FINAL TECHNICAL REPORT

Determining Earthquake Recurrence and Slip Over the Past 3 - 4 events on the Southern Santa Cruz Mountains Segment of the San Andreas Fault: Collaborative Research between Geological Sciences, University of Oregon and the California Geological Survey.

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ABSTRACT

The Santa Cruz Mountains section (SAS) of the San Andreas fault last ruptured during the 1906 earthquake, an event that ruptured about 470 km, from Point Arena to San Juan Bautista, California. Paleoseismic studies on the SAS at the Grizzly Flat (GF) and Arano Flat – Mill Creek (AF-MC) paleoseismic sites provide evidence of 1906 surface deformation, but have yielded differing records of prehistoric surface-fault ruptures. GF is located 14 - 21 km northwest of the MC-AF sites (respectively) and records one 17th Century earthquake dated between 1632-1659 (Schwartz and others, 1998). The record at MC includes four earthquakes in the last 500 years; 1906, a penultimate earthquake between AD 1711 – 1770 or AD 1789-1904, with a third event between AD 1660-1720 (Fumal, 2012).

The Hazel Dell site is located between the MC - AF and GF sites. This site has yielded good evidence of the most recent earthquake the 1906 surface rupture (E1), and 3 to 4 earlier events, including new evidence for two 1800's earthquakes. Evidence for the penultimate event, E2, is expressed as upward fault terminations within a massive sand infilling a topographic low. This sand infilled a depression formed by the pre-penultimate earthquake, E3. We identified axe-cut wood stratigraphically below the pre-penultimate earthquake horizon, which suggests that surface rupturing earthquakes E2 and E3 occurred after deposition of the cut wood stratigraphic unit. Lumber harvesting began in the area, around 1832, which demonstrates that earthquakes E2 and E3 are historical. Based on the presence of axe-cut wood and the generation of a thick sediment filled depression during E3, the stratigraphic record at Hazel Dell appears more complete during the early historical period than at the AF and GF sites. These new event data for the SAS suggest more frequent surface rupturing earthquakes within historical time than previously recognized.

The data require at least two modes of behavior in strain release through time. One mode of strain release, is through large multi-segment earthquakes; the 1906 earthquake was a large multi-segment earthquake 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 a second mode, characterized by moderate seismicity, with six M≥ 6 earthquakes between 1838 and 1890 (Bakun, 1999), all located along the southern half of the segment near the Hazel Dell study area. The two 1800's earthquakes identified in this study support this second mode of moderate seismicity on the SAS.

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1.0 INTRODUCTION

This report presents 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; 37°N, 121°44’30”W). The objective of this project was to develop paleoearthquake timing and recurrence data at the Hazel Dell (HD) site. This site is located between the Grizzly Flat paleoseismic site of Schwartz and others (1998) (located about 6 km northwest of HD) and the Mill Canyon paleoseismic site (about 8 km southeast of HD) of Fumal (2012). The record at MC suggests 4 earthquakes in the past ~500 years (Fumal, 2012). Grizzly Flat records 1906, and at least one previous earthquake dated between A.D. 1632-1659, although Fumal (2012) identifies two possible additional earthquakes dated between 1733 – 1906. By comparing the earthquake records at HD with MC and GF, we will refine our understanding of the behavior of surface rupturing earthquakes on this part of the SAF.

This project is a continuation of work started in FY2008 at the Hazel Dell site. We received NEHRP funding to continue work at Hazel Dell and we returned in 2010 and 2011 to re-excavate trenches from 2008 and excavate new trenches to find additional evidence of events identified in FY2008, look for older events, and explore the site for buried channels for slip rate and slip per event data. All trenches were photo-logged and trenches and exposures were surveyed using a total station.

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 (WG07, 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 locations of the M 6.9 1989 Loma Prieta earthquake and the active Sargent fault (Figure 1). Additionally, immediately south of the SAS at Melendy Ranch the San Juan Bautista section (SJB) is creeping at a rate of 22 mm/yr (Perkins et al., 1989; Figure 1), and has a slip deficit of ~12 mm/yr less than the long term rate to the south. Earthquakes may initiate on the creeping section and extend to the southern potion of the SAS, essentially acting as a transition zone between the locked and creeping sections (Johanson and Bürgmann, 2005).

Historically, the SAS last ruptured during the **M** 7.9 1906 earthquake that produced about 470 km (300 mi) of surface rupture from Point Arena to San Juan Bautista. The **M** 6.9 1989 Loma Prieta earthquake didn’t rupture to the surface and is 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 the SAS section.

