Paleoseismic Evidence of the 1890 and 1838 Earthquakes on the Santa Cruz Mountains Section of the San Andreas Fault, near Corralitos, California

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Abstract Paleoseismic investigations at the Hazel Dell site on the Santa Cruz mountains section (SAS) of the San Andreas fault provide the first definitive geologic evidence of two pre-1906 nineteenth-century earthquakes based on the presence of anthropogenic artifacts at the antepenultimate earthquake (E3) horizon. We review historic accounts of candidate events and interpret the penultimate earthquake and E3 to be the April 1890 and June 1838 earthquakes, respectively. These new data suggest more frequent surface-rupturing earthquakes within historical time than previously recognized and highlight variability of interseismic intervals on the SAS of the San Andreas fault. We correlate earthquakes between Hazel Dell and nearby paleoseismic sites based on revised timing, similarity of stratigraphy, style, and size of displacement, and build a composite paleoseismic record. The composite record requires at least two modes of behavior in strain release on the SAS through time. One mode is through great multisegment earthquakes, like that in 1906. Historic records and geologic studies suggest that prior to 1906 the Santa Cruz mountains region was characterized by a second mode of moderate seismicity, with three M $\geq 6$ earthquakes between 1838 and 1890, including two that caused surface rupture at Hazel Dell. In the 700 years prior to 1800, individual sites have evidence ranging from 1 to 5 events, suggesting that the longer record remains unresolved.

Online Material: Additional Hazel Dell trench logs, figure of age ranges for wood chips, Arano Flat OxCal model, and table of radiocarbon samples.

Introduction

The Santa Cruz mountains section (SAS) of the San Andreas fault is a 62 km long zone between Los Gatos and San Juan Bautista (SJB) (Working Group on California Earthquake Probabilities [WGCEP], 1990, 2002, 2007) and is defined by a broad restraining bend through the Santa Cruz mountains (Fig. 1). This section of the fault is located between the locked Peninsula section to the north and the creeping San Juan Bautista section to the south. The loading rate on the northern SJB is similar to that in Parkfield, but historically the creeping SJB has not experienced frequent M $\approx 6$ earthquakes, as Parkfield did in the twentieth century (Johanson and Bürgmann, 2005). Based on the current distribution of creep, Johanson and Bürgmann (2005) find that the SJB section is accumulating a moment deficit at the rate of one M $\approx 6.3$–6.7 earthquake per century and propose that the SJB releases centuries of strain accumulation in clusters of earthquakes spanning a few decades. It has been proposed that, like Parkfield, earthquakes initiate on the southern portion of the SAS and extend to the north, essentially acting as a transition zone between the locked Peninsula section to the north and creeping section to the south (Johanson and Bürgmann, 2005).

The SAS last experienced surface rupture during the 1906 M $\approx 7.9$ earthquake that produced about 470 km of rupture from Point Arena to San Juan Bautista (Lawson, 1908; Thatcher et al., 1997; Prentice et al., 1999). The reported paleoseismic recurrence interval for surface-rupturing earthquakes ranges from $\approx$125 years at the southern end of the SAS (Fumal, 2012) to 300+ years along the central portion of the SAS (Schwartz et al., 1998). Schwartz et al. (1998) report that the Grizzly Flat site, on the central SAS, recorded the 1906 event and one seventeenth century earthquake. Two historic earthquakes were observed at Mill Canyon and Arano Flat sites on the southern SAS (Fumal, Heingartner, Dawson, et al., 2003; Fumal, Heingartner, Samrad, et al., 2003; Fumal, 2012). We present a new paleoseismic record from Hazel Dell, located between these earlier studies, with evidence of four surface-rupturing earthquakes. This study
provides the first conclusive paleoseismic evidence for three historic earthquakes in the Santa Cruz mountains and provides slip and magnitude estimates for these historic events. We also reevaluate event evidence for the Grizzly Flat, Mill Canyon, and Arano Flat studies and conclude that all three sites experienced three earthquakes that occurred in the historic period, within a 70 year period of heightened seismic activity. The SAS has ruptured both with and independently of the Peninsula section to the north and may be a transition zone with more frequent ruptures between the creeping section to the south and the Peninsula section to the north.

