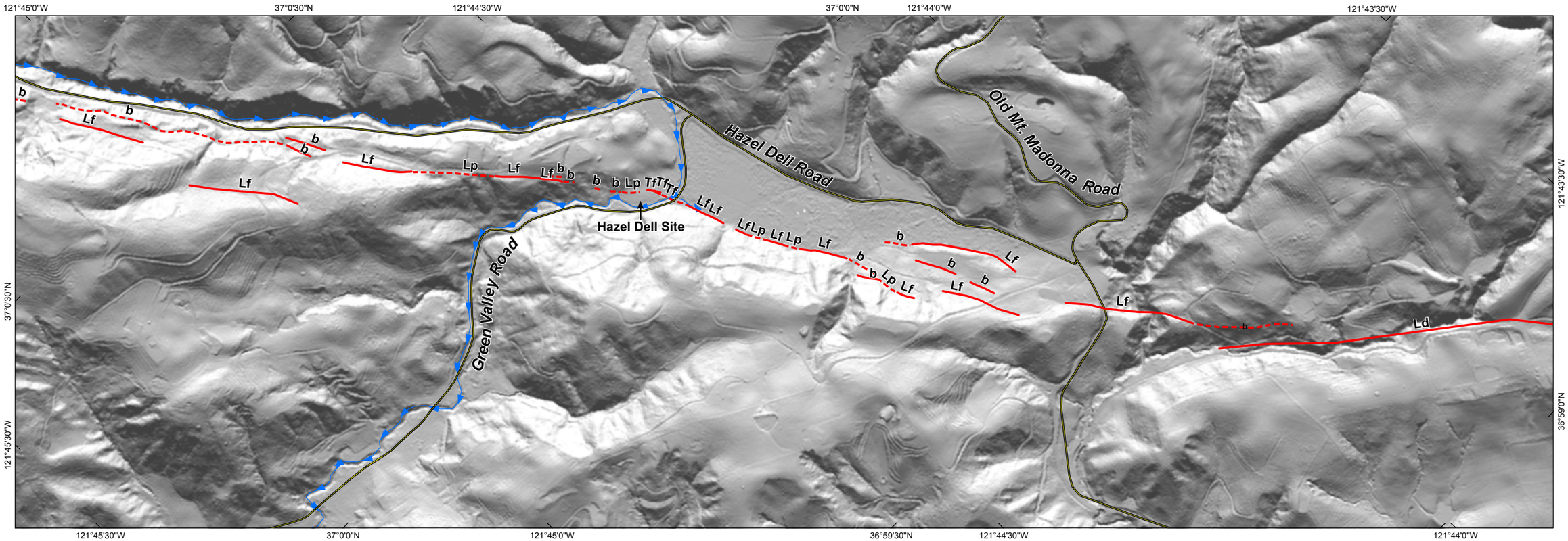


Figure 1. Location map showing the Santa Cruz Mountains section (SAS) of the San Andreas fault



Basemap: shaded relief compiled from GeoEarthScope 0.5-meter resolution LiDAR data.

Figure 2. Strip map of Alquist Priolo traces for the San Andreas Fault along the central Santa Cruz Mountains.



Basemap: shaded relief compiled from GeoEarthScope 0.5-meter resolution LiDAR data.

Explanation

Symbols

Fault; dashed where approximate (fault traces mapped from LiDAR, this study)

Stream, arrows show flow direction

Geomorphic Features

Ld – linear drainage
Lf – linear range front / base of slope
Lp – lineations projected across slump blocks or cultural features
b – break in slope
Tf – trench fault exposure

0 1,000 ft
0 200 m

Figure 3. LiDAR strip map of the Hazel Dell Road area (central SAS)

Figure 4. Google Earth 3D aerial image of the Hazel Dell Road area.