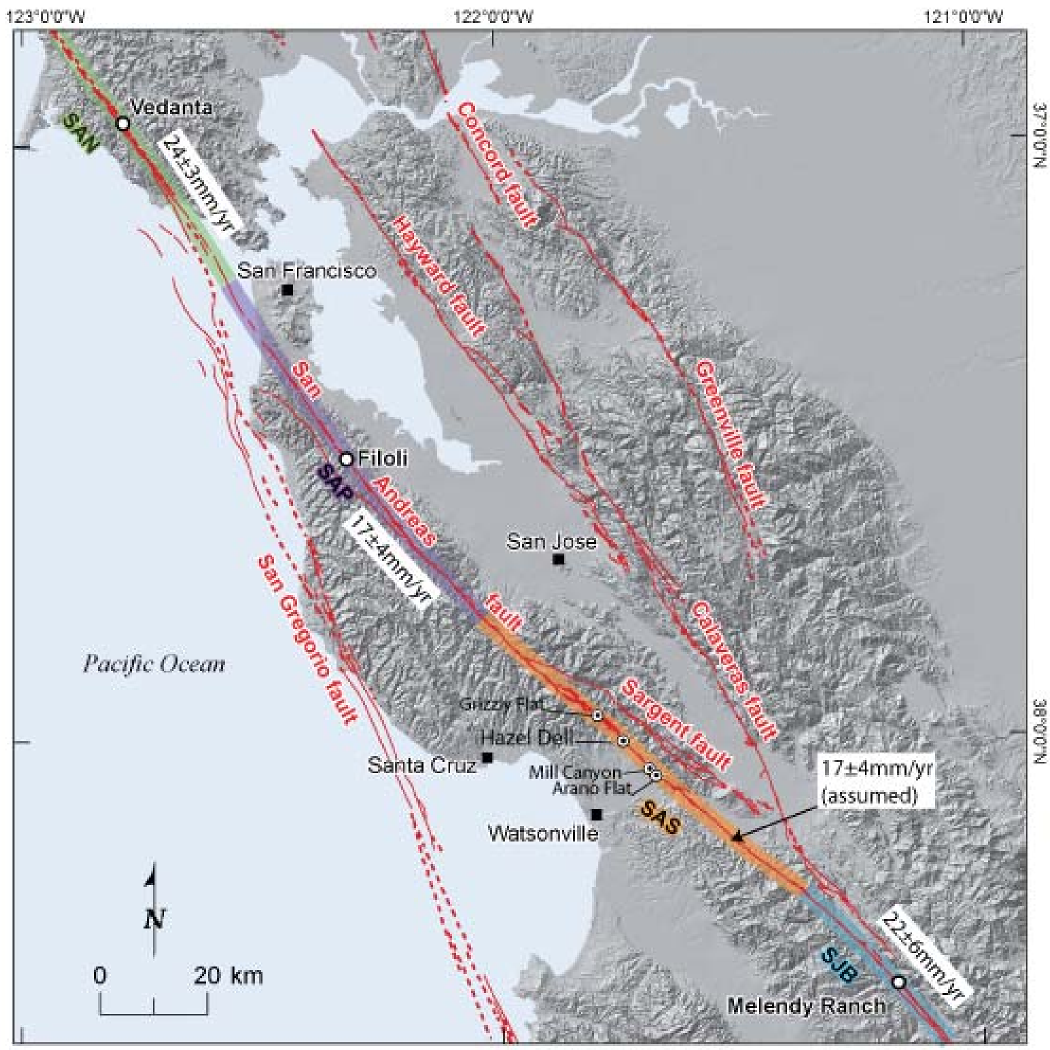


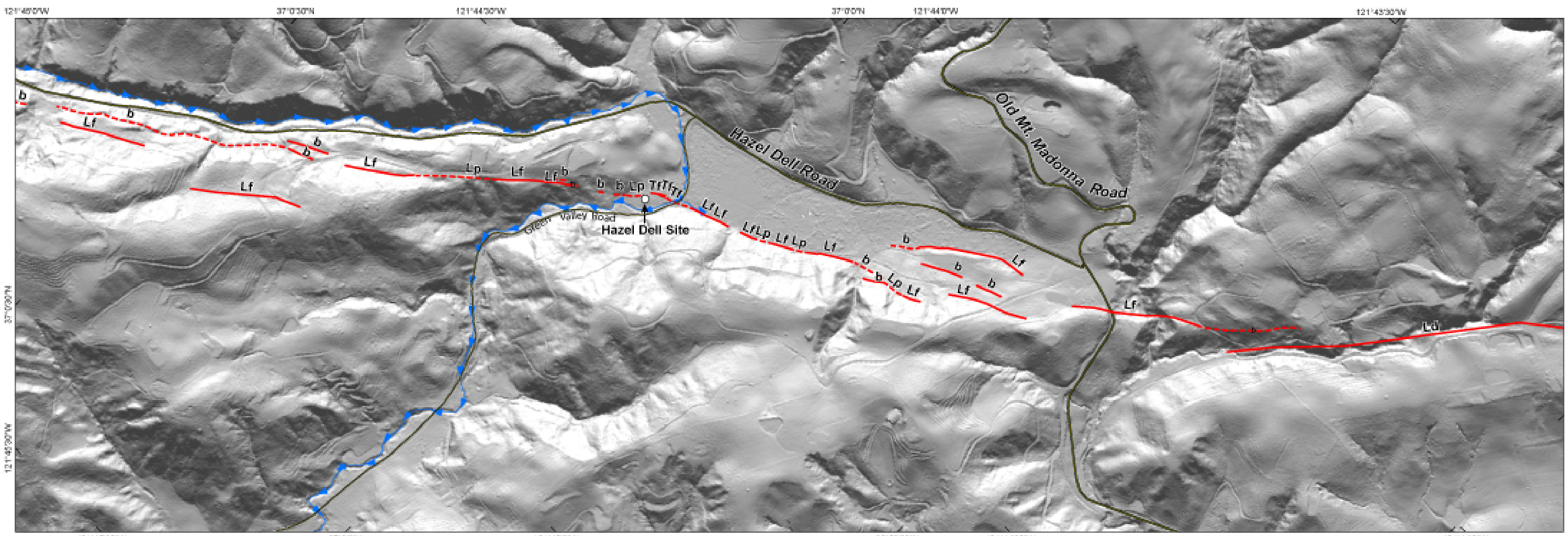
Figure 1. Location map showing the Santa Cruz Mountains section (SAS) relative to San Andreas fault sections to the north and south (North Coast section (SAN), Peninsula section (SAP) and the creeping section (SJB)) and other principal Bay Area faults. Paleoseismic investigation sites along the SAS are shown as closed circles and include (from N-S) Grizzly Flat, Hazel Dell - Simas Lake, Mill Canyon and Arano Flat sites. Geologic slip rate sites are shown as open circles and include: Vedanta on the North Coast section, Filoli on the Peninsula section and Melendy Ranch on the creeping section. Slip rates determined at these sites and adopted by WGCEP 02 and 07 are shown in white boxes.

2.0 HAZEL DELL ROAD PALEOSEISMIC INVESTIGATION SITE

2.1 Site Geology

The SAF in the Hazel Dell area 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 Formation 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). The fault 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 by mapping features on 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 2). Using these data we were able to map small scale (<1m relief) fault features projecting into the investigation site. Immediately north-northwest of the site, located within a stand of redwoods, LiDAR data reveals that 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 2). We projected these features across the investigation site in order to choose exploratory fault trench locations.



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

2.2 Geomorphology of the SAF in 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 (Figure 3). These ponds dry to the north and transition to a seasonal marsh, this transition coincides with a slight rise in elevation as the valley tapers and ends to the north near Green Valley Road (Figure 3). Some years the ponds dry completely. The Hazel Dell site is located north of Simas Lake at the distal end of the valley where a small ephemeral creek drains the basin occupied by the sag ponds.

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 hillslopes of the sandstone member of the Mt. Pajaro formation on the northeast. Green Valley Creek flows from the northwest, making an abrupt ~90° turn to the southwest, and flows due southwest out of the valley. The creek crosses the fault at the southwest corner of the site (Figure 2). The Hazel Dell site is within the floodplain and has been inundated by flood waters in 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 an apple orchard between roughly 1950 and 1980 (personal communication property owner, D. Dent, 2008). The ground surface has been tilled, disturbing 20 to 50 cm below the ground surface. These farming activities combined with historic overbank deposits sourced by Green Valley Creek obscure surface expression of 1906 surface rupture across the site.

Figure 3. Google Earth image Hazel Dell and Simas Lake, oblique view looking towards the northwest. The San Andreas fault runs along the base of the hillslope bounding the west edge of Simas Lake. Hazel Dell investigation site highlighted with white arrow.

3.0 RESULTS

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 4). Alluvial deposits were encountered in trenches; T1-5 and T7-16 (Figure 4). Moderately coarse-grained slope derived colluvium was only encountered in one trench, T6, where the trench traversed the west facing bedrock hillslope (Figure 4). Slope derived colluvium was observed to interfinger with fine-grained overbank alluvial deposits of unit 300 (described below).

Description of Stratigraphic Units:

Unit 700 is a massive greenish gray clay, observed only west of the structural depression (sag) bounding fault (Plate 1, Plate 2). The base of the unit was not exposed, however as much as 50 to 65 cm of unit thickness is exposed in trenches T8 and T10a (Plate 2 and Plate 3, respectively). This is the oldest unit observed and correlated between trenches.