The Hazel Dell Site

The Hazel Dell site is located at the north end of a fault-bounded valley and sag pond, at which a small ephemeral creek drains the basin; the San Andreas fault bounds the western edge of the valley and trends N30°W to N40°W (Fig. 2). Locally, the fault juxtaposes sandstone and shale of the Pliocene and upper Miocene Purisma formation on the west against Miocene to Oligocene Shale of Mt. Pajaro Formation on the east (Brabb et al., 1997). Although local fault traces were previously mapped at a scale of 1:24,000 (Quaternary fault database; Sarna-Wojcicki, et al., 1975; Bryant and Lundberg, 2002), we mapped small-scale (<1 m relief) fault features projecting to the investigation site on shaded relief, contour, and slope maps generated from 0.5 m resolution Light Detection and Ranging (LiDAR) data (Fig. 2). The fault is geomorphically well expressed as well-defined linear breaks in slope along east-facing hillslopes bounding the valley and as aligned linear drainages and topographic escarpments north and south of the site (along Green Valley Road and Old Mt. Madonna Road, respectively, Fig. 2). The 1906 rupture is interpreted to have occurred along the main trace of the San Andreas fault in this valley; however, at that time roads and bridges leading to this area were impassable, and the stretch between Grizzly Flat and

Figure 1. Location map of the San Francisco Bay region, showing the Santa Cruz mountains section (SAS) relative to San Andreas fault sections to the north and south. The north coast section (SAN), Peninsula section (SAP), and the creeping section (SJB) are shown as alternating gray and white shaded sections along the San Andreas fault; other principal Bay Area faults are labeled accordingly. Faults are shown as bold lines. Open circles on the SAS are paleoseismic study sites, including Hazel Dell (this study). A solid black arrow shows where the Pajaro River crosses the SAS, a second arrow shows the location of Wright’s tunnel. Fault traces are from the Quaternary Fault and Fold Database for the United States (see Data and Resources). Cities are shown as large black squares; small black squares are present day locations for Salsipuedes (S) and Corralitos (C). The color version of this figure is available only in the electronic edition.

Figure 2. Detailed fault map of the geomorphic lineaments in the Hazel Dell area (central SAS). Locally, the fault is expressed as a series of aligned drainages, linear range fronts, aligned topographic escarpments, and a sharp base of slope along east-facing hillslopes. The Hazel Dell investigation site is located in the northwest corner of the fault-bounded valley, associated with a transtensive (right) bend in the fault zone. In the basemap, the shaded relief was compiled from bare earth GeoEarthScope 0.5 m resolution LiDAR data downloaded from OpenTopography (Data and Resources; Prentice et al., 2009). The color version of this figure is available only in the electronic edition.
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Hazel Dell was not visited during the postearthquake investigation (Fig. 1; Lawson, 1908; Prentice and Schwartz, 1991). Prentice and Schwartz (1991) reconstruct the route taken by G. A. Waring, who mapped this area (reported in Lawson, 1908), and find he returned to the main rupture trace just southeast of Hazel Dell along Gaffey Road (Fig. 2). Prentice and Ponti (1997) estimate 1.7–1.8 m of 1906 surface slip at Wright’s tunnel (Fig. 1), roughly 24 miles northwest of Hazel Dell.

The Hazel Dell trench site is located within an area characterized by overbank deposits on the north side (east) of Green Valley Road; it is flanked by Green Valley Creek to the south and west and by hillslopes of Miocene to Oligocene sandstone to the north and east. Green Valley Creek crosses the fault at the southwest corner of the site (Fig. 2). The Hazel Dell site is within the floodplain and has been inundated by floodwaters in recent high rainfall years (D. Dent, personal comm., 2008). In these flood events the site was documented in trenches T1, T2, and T6; these did not cross a fault trace and were located to span the site to explore for other possible fault traces. We collected detrital charcoal, wood chips, and block samples of key stratigraphic units for macrofossil analysis in the lab and used all three sample types to constrain the ages of the deposits using 14C dating. We surveyed trench outlines, faults, string grids, and key stratigraphic units using a total station, then used a network of base stations and a differential Global Positioning System unit to tie together each survey and incorporate these data in an ArcGIS database (Fig. 3).