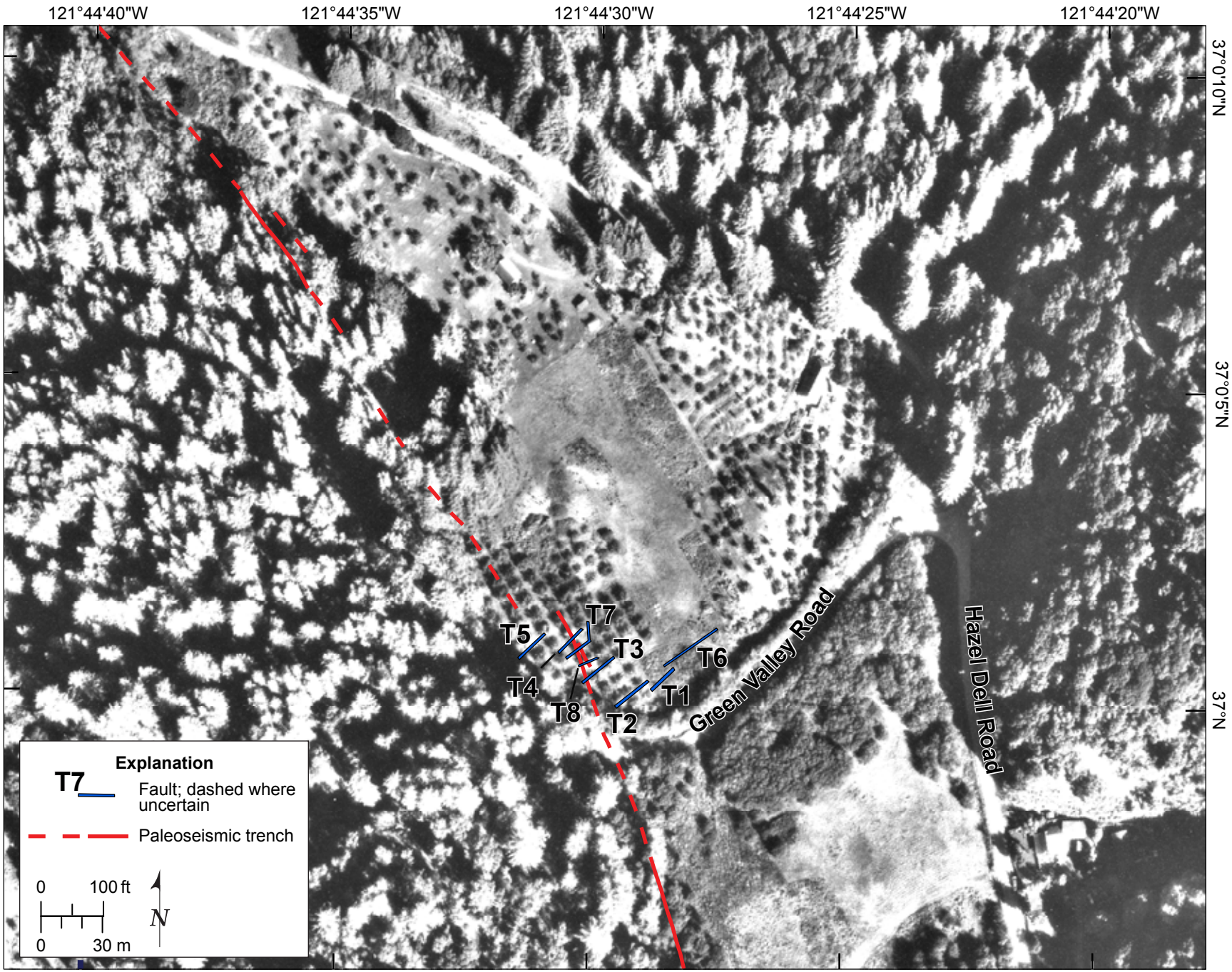
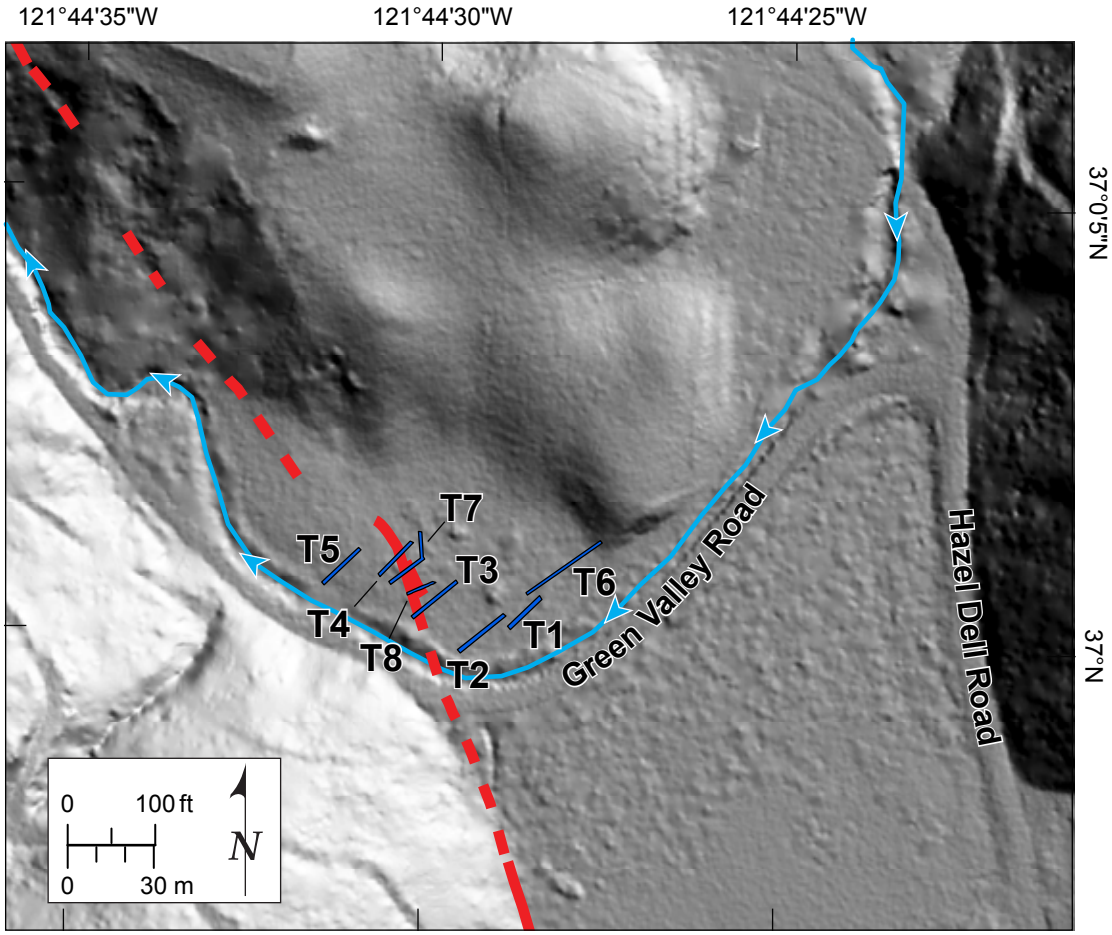