Unit 600 is a silty clay coarsening upward to silty sand, and is divided into subunits 600a and 600b. 600a is a light gray silty sand to silt, with some brown to strong brown mottles. This unit has a gradational basal contact to unit 600b. Unit 600b is light gray clayey silt to silty clay with common brown to strong brown mottles in the upper 15 cm. the basal contact is sharp over 5cm, and wavy. Unit 600a is discontinuous, and directly underlies the gravel unit 500. Unit 600a ranges between 10 to 15 cm thickness, where preserved, and unit 600b is 20 – 30 cm thick in trenches T8 and T10a. These units are observed west of the depression-bounding fault, and are correlated between trenches. Unit 600b has an OxCal modeled age of A.D. 717 – 974 (Figure 6).

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). Unit 500 is 20 to 35 cm thick west of the fault, the base of the unit was not exposed east of the western sag-bounding fault. This unit unconformably overlies unit 600a and 600b.

Unit 400 is a massive gray to black clayey silt with abundant detrital charcoal fragments, this is subdivided into units 400a and 400b. The upper horizon, 400a (15-20 cm) is defined by a distinct dark gray to black color that grades downward to medium grey, it is massive to weakly laminated in areas with parted organic layers and abundant detrital charcoal. 400b is dark gray to gray blue clayey silt with lesser amounts of charcoal. The basal contact of the unit is slightly wavy and gradational over 5 to 10 cm. This unit represents fine-grained overbank alluvial deposits with strong organic development in unit 400a, the upper 20 to 30 cm of the deposit, is a buried soil and shows a period of marsh stability prior to deposition of the overlying sandy alluvial unit 300. Unit 400a is 5 cm thick west of the depression-bounding fault, and 8 – 20 cm thick east of the fault (Plate 1, Plate 2, Plate 3, Plate 4). Unit 400b is 20 to 30 cm thick where the base of the unit is exposed in T8 (Plate 2). Unit 400 has an OxCal modeled age range between A.D. 1268 – 1596.

Unit 300 is a light tan to grayish-orange silty sand to sandy silt and consists of three distinct alluvial deposits, subunits 300a, 300b and 300c. Subunit 300c is a massive to finely laminated light grayish yellow silty sand, within the structural depression in trench T10 the unit is interbedded very fine sand, silt and organic layers, with some angular axe-cut wood chips at the base of the unit. Unit 300c infills a depression formed on the unit 400a surface. 300c is 20 – 25 cm thick in trenches T7 and T8 (Plate 1, Plate 2), and thickens substantially within the depression. At its thickest it is 70 cm in T10a, unit thickness decreased in subsequent cuts northward to 50cm in cut T10f, (Plate 3, Plate 4). A piece of detrital charcoal sampled from the base of Unit 300c has an OxCal modeled age of A.D. 1534 – 1796, historical axe-cut wood chips were also found at the base of Unit 300c provide another age constraint (discussed in Deposit Age Estimates below). Subunit 300b is a massive to locally laminated and crossbedded tan to light orange silty sand. Unit 300b ranges from 15 to 30 cm thickness in all trench exposures. 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, is 10 to 25 cm thick, and is not preserved everywhere. Units 300a, b and c represent relatively low energy water-lain and marsh deposits.

Unit 200 is a light gray to grayish brown massive clayey silt with sand to coarse sand and consists of subunits 200a, 200b, 200c, 200d and 200f. Unit 200a is a light grayish brown silt, well sorted and massive, and is 10 – 25 cm thick. Subunit 200b is massive, contained abundant roots and rootlets and has a relatively planar basal contact that is gradational over roughly 5cm, and is 15 – 30 cm thick. 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. Unit 200c is massive, poorly sorted silt to coarse sand, this unit grades into 200d which has pockets of grain supported coarse sand along the base. Unit 200c is 35 cm thick in trench T10, and tapers to the north and south to 25 cm thickness in T7 and T8 (Plate 1, Plate 2). Unit 200d is only observed in trench T10 cuts A through F, and is 15 – 30 cm thick (Plate 3, Plate 4). Unit 200f is a medium to dark gray brown massive silty sand with a weak incipient soil developed. 200f is only observed in trench T10 A through F, and is 5 – 10 cm thick. Unit 200 reveals a depositional change from well-sorted laminated sands and interbedded silts, clays and organic layers of Units 300a, 300b and 300c, to higher energy, coarse grained, massive mud flow deposits of Unit 200. Unit 200f reveals that there was a brief hiatus in deposition of the unit 200 sequence, 200f was deposited and persisted at the surface long enough to develop a weak soil, then was subsequently buried by 200d through 200a.

Unit 100 represents agriculturally modified stratigraphy immediately below the ground surface including the depth of the till-zone and roots from former apple trees. This unit ranges from 30 to 40 cm thickness, and has a sharp (over 1 -2 cm) wavy basal contact.