Methodology

We excavated a combination of slot and benched trenches across the site during the summer and fall of 2008, 2010, and 2011 (Fig. 3). Trench exposures were cleaned, gridded with a 1 m × 0.5 m string-and-nail grid, and photographed. All trench exposures were logged on a printed photomosaic of high-resolution digital photographs at a scale of roughly 1:10. Stratigraphic units and structural relationships were documented and described on photo logs (see the electronic supplement to this article for supplemental trench logs and unit descriptions). Both walls were documented in trenches that crossed the fault and in fault-parallel trenches adjacent to the fault. Only the north wall was documented in trenches T1, T2, and T6; these did not cross a fault trace and were located to span the site to explore for other possible fault traces. We collected detrital charcoal, wood chips, and block samples of key stratigraphic units for macrofossil analysis in the lab and used all three sample types to constrain the ages of the deposits using 14C dating. We surveyed trench outlines, faults, string grids, and key stratigraphic units using a total station, then used a network of base stations and a differential Global Positioning System unit to tie together each survey and incorporate these data in an ArcGIS database (Fig. 3).

Stratigraphy

Trenches across the site exposed mudflow, and waterlain alluvial, slope-derived colluvial, fissure, and scarp
deposits. Coarse-grained gravel and medium- to fine-grained alluvial stream deposits interfinger with colluvium proximal to bedrock hillslopes. Alluvial deposits were broken into nine major units, 100–900 (youngest to oldest; Fig. 4; see the electronic supplement for detailed unit descriptions).

The oldest stratigraphic unit, 900, is light-gray silty clay and is observed only in trench T4. Unit 700 is massive greenish-gray clay and is the oldest and deepest unit correlated between trenches. Units 600 and 700 are only observed west of the fault and are correlated between trenches that expose them (Fig. 4). Unit 600 consists of silty clay, and subunit 600a fines downward to silty sand in 600b. Unit 600a is discontinuous, eroded in places, and directly underlies the characteristic and widespread gravel unit 500. Unit 500b is a sandy gravel, with cobbles and is the deepest and oldest stratigraphic unit observed both east and west of the fault (Figs. 4 and 5); it unconformably overlies unit 600 on the west side. Unit 500a is a sandy gravel and has a weak soil developed in the upper 10 cm of the deposit that overprints the matrix.

Unit 400 consists of massive clayey silt. Subunit 400a is a buried soil, indicating a stable ground surface that led to soil development, and shows a period of marsh stability prior to deposition of the overlying sandy alluvial unit 300. Unit 400a has abundant detrital charcoal and is defined by a distinct dark-gray to black color that grades downward to medium gray of unit 400b (Fig. 4). The dark color of unit 400a suggests the unit was on the surface long enough to develop a significant organic A horizon. Units 300a, b, and c are water-lain overbank deposits ranging from cross-bedded sand and silt to interbeds of fine sand, silt, and layers of redwood needle hash. Subunit 300c consists of interbeds of very fine sand, silt, and organic layers, with some angular axe-cut wood chips at the base of the unit. Trench T6 crossed...
the bedrock hillslope bounding the east side of the site and exposed unit 300f, a moderately coarse-grained slope-derived colluvium that interferes with units 300a, b, and c.

Unit 200 consists of light-gray to grayish-brown massive clayey silt with layers of sand to coarse sand and consists of subunits 200a–f. A depositional change from well-sorted laminated sands and interbedded silts, clays, and organic layers of units 300a, b, and c occurred before the higher energy, coarse-grained, massive mudflow deposits of unit 200 was deposited. The uppermost unit, 100, is heavily bioturbated light-grayish-brown massive clayey silt and represents agriculturally modified stratigraphy immediately below the ground surface, including the till zone and roots from former apple trees.