Figure 5. Aerial photograph of the Hazel Dell Road area, (1989 vintage photograph, original image 1:6,000 scale).

1959 Hazel Dell



Basemap: shaded relief compiled from GeoEarthScope 0.5-meter resolution LiDAR data.

Explanation

T7 — Fault; dashed where uncertain

Paleoseismic trench

Green Valley Creek, flow direction

Figure 6. Hazel Dell site trench location map.

A)

B)

Figure 7. Photographs of trenches, A) photograph of trenches 1 through 6, looking southeast. B) Photograph of fault trenches 4, 7 and 8, looking southwest.

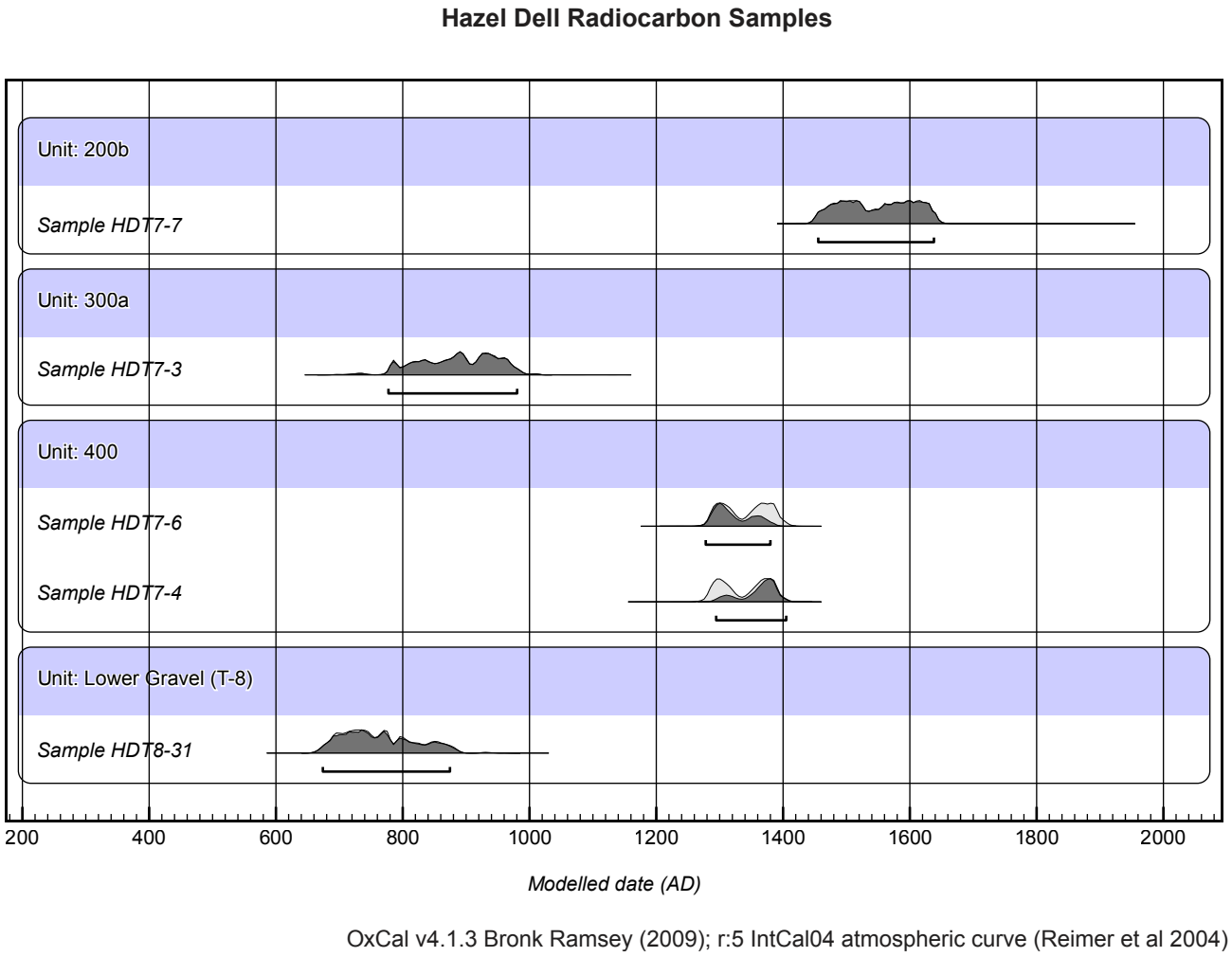
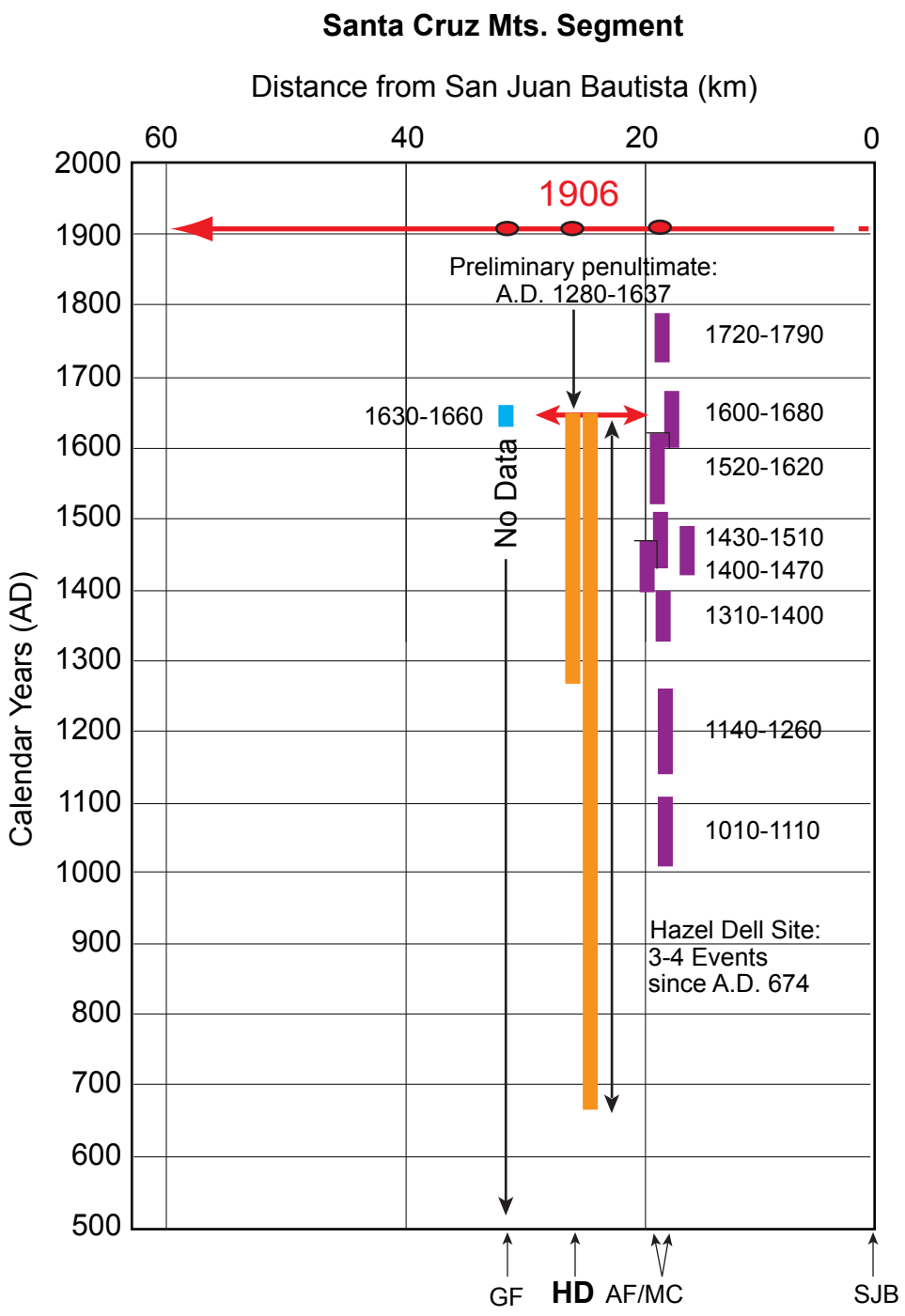