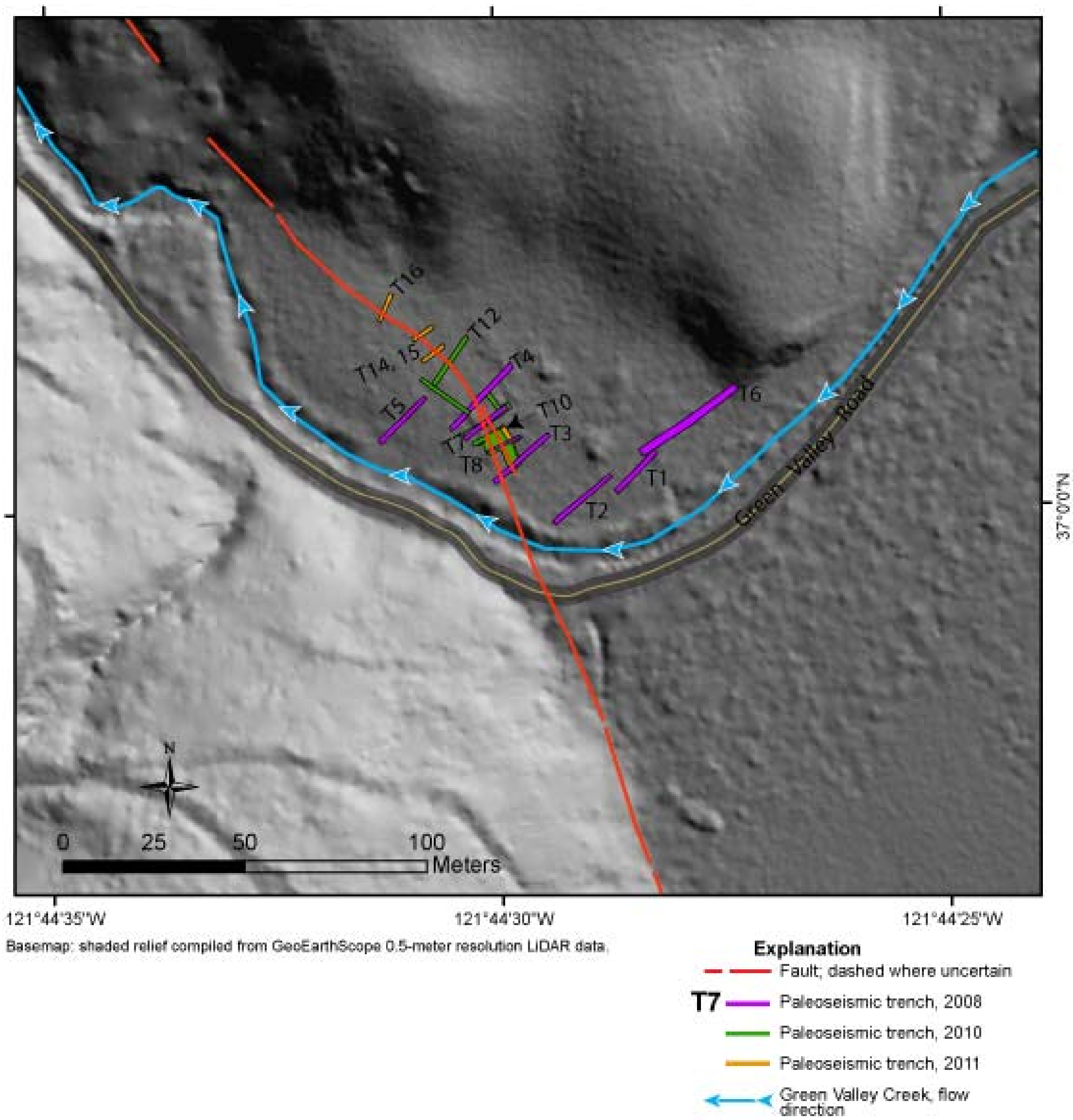


Figure 4. Hazel Dell site map showing the fault trace across the investigation site in red and the locations of 2008, 2010 and 2011 trenches.

Deposit Age Estimates:

The site revealed fine-grained stratigraphy, historical axe-cut wood chips (Figure 5), an abundance of datable material including organic stringers/peats, wood, marsh plants (tules), and detrital charcoal was collected from all stratigraphic units.

Figure 5. Four photographs of transverse axe-cut wood chips with a 15cm ruler for scale, collected from the upper few centimeters of unit 400a, and the base of unit 300c. Some fragments, such as the photo in the bottom left corner, have very fine 1-2mm width transverse cuts of opposing angles.

Axe-cut redwood chips were collected from the upper few centimeters of unit 400a, and within the base of unit 300c. The wood chips range in size from a few centimeters to >20 cm length. All wood chips collected at this horizon have very sharp, angular cuts transverse to the wood grain. These very sharp cuts reveal that the wood has not been transported a significant distance and is well preserved in its original cut shape. There are no known ethnographic or historical accounts of pre-contact native people chopping down large trees in the way that European colonists would have. Local indigenous populations didn't make large hafted axes needed to cut large trees (*Personal communication with Rob Cuthrell, Archeology graduate student UCB*). Redwood lumber harvest began in this area sometime around or before 1832, "Amesti is said to have had a whipsaw lumber mill in 1832 on the upper Corralitos ." (http://www.corralitoshistory.com/additions.html, on 1/20/2010). The timing of this lumber mill indicates that the earthquakes E2 and E3 are historical.

Detrital charcoal samples were also collected, and were prioritized for ^{14}C analysis based on the sample size and the location within the stratigraphic unit from which they were recovered. We selected nine detrital charcoal samples from key stratigraphic units for preliminary radiocarbon analysis (Table 1). We used OxCal (v. 4.1.3; Bronk Ramsey,

2009) to construct a chronological model first using just radiocarbon dates from detrital charcoal, and identified three samples that were out of stratigraphic order. We removed these from the final calibrated OxCal model, and included boxcar dates for historic information, such as the 1906 San Francisco earthquake, and an estimated age range between A.D. 1800 to 1900 for the wood chips at the base of unit 300c. Calibrated probability distribution functions for the six remaining samples are shown in stratigraphic order in Figure 6, along with estimated probability distribution functions for the timing of the four earthquakes identified at the site.

The success of the Hazel Dell site is largely attributed to the large depression caused by E3 that provided exceptional stratigraphic section to distinguish E2 from E3 below, and 1906 above, and the presence of historical artifacts at the base of unit 300c (in the form of cut wood, Figure 5), allowing us to assign the three most recent earthquakes to 1906 and two earthquakes in the 19th Century. However, the fourth earthquake is relatively poorly constrained, in part, because the radiocarbon dating relies on charcoal samples largely derived from redwood trees, which are long lived and also likely have a long residence time in the environment, leading to larger contextual dating uncertainties. This is an issue endemic to the Santa Cruz Mountains, as it is heavily forested and successful dating of earthquakes rely on large numbers of radiocarbon samples in order to examine the range of ages within a deposit (e.g. Fumal and others, 2003).

Table 1. Radiocarbon Samples: Hazel Dell

Sample Number	Laboratory Name	Stratigraphic Unit	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age *
HD 8-2	Beta - 264164	300c	310 ± BP	-23.9 o/oo	330 ± 40 BP
HD7-7	Beta - 254277	200b	330 ± 40 BP	-23.8 o/oo	350 ± 40 BP
HD7-2	Beta - 264162	200b	210 ± BP	-24.1 o/oo	220 ± 40 BP
HD7-3	Beta - 254274	300a	1160 ± 40 BP	-25.5 o/oo	1150 ± 40 BP
HD7-1	Beta - 264161	400a	550 ± 40 BP	-22.4 o/oo	590 ± 40 BP
HD7-4	Beta - 254275	400a	630 ± 40 BP	-23.9 o/oo	650 ± 40 BP
HD7-5	Beta - 264163	400a	300 ± 40 BP	-22.6 o/oo	340 ± 40 BP
HD7-6	Beta - 254276	400a	670 ± 40 BP	-26/7 o/oo	640 ± 40 BP
HD8-31	Beta - 254278	600b	1200 ± 40 BP	-21.9 o/oo	1250 ± 40 BP

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

3.2 Event Evidence

The Hazel Dell trenches revealed evidence of at least three 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.

Evidence of Event E1 – 1906

Evidence for the most recent event, E1, the 1906 rupture is expressed in trenches 7 and 8 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 and plough zone associated with an apple orchard at the site (Plate 1, Plate 2). E1 clearly displaces 200a, the uppermost mudflow unit (Plate 1, Plate 2).

Evidence of Event E2

The penultimate event places unit 200c in vertical fault contact with unit 300b, this relationship was exposed in multiple cuts of trench 10 (Plate 3 and Plate 4). Thickness changes across faults in multiple units that post date E3 formation of the structural depression was observed in T7, T8 and T10 (units 300a, 300b and 300c) across faults that do not extend upward or displace unit 200b.