**Earthquake Evidence**

We find evidence of four earthquakes, and enough exposure to suggest that there is a complete record, since the formation of a buried soil on unit 400a, recording the last three earthquakes (E1, E2, and E3). The exceptional stratigraphic resolution between events E1 and E3 is largely attributed to deformation caused by E3 that created a structural depression subsequently filled in with deposits, leading to a thickened stratigraphic section not seen elsewhere at the site. While the evidence for E4 is clear, the lack of stratigraphic section and the long time between E3 and E4 makes it impossible to rule out the possibility that E4 combines evidence for more than one event. Alternatively, it represents a longer earthquake recurrence interval in which a soil developed. We compile earthquake evidence as trench logs and label event horizons E1–E4 (Fig. 5). Details on the location and quality of each observation of event evidence are summarized in Table S2 in the electronic supplement (following the methodologies outlined by Scharer et al., 2007).

**Event E1 (1906)**

Evidence for the most recent event, E1, the 1906 rupture, is expressed in trenches T7 and T8 as one to two fault strands that extend upward to the base of unit 100, and also terminate within unit 200a the upper mudflow unit. Units 200b and 300a are vertically displaced across the E1 fault (Fig. 5; for additional earthquake evidence, see Fig. S1 in the electronic supplement). Vertical separation of unit 300a across these strands range from 25 to 50 cm across the 1906 trace (Fig. 5).

**Event E2**

The penultimate earthquake places units 200c and d in vertical fault contact with units 300a and b; this relationship was exposed in multiple cuts of trench T10 (Figs. 5 and 6; Fig. S1 in the electronic supplement). E2 fault traces do not extend upward into 200a and do not clearly extend up into 200b. Unit 200b has no vertical separation or change in thickness across the projected E2 fault traces, whereas units 300d are vertically displaced across the eastern depression-filling stratigraphy logged in the previous cut, T10-2011, overlain with linework; bold subvertical shaded lines are faults, and black and all other subhorizontal lines are unit horizons. (b) Simplified linework for cut D of T10-2011, showing E2 and E3 deformation. E2 completely truncates 200d and 200c; overlying units are continuous across the fault and are unfaulted. We add the deeper depression-filling stratigraphy logged in the previous cut, T10a-2010. (c) Schematic reconstruction of E2, showing the E3 depression prior to the E2 event. The hatch-mark lenticular polygon is a gravel lens within unit 300b (shown as a faulted polygon in [a] and [b]) that has over 26 cm vertical separation across the eastern trace. The E2 deformation is removed by reconstructing the shaded polygon shown in (a) and (b) and reconstructed in (c). Vertical separation of unit 400a across the eastern depression-bounding fault is enhanced by lateral slip in E2. The color version of this figure is available only in the electronic edition.

200c and d are truncated by the fault and placed in vertical contact against unit 300b (Fig. 5b). This event generated 26 cm of vertical separation of a gravel lens within unit 300b across the eastern trace and completely truncated units...
200d and c; overlying units are continuous across the fault and are unfaulted. This earthquake occurred sometime after the depression formed by E3 was filled with units 300, 200d, and 200c (see the Event E3 section); it probably happened while 200c was at the ground surface, as shown in the cartoon reconstruction (Fig. 6). After E2, this horizon was probably modified by the high-energy deposition of 200b, a mudflow, making upward terminations unclear. Evidence of E2 was clearest in trench T10-A and in subsequent T10 cuts D, E, F, and G (cut incrementally 10–20 cm northward into the wall; see Fig. S1 in the electronic supplement). Cuts T10-B and C were excavated in 2010 and were small hand dug trenches to the south of T10-A.

Event E3

Earthquake E3 occurred when the top of unit 400a was the ground surface. Axe-cut wood chips are incorporated in the upper few centimeters of unit 400a and at the base of the overlying sequence 300c. E3 formed a roughly 7 m long × 1.5 m wide × 1.5 m deep oblong structural depression, or fissure (Fig. 5). The depression extends between trenches T7 and T8. At the north end, in trench T7, the depression is 20 cm deep. At its center in trench T10 the depression is as much as 1.6 m deep (Fig. 5) and decreases to 20 cm down on the east relief to the south in trench T8 (Fig. 5). The E3 depression is infilled by stratigraphic units 200b, 200c, and 300. In trench T8, the depression formed by E3 is associated with folding of unit 400, with units 300b and c deposited as an onlap sequence against the fold scarp (Fig. 5a; see Fig. S1 in the electronic supplement). Unit 300c infills a depression formed on the unit 400a surface; 300c is 20–25 cm thick in trenches T7 and T8 and thickens substantially within the depression; at its thickest it is 70 cm in T10-A. Unit thickness decreases in subsequent cuts northward to 50 cm in cut T10-F (Fig. 5). Additional evidence for E3 includes a small fissure filled with sediment derived from unit 400 in trench T7.