Figure 8. Probability-distribution functions (PDF) for radiocarbon ages.

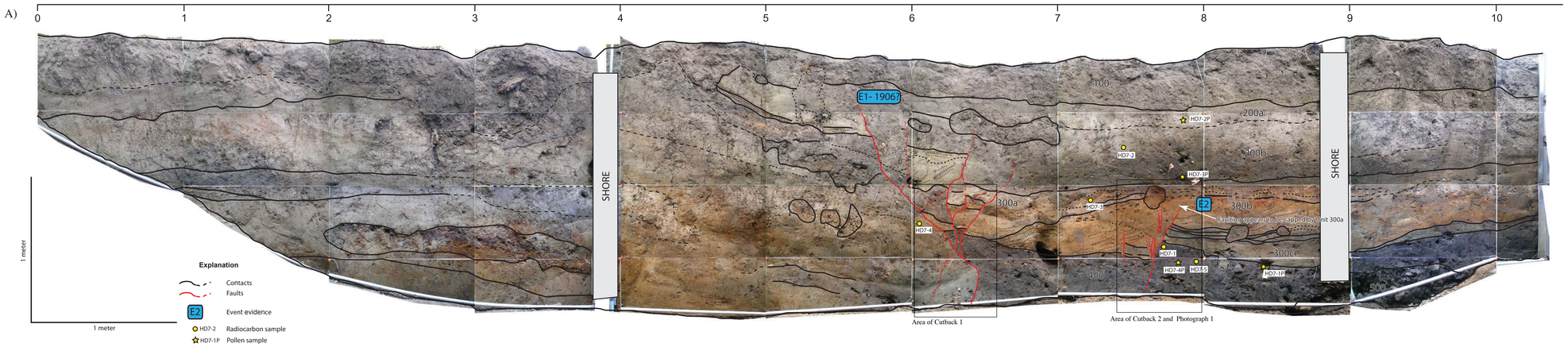


GF = Grizzly Flat, HD = Hazel Dell (This study), AF/MC = Arano Flat-Mill Canyon, SJB = San Juan Bautista. Red lines = correlations between sites. Note that there is no correlation for the mid-1700's event at AF/MC.