Evidence of Event E3

Earthquake E3 occurred when organic rich unit 400a was at the surface. In Trench 8 a depression was formed by E3 and is expressed as folding of unit 400, with unit 300b and 300c deposited as an on-lap sequence against the fold scarp. E3 created a structural depression that is in-filled by stratigraphic units 300. The depression extends between trenches 7 and 8 and at its deepest has 1.6 meters vertical relief observed in trench 10 (Plate 4, trench 10 sequence), and tapers to 20 centimeters of vertical relief to the north and south in trenches 7 and 8 (Plate 1, Plate 2). On the north wall of Trench 10f, the depression is expressed as a < 1 m-wide fissure filled with alternating finely laminated sands and organic units that narrows with depth. Additional evidence for this event includes a small fissure filled with sediment from unit 400 (Plate 1; Part B, cutback 1, Trench 7 - 2008). The majority of the axe-cut wood chips are found resting on unit 400a at the base of unit 300c, and are also found in lesser amounts in the basal 20 cm of unit 300c. The wood chips were probably deposited shortly after E3, because the woodchips are localized within the structural depression and concentrated within the lowermost part of unit 300, with the majority resting in the deposit just above unit 400. Although the deposition of the woodchips appear to post-date the event, the time between the earthquake and the filling of the fissure is likely short, because of the relatively undegraded nature of the sides of the fissure and because the fissure is filled with stratified fluvial sediments, rather than blocks of material derived from unit 400.

Evidence of Event E4

Evidence for the oldest event, E4 was identified in trench T8, and T7. This event is expressed as upward fault terminations within the oldest gravel unit 500, and as upward terminating fissures which incorporated gravels from the overlying unit, 500, in the fissure fill. Gravel filled fissures were observed in trench T8 near meters 2, 3 and 4.5 (Plate 2). Event E4 occurred after deposition of the gravel, unit 500 and before units 400a and 400b were deposited.

3.3 Event Timing

We find evidence of four earthquakes, and enough exposure to suggest the last three events represent a complete record of surface-rupturing earthquakes since the formation of a buried soil on unit 400a. We identified axe-cut wood stratigraphically on the pre-penultimate earthquake horizon, which suggests that surface rupturing earthquakes E2 occurred after, and E3 is nearly coincident with deposition of the axe-cut wood stratigraphic unit. Logging began in this area by 1832, these units were deposited after lumber harvesting began in the area which suggests that earthquakes E2 and E3 are historical. Historical records indicate three local M > 6 earthquakes in this time period, a June 1838 event which had high intensities in the Santa Cruz and Monterey Bay region and is interpreted to have ruptured part of the Peninsula and a portion of the Santa Cruz Mountains sections (Bakun, 1999; Hall and others, 1999; Toppozada and Borchardt, 1998; Toppozada and others, 2002). An October 8, 1865 earthquake caused ground cracking in the Santa Cruz Mountains, and an April 24, 1890 earthquake in the region caused significant damage in the vicinity of Hazel Dell, from Corralitos south to San Juan Bautista (Bakun, 1999; Tuttle and Sykes, 1992), with reports of possible surface faulting near the Pajaro River (Bakun, 1999).

The June 1838 earthquake was the first major earthquake, M ~ 7 (or larger), since the founding of Mission San Francisco Dolores in 1776 (Toppozada and others, 2002). On the Peninsula segment at Filoli (Figure 1), Hall and others (1999) document channel deposits offset 4.1 m (±0.5). Based on observed offsets in 1906 of 2.4 meters 5 km north of the Filoli site, and observed offsets of 2.4 to 2.6 m in the town of Woodside, located ~9 km south of their site, Hall et al inferred the channel was offset by 2.5m (±0.2) in 1906 and 1.6m (±0.7) in a prior event, inferred to be the 1838 earthquake. Tuttle and Sykes estimated that the 1838 rupture extended from San Francisco to Hughes Creek, roughly 3 km south of the Hazel Dell Site, and 5 km north of the Mill Canyon Site (Fumal, 2012). Topozzada and Borchardt (1998) conclude that 1838 ruptured from near San Francisco to San Juan Bautista, the entirety of the SAS. At the Mill Canyon site, near Watsonville and 8 km south of Hazel Dell, Fumal (2012) interprets evidence of the penultimate earthquake, in the form of a large fissure 1m wide and 1.5 meters deep which produced a much larger fissure than those associated with the 1906 event horizon at the site. Based on his dating, the earthquake was either a late 18th Century earthquake, or more likely given the stratigraphic relations and historical constraints, a 19th century earthquake, probably the 1838 earthquake. Similarily, at Hazel Dell, our E3 formed a ~ 3 m long, 2 m wide fault bound- depression, with similar amounts of deformation. The E3 earthquake horizon and overlying units incorporate historical artifacts (axe-cut wood chips) which places this event in the historic, post-European time period. 1838 is the largest event reported in historic time for the area, and best explains deformation associated with our event E3, deformation at our site is similar to that observed at Mill Canyon for MC-2, which Fumal (2012) interprets to be 1838.

The October 8, 1865 earthquake was most destructive in the Watsonville - Santa Cruz - San Jose area (Toppozada and others, 2002). McNutt and Toppozada (1990) and Tuttle and Sykes (1992) found that the 1865 earthquake was smaller than the 1989 Loma Prieta earthquake, which occurred along a 70° southwest-dipping blind reverse fault. Tuttle and Sykes (1992) reviewed felt reports for the 1865 event and found grater damage northeast of the SAF than in 1989, and concluded that the event occurred on a reverse fault northeast of the SAF and assigned the event M ~6.5. This result is consistent with later analysis by Bakun (1999).

The April 24, 1890 earthquake has an estimated M 6 by Toppozada and others (1981), M ~6.3 by Bakun (1999) and Tuttle and Sykes (1992). This event caused significant damage at Corralitos, Green Valley, Pajaro, San Juan Bautista and Sargents (Bakun, 1999). Surface cracks observed in 1890 were located on the trace of the SAF where offset was observed in 1906 (Bakun, 1999). Given these reports we conclude that E1 is 1906, E2 could be either 1890 or 1865, and that E3 could be either 1865 or 1838 historic earthquakes.