Event E4

Evidence for the oldest event (or possibly events; in either case we refer to all evidence at this horizon as E4) was identified in trenches T8 and T4. E4 is expressed as upward fault terminations within the oldest gravel unit 500b and as upward terminating fissures that incorporated gravels from the overlying unit (500b) in the fissure fill. Gravel-filled fissures were observed in trench T8 north of meters 2, 3, and 4.5 (Fig. 5c; see Fig. S1 in the electronic supplement). Event E4 occurred after deposition of the gravel (unit 500b) and before a soil formed in the upper 10–20 cm of the gravel (unit 500a). The soil is not displaced and does not change in thickness or follow vertical separations of the lower part of the unit (500b), but is instead continuous across the fissures. Because the soil is continuous and not warped downward into the fissures, the E4 earthquake(s) probably occurred before the soil formed or early in its development (Fig. 5a).

Figure 7. Examples of wood chips collected from unit 400a. (a) Larger sample, 10 cm wide × 20 cm long. Transverse cut across wood grain. (b) Smaller wood chip with very fine ∼1–2 mm wide cuts at opposing angles suggests narrow bladed steel axe. (c) Wood chip with bark, 180 growth rings; inner and outer rings were sampled and used in 14C analysis (sample HD-2011-WC1 samples: A, inner ring and B, outer ring). (d) Wood chip with bark, 24 growth rings; inner and outer rings were sampled and used in 14C analysis (sample HD-2011-WC2 samples: A, inner ring, and B, outer ring). The color version of this figure is available only in the electronic edition.

Deposit Age Estimates

Age constraints at the site are provided by historical artifacts and an abundance of organic material, including redwood needles, redwood cone fragments, wood, and detrital charcoal. These materials were sampled from key stratigraphic units and used for accelerator mass spectrometry (AMS) 14C age determination. Wood, needles, and some charcoal samples were analyzed at the Center for Accelerator Mass Spectrometry (CAMs) at Lawrence Livermore National Laboratory (LLNL). Detrital charcoal samples collected in the first year of the study (2008) were submitted to Beta Analytic Inc., Florida. Each sample was pretreated with acid–alkali–acid washes and results are reported as conventional radiocarbon ages (years B.P.) in Table A1. We use these and other data to build an age model and estimate age distributions for the earthquakes using OxCal v.4.1.7 (Data and Resources; Bronk Ramsey, 2009).

The fourth earthquake (E4) is relatively poorly constrained, in part because the radiocarbon dating for this event relies on charcoal samples largely derived from redwood trees, which are long lived and also 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 relies on large numbers of radiocarbon samples in order to constrain the range of ages within a deposit (Fumal, Heingartner, Samrad, et al., 2003; Fumal, 2012).