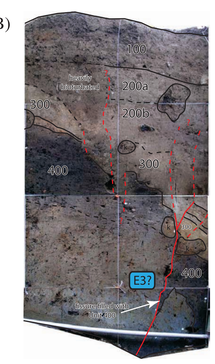
Figure 9. Time-space diagram for the SAS.

Hazel Dell Road Trench 7 - North Wall

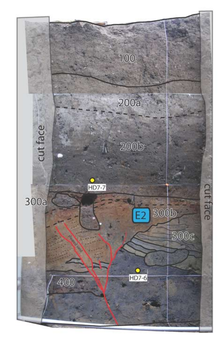
A)



B)



Cutback 1 - Trench T-7, north wall - 10 cm cutback exposure of E3?



Cutback 2 - Trench T-7, north wall - 10 cm cutback exposure of E2

Photograph 1 - Trench T-7, north wall - photograph of E2

Hazel Dell Road Trench 7 - South Wall

C)

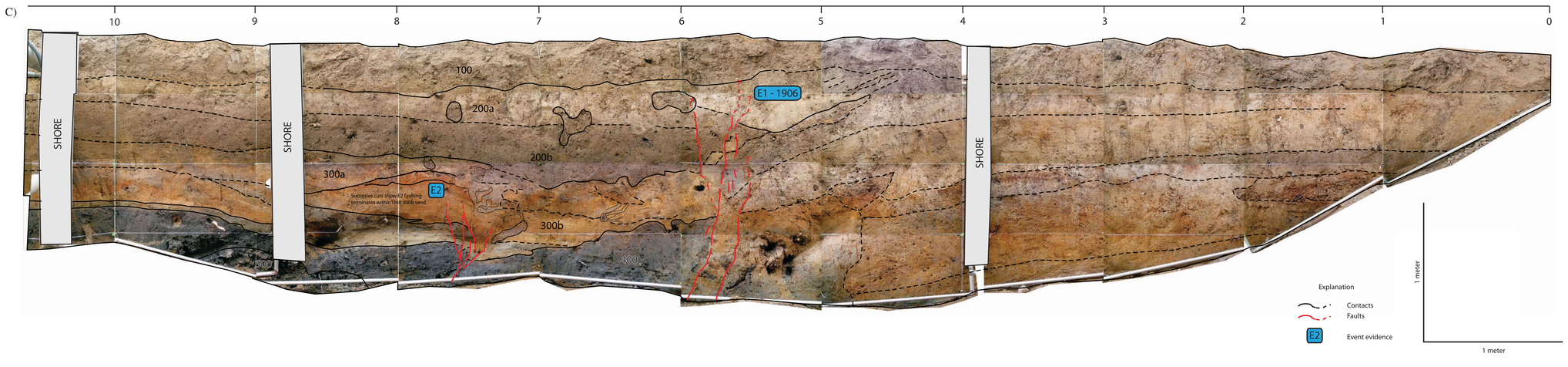
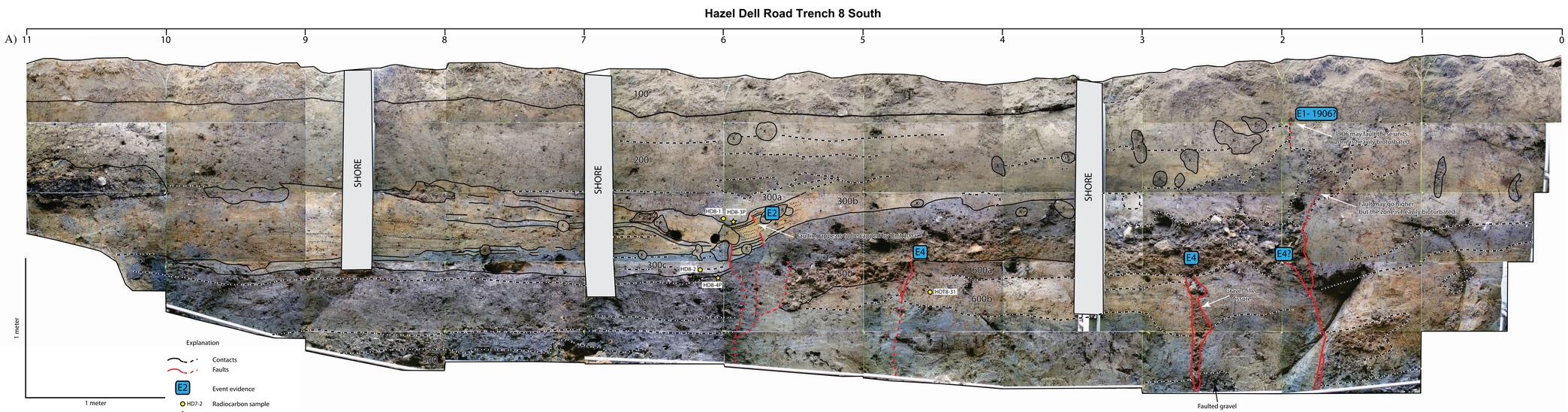