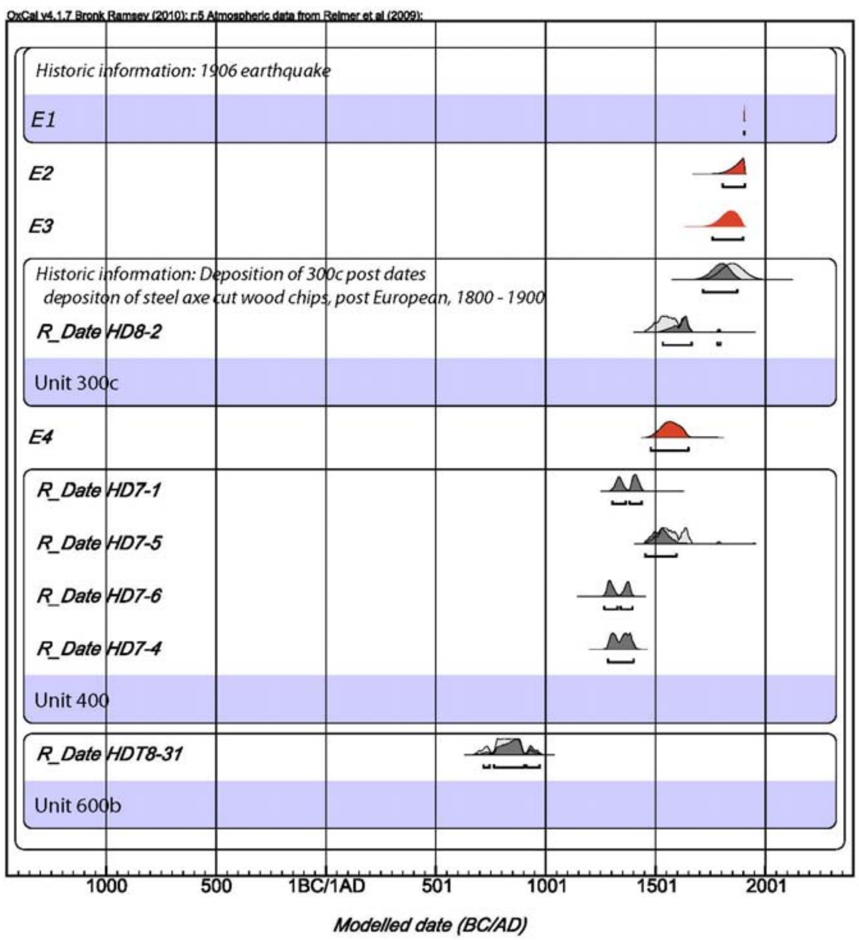


Figure 6. OxCal model of stratigraphic ages constraining the timing of earthquake horizons at the Hazel Dell site. Prior Probability distribution functions (pdf's) for radiocarbon samples shown in light gray, posterior pdf's shown in dark gray. Unit numbers shown on the light blue bars. Modeled earthquake ages shown by red pdf's and labeled by event name.

4.0 SIGNIFICANCE OF RESULTS

The Hazel Dell (HD) site, on the Santa Cruz section of the San Andreas fault (SAF), has yielded good evidence of the 1906 surface rupture, and three earlier earthquakes in the form of filled fault bounded depressions, upward terminations, and stratigraphic thickness changes. Evidence for E1, the 1906 earthquake, consists of faults that extend to the base of unit 100, a unit characterized by bioturbation and agricultural use. Evidence for the penultimate event, E2, is expressed as upward fault terminations within a massive sand infilling a topographic low. This sand was deposited within a depression formed by the pre-penultimate earthquake, E3. Earthquake E3 formed a structural depression, or sag, roughly 3 meters long and 2 meters wide with as much as 1.5 meters vertical relief at the apex of the sag.

We identified milled wood stratigraphically coincident with the pre-penultimate earthquake horizon, which suggests that surface rupturing earthquake E2 occurred after deposition of the milled wood stratigraphic unit, and E3 occurred either immediately after the wood chips were deposited on the surface. Logging began in this area sometime around or before 1832, these units were deposited after lumber harvesting began in the area which suggests that earthquakes E2 and E3 are historical. Based on the presence of milled wood, the stratigraphic record at Hazel Dell appears more complete during the early historical period than at the AF and GF sites. These new geologic event data for the SAS suggest more frequent surface rupturing earthquakes within historical time than previously recognized.

5.0 CONCLUSIONS

The data require at least two modes of behavior in strain release through time. One mode of strain release, is through large multi-segment earthquakes; the 1906 earthquake was a large multi-segment earthquake 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 a second mode, characterized by moderate seismicity, with six $M \geq 6$ earthquakes between 1838 and 1890 (Bakun, 1999), all located along the southern half of the segment near the Hazel Dell study area. The two 1800’s earthquakes identified in this study support this second mode of moderate seismicity on the SAS.

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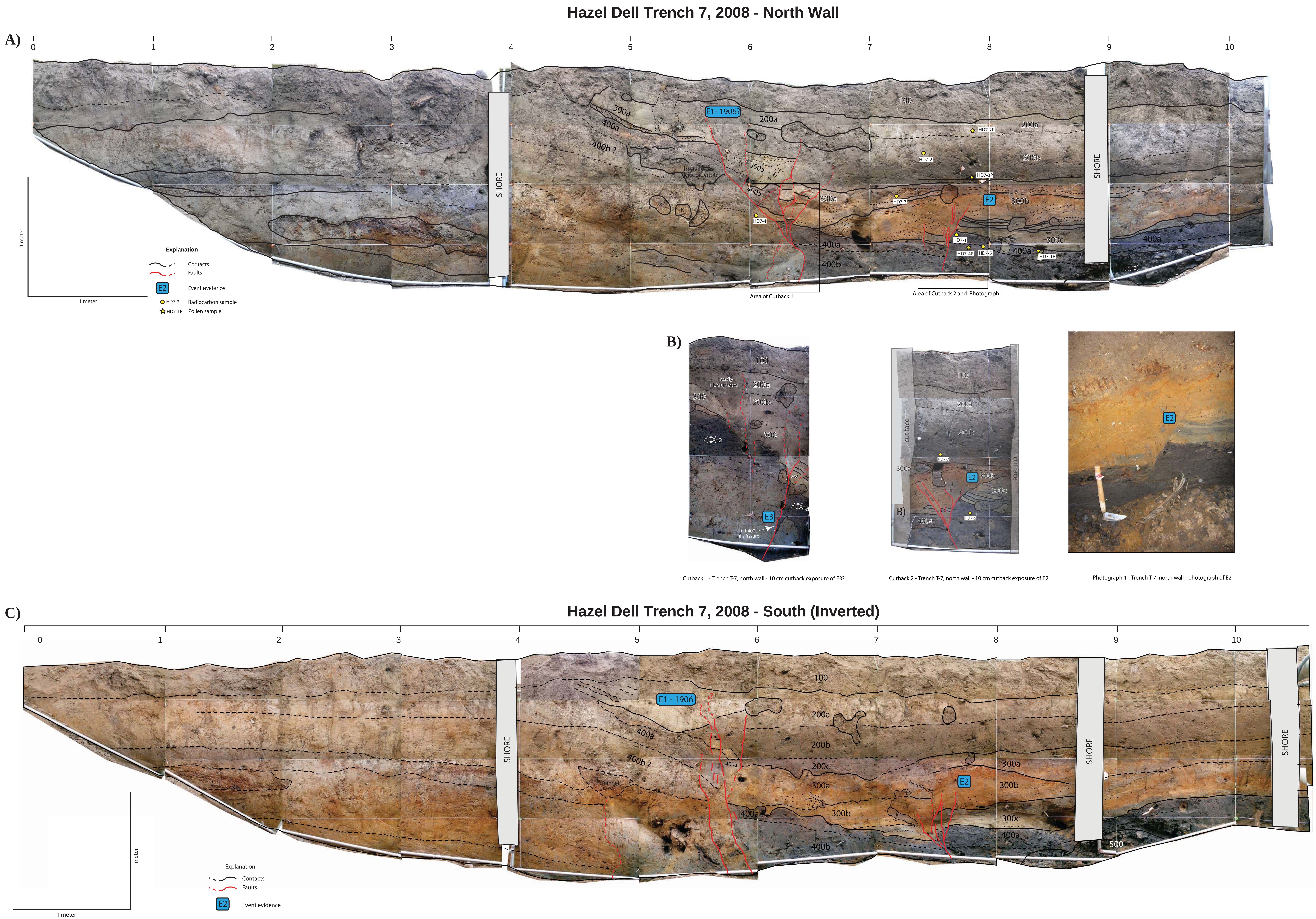
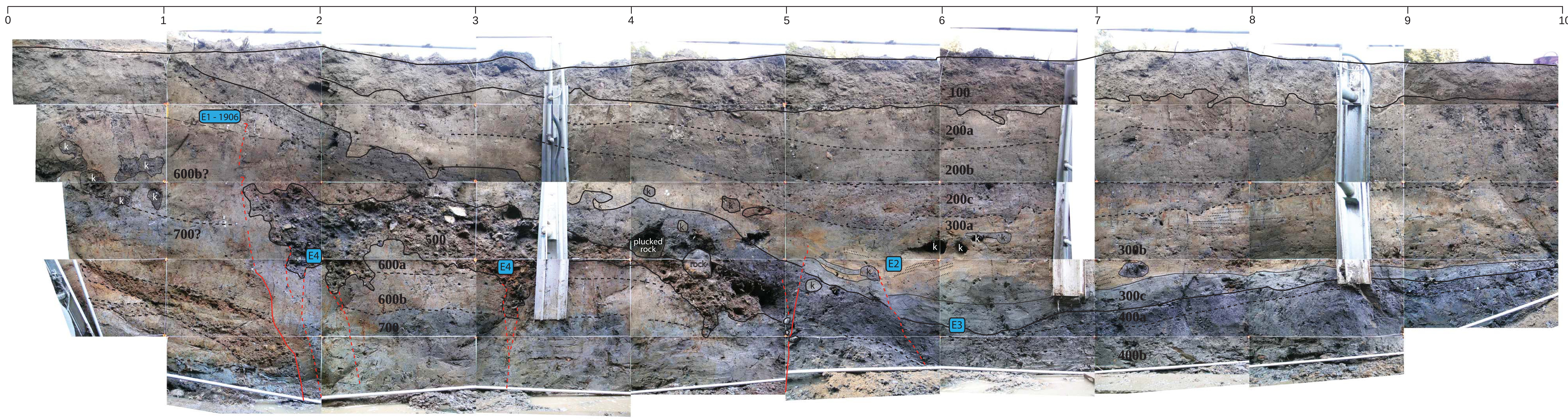