Historical wood chips and historical accounts of settlement in the area provide additional age constraints that are not possible using radiocarbon dating alone. Embedded into
and at the top of unit 400a, we found hundreds of pieces of cut wood, ranging from small pieces a few centimeters long to >30 cm long. Ends of the wood chips are characterized by smooth, angled cuts transverse to the wood grain (Fig. 7), indicating they were cut by a sharp metal tool, likely an axe. On one piece (Fig. 7b), the cut shows where the edge of the tool was embedded, in the form of a narrow, sharp incision in the wood, indicating the sharpness of the tool used to make the cut, consistent with the taper of an iron or steel blade. Some pieces also have remnants of bark on the outer perimeter. Given the preserved sharpness of the cuts, we hypothesize that (1) the wood chips were not transported very far (the sharp edges would have been degraded from transport) and (2) they were embedded into the top of unit 400a very soon—within a few years, and probably less—after they were cut (the cut edges would have been degraded from weathering and decay, particularly the smaller, sharply angular pieces). The extent of the wood chips residing at the 300/400 interface appears limited to the area of T10, within the localized depression created by E3. Wood chips were also found in unit 300; most abundantly near the base of 300c, with fewer and smaller wood chips found stratigraphically higher in the upper part of 300c and none found in 300b or above. Given the location, it appears the wood chips were on the ground when unit 400a was at the surface and subsequently were buried, as well as being incorporated into the lower part of unit 300. If these chips were deposited at the same time as unit 300c, then we might expect to see the wood chips more uniformly distributed throughout the deposit rather than concentrated at the 300/400 contact. A cut and burnt redwood burl rooted in unit 400 was exposed in T10 within a couple of meters of the wood chips (Fig. 6a), and, although it is somewhat speculative whether the chips came from the cutting of that particular redwood tree, it does show that redwood trees were very near where we found the redwood chips, and other cut redwood stumps were found in other trenches. Given that the wood chips were embedded in the top of unit 400a, and below the post-E3 fill sequence, the wood chips were deposited before E3. It is possible the wood chips were cut after E3 and deposited on the ground surface immediately after the earthquake before the E3-generated depression was filled by unit 300. However, the time between E3 and the filling of the depression appears short given the rapid filling of the E3 depression with interbedded sands and organic debris. There is no indication that the depression persisted at the surface long enough to either accumulate in situ organic material or to become significantly degraded or eroded, as evidenced by the steeper western side of the depression (Figs. 5 and 6).

There are no known ethnographic or historical accounts of precontact native people chopping down large trees in the way that European colonists would have. Local indigenous populations did not make large hafted axes needed to cut large trees (Anderson, 2005; Lightfoot et al., 2009). In 1769, the Portola expedition crossed what later became Rancho de Los Corralitos and provided the first written record of the size and abundance of redwood trees in the area. The Portola expedition observed that many of the redwood trees measured from 3.4 to 4 m in diameter (Pybrum-Malmin, 1998). We exposed shallowly buried redwood stumps at the intersection of trenches T1–T2 and T1–T6 that were 1.75 m wide and were chopped off. Between 1803 and 1807, the Branciforte Villenos unsuccessfully attempted to settle the Corralitos area, and by 1807 the Presidio at Monterey pastured 500 cattle and horses in the Salsipuedes and Corralitos Ranchos (Fig. 1; Pybrum-Malmin, 1998). The Hazel Dell site is within the original Spanish land grant to Don Jose Amesti, granted in 1827 (Pybrum-Malmin, 1998). Large-scale redwood lumber harvest began in this area sometime around or before 1832, “Amesti is said to have had a whip-saw lumber mill in 1832 on the upper Corralitos.” (Pybrum-Malmin in Data and Resources). Amesti was making and selling shingles in the Corralitos canyon area in 1832–1836 (Ellison and Price, 1953). These early records of local redwood harvesting, combined with the knowledge that local native populations did not chop down large trees indicates that unit 400a was at the surface at the time of European settlement and that earthquakes E2 and E3 postdate European settlement and are historical.

To confirm this age range, we sampled growth rings on two of the wood chips and obtained AMS 14C radiocarbon ages. These wood chips were selected based on the presence of preserved bark on the sample, meaning that we were able to sample the outer rings, as well as sample the innermost ring preserved on the sample, providing a growth period of 180 years for sample HD-2011-WC-1 and 24 years for sample HD-2011-WC-2. The radiocarbon dates were ‘wiggle matched’ with the intercepts for the radiocarbon age and error with the known interval between growth rings on the INTCAL04 terrestrial 14C calibration curve (Reimer et al., 2004). A Bayesian approach combining the 14C dates with the relative age between samples (years determined by counting the number of growth rings) was employed to wiggle match the results using OxCal v.4.1.7 (Bronk Ramsey et al., 2001; see also Data and Resources). Using their wiggle-matching technique OxCal yields a 2σ modeled outer growth ring/chopping age range between 1698 and 1850 for sample HD_2011_WC1 (© see Fig. S2 in the electronic supplement for full results and sample HD_2011_WC2). Based on this modeled age range and the historical record, the death of the wood chips could have occurred as early as 1803, the earliest possible date from the historic record of land use once the region was inhabited by the Spanish to 1850, the youngest possible age for the wood chips. We infer a probable chopping date around 1827, when the property became a Spanish land grant and soon after which redwood logging is documented to have begun in the upper Corralitos area (Pybrum-Malmin, 1998; see also Data and Resources). We use these values, 1827 ± 22–24 years, in our OxCal age model (Fig. 8).
We used OxCal v.4.1.7 (Data and Resources; Bronk Ramsey, 2009) to construct a calibrated age model for earthquakes identified at Hazel Dell. We included boxcar dates for historic information, such as the 1906 San Francisco earthquake, and an age range of 1827 + 23/− 24 years as a constraint on the timing of the chipping of the tree and wood chips at the contact between units 300c and 400a. Calibrated probability distribution functions for the remaining samples are shown in stratigraphic order in Figure 8, along with estimated probability distribution functions for the timing of the four earthquake horizons identified at the site.