Plate 1. Photo mosaic trench logs, A) Trench 7 north wall, B) 10cm cut-back north wall exposures of E2 and E3, C) Trench 7 south wall



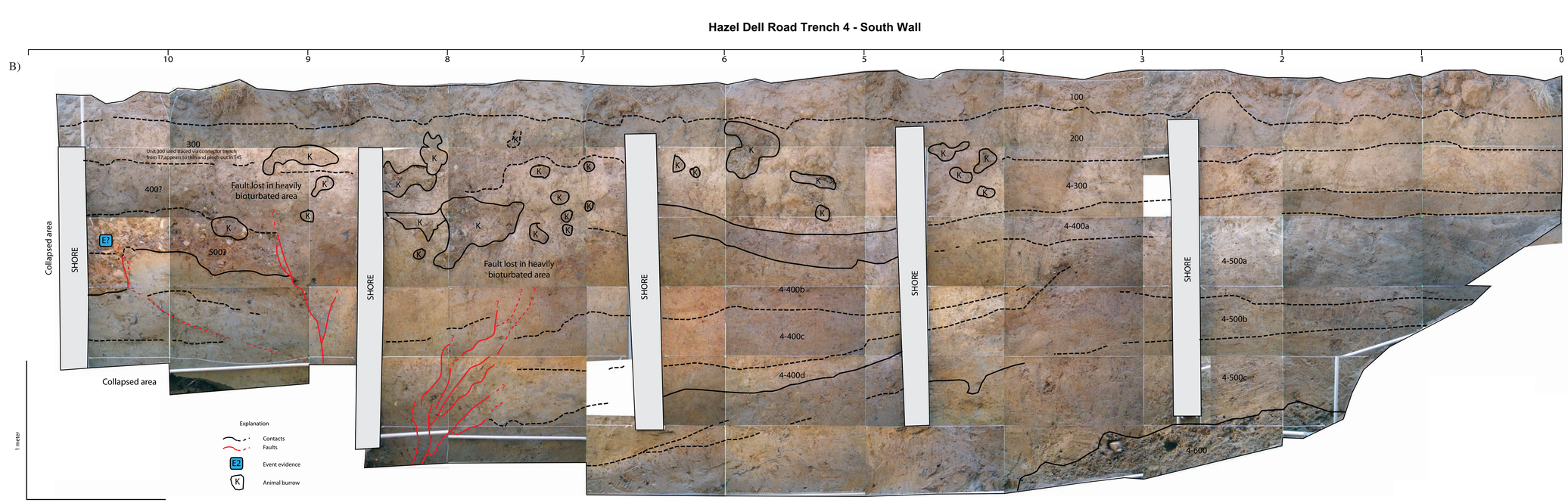


Plate 2. Photo mosaic trench logs, A) Trench 8 south wall, B) Trench 4 south wall.