Plate 1. Photo mosaic trench logs A) Trench 7 north wall, B) 10 cm cut-back north wall fault exposures of E2 and E3, locations shown by boxes on the log, C) Trench 7 south wall, inverted.

Hazel Dell Trench 8, 2008 - North

A)



Hazel Dell Trench 8, 2008 - South (Inverted)

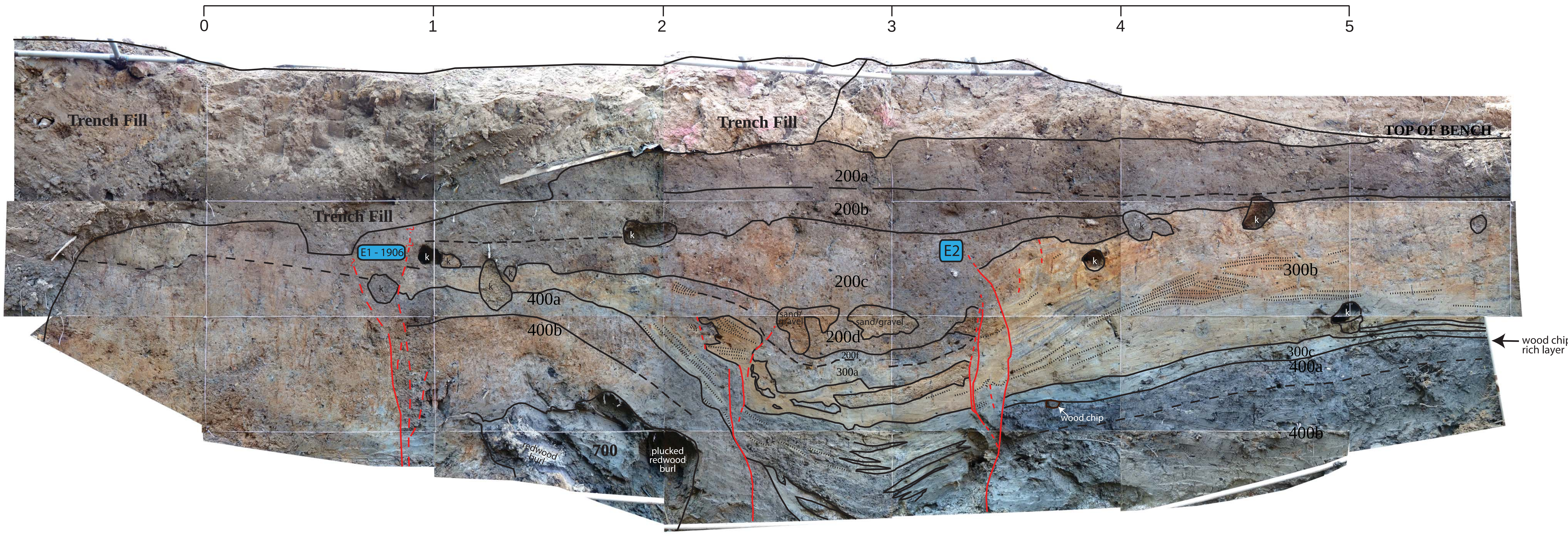
B)