We have exceptional stratigraphy in the period since the redwood chips were deposited into the nineteenth century. However, we recognize that we may be missing events in what appears to be a depositional hiatus between E3 and E4. Unit 400a is a mature buried soil, which had old growth redwood trees rooted in it at the site. Based on the soil development and the size of stumps seen in other exposures at the site, this was a long-lived surface, likely spanning hundreds of years. Other events could have occurred in the time after deposition of unit 500 gravel and earthquake E4, but before the soil developed on unit 400a had formed. Our trenches exposed the top of the gravel unit in the E3 depression, but the water table prevented us from safely exposing the base of the gravel in this area and looking for additional evidence of events prior to E3. We infer much older material west of the fault in T4 and T7; unit 700 yielded a modeled age of 40–350 B.C., and unit 900 ranged from 800 to 900 B.C. (see Appendix).

Event Ages and Correlation with Historical Earthquakes

We interpret E1, the most recent event at Hazel Dell, to be the 1906 rupture, based on historical accounts of the earthquake rupturing through the Santa Cruz mountains to the vicinity of San Juan Bautista (Prentice and Schwartz, 1991). Based on the historical constraints from the cut wood chips, we have two additional historical earthquakes that occurred in the nineteenth century; and, with these constraints, the OxCal modeled age for E2 is 1840–1906 (2σ uncertainty, Fig. 8) and for E3 is A.D. 1815–1895. E4, our oldest paleoearthquake is prehistoric with a modeled age with 2σ uncertainties between A.D. 760 and 1318. In this section, we examine the historical record of moderate to large earthquakes in the Santa Cruz mountains in order to correlate historical earthquakes to events E2 and E3 observed in the trenches at Hazel Dell.

Historical records indicate three M > 6 earthquakes in this time period. The earliest was a June 1838 event, which had high intensities extending from the Peninsula to the Santa Cruz and Monterey Bay region and is interpreted to have ruptured part of the Peninsula and a portion of the SAS of the San Andreas fault (Toppozada and Borchart, 1998; Bakun, 1999; Hall et al., 1999; Toppozada et al., 2002). An 8 October 1865 earthquake caused ground cracking in the Santa Cruz mountains (Bakun, 1999); and a 24 April 1890 earthquake in the Pajaro region caused significant damage from Corralitos south to San Juan Bautista, cracking in places along the same trace as the 1906 rupture (Tuttle and Sykes, 1992; Bakun, 1999).

1838

The June 1838 Mw ~ 7.2 earthquake was the first major earthquake since the founding of Mission San Francisco Dolores in 1776 (Tuttle and Sykes 1992; Toppozada et al., 2002). On the Peninsula section at Filoli (Fig. 1), Hall et al. (1999) observe channel deposits offset 4.1 m (±0.5) and interpret this to be combined 1906 and 1838 displacements. They infer approximately 2.5 m (±0.2) displacement at their site in 1906 from an average of nearby offset measurements reported in Lawson (1908) and estimate that the difference, 1.6 m (±0.7), of the total measured displacement occurred in 1838. Hall et al. (1999) estimate that this displacement is consistent with an Mw 7.0–7.4 earthquake. Tuttle and Sykes (1992) estimated that the 1838 rupture extended about 100 km 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), and estimated an $M_w$ 7.2 earthquake based on this length and intensity data. Toppozada and Borchardt (1998) conclude that the 1838 event ruptured from near San Francisco to San Juan Bautista, a rupture length totaling ~140 km and indicating an $M_w$ ~ 7.4 earthquake, and caused at least two notable large aftershocks in 1840 and 1841 (Toppozada and Borchardt, 1998; Toppozada et al., 2002). Toppozada and Borchardt (1998) compile damage reports of the extent of faulting in this event, as reported by Loudback (1947), and report strong intensities in Woodside, where solid adobe houses were cracked severely and redwoods were “broken off and hurled.” We interpret this to be the best candidate event for the earliest historic earthquake, E3, at the Hazel Dell site.