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

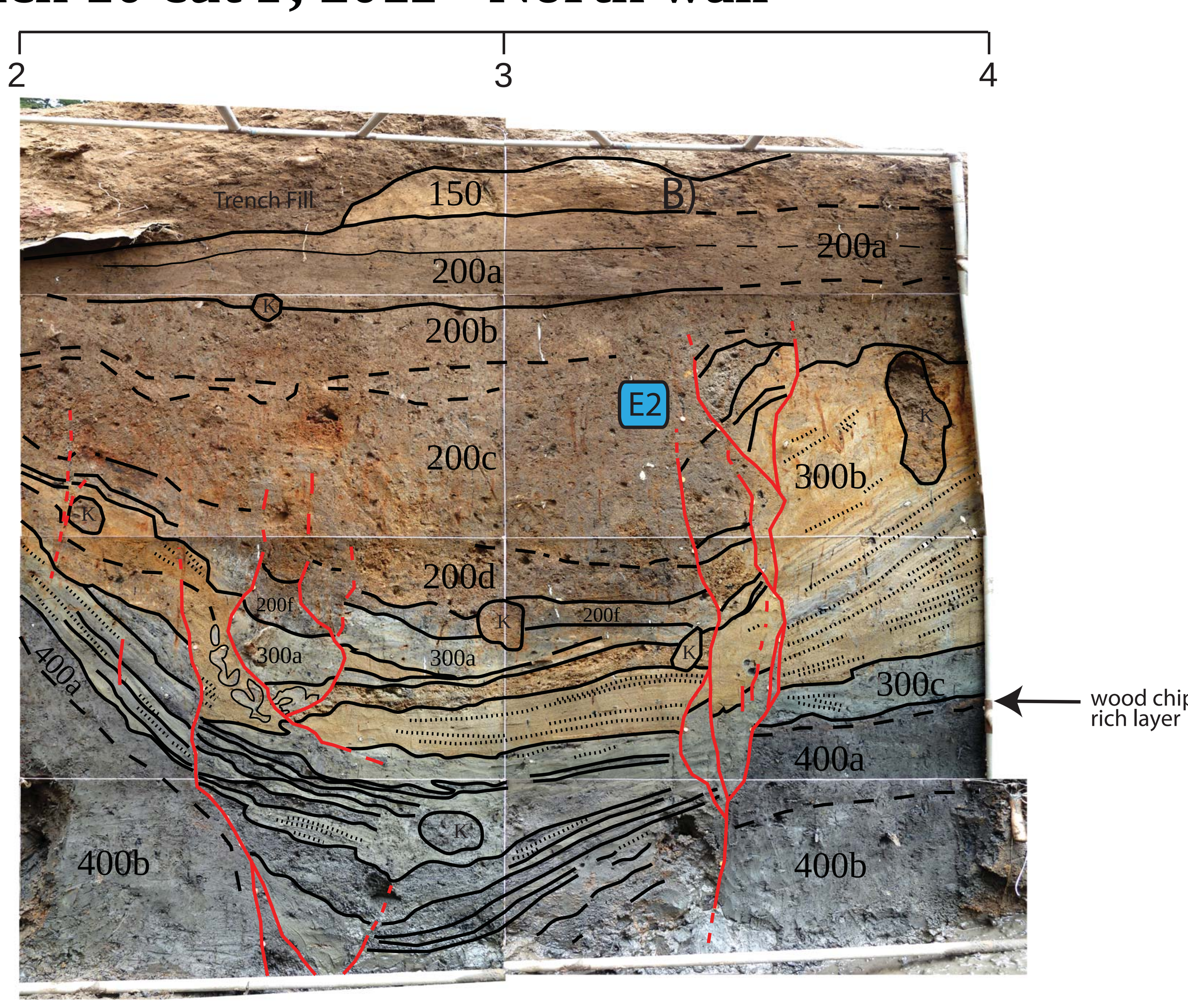
Trench 10 cut A, 2010 - North wall

Plate 3. Photo mosaic log of Trench 10a north wall, 2010 exposure.

A) **Trench 10 cut D, 2011 - North wall**



B) **Trench 10 cut F, 2011 - North wall**



C) **Trench 10 cut G, 2011 - North wall**

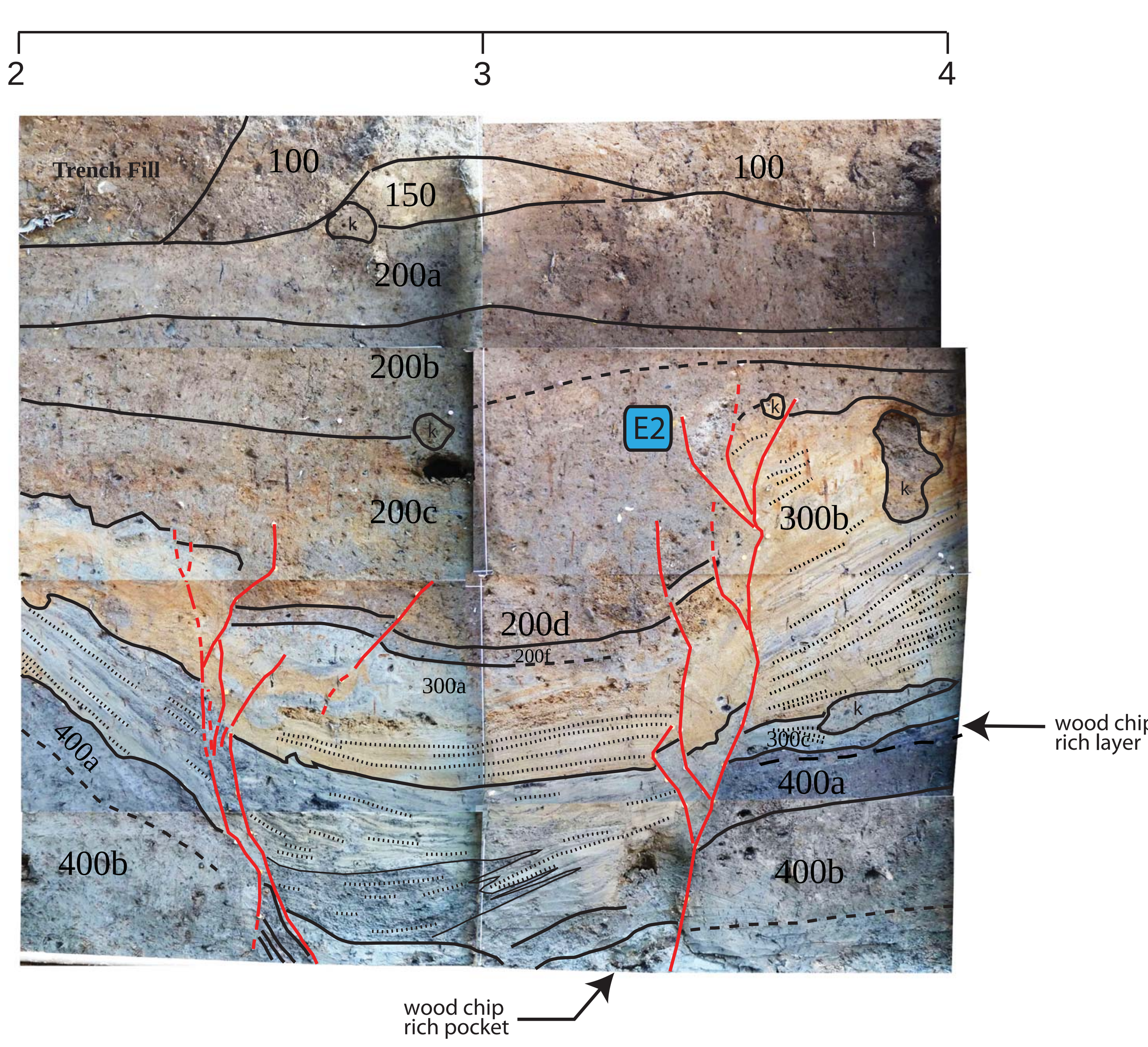


Plate 4. Photo mosaic log of Trench 10 cuts D, F and G, north wall, 2011 exposures. Cut F is ~20 cm back (northward) from cut D. Cut G is a cut back from meters 2 to 3, a 10 cm cut back from exposure F.