1865

The 8 October 1865 earthquake was most destructive in the Watsonville–Santa Cruz–San Jose area (Toppozada et al., 2002). McNutt and Toppozada (1990) and Tuttle and Sykes (1992) found that the 1865 earthquake was smaller than the 1889 Loma Prieta earthquake, which occurred along a 70° southwest-dipping blind oblique reverse fault in the SAF zone (Wald et al., 1991). Tuttle and Sykes (1992) reviewed felt reports for the 1865 event and found greater damage northeast of the SAF than in 1889. They concluded that the event occurred on a reverse fault northeast of the SAF and assigned the event an $M_w$ ~ 6.5. This result is consistent with later analysis by Bakun (1999). Triangulation data collected between 1853–1860 and 1876–1891 record northeastward displacement of station Loma Prieta, which Yu and Segall (1996) conclude is a result of the 1865 earthquake. Yu and Segall (1996) find that the displacement is consistent with an $M_w$ 6.75 thrust earthquake northeast of the San Andreas fault in the Santa Cruz Mountains thrust belt. Based on triangulation and intensity data that suggests this earthquake was northeast of the San Andreas fault, we find it unlikely that the 1865 event is a candidate for one of the historical earthquakes on the main trace of the San Andreas fault and observed in the paleoseismic record at Hazel Dell.

1890

The 24 April 1890 earthquake was estimated to be $M_w$ 6 by Toppozada et al. (1981) and $M_w$ ~ 6.3 by Bakun (1999) and Tuttle and Sykes (1992). This event caused significant damage at Corralitos, Green Valley, Pajaro, San Juan Bautista, and Sargent’s (Bakun, 1999). Surface cracks observed in 1890 were located on the trace of the SAF where offset was observed in 1906, south of the Pajaro River (Lawson, 1908; Prentice and Schwartz, 1991; Bakun, 1999), and was felt as far away as Carson City, Nevada (Holden, 1892). Holden (1892) reports duplex seismograph readings from Mount Hamilton, Mills College, and other Bay Area institutions for the 24 April 1890 earthquake. Holden also catalogs local reports of a series of earthquakes, or aftershocks, in the months following the April 1890 earthquake.

Santa Cruz, May 14. —Ever since the big earthquake of 24th of April there have been seismic disturbances along the line between Pajaro and San Juan, where the earthquake was heaviest. Each day three or four small shocks occur, and yesterday six quite pronounced ones were felt... (Holden, 1892, p. 17 of 31).

These earthquake and aftershock observations described by Holden suggest that the 24 April 1890 earthquake was substantial and caused aftershocks on the main trace of the San Andreas fault. This suggests that the San Andreas is the source area for the mainshock. We find that this is the best candidate historical earthquake for E2, given reports of possible rupture along the SAF and the intensity reports that appear to be centered in the vicinity of the Hazel Dell site (e.g., Bakun, 1999).

Event Evidence from Nearby Paleoseismic Sites

We review event evidence and dating methods employed at Grizzly Flat, Arano Flat, and Mill Canyon paleoseismic sites. Mill Canyon and Arano Flat are located 1.5 km apart, and a hiatus in sediment accumulation is observed at both sites between 1906 and 1838 (Fumal, Heingartner, Dawson, et al., 2003; Fumal, Heingartner, Samrad, et al., 2003; Fumal, 2012). While the authors interpret no event in the intervening time, we point out that a hiatus in deposition occurred at the critical time to record the 1890 event. Although they do discuss the possibility that it may have occurred at their sites but was not distinguishable from the 1906 event. Lack of sedimentation does not preclude an earthquake between 1906 and 1838, but we review the assumptions made in these papers and argue that the authors missed the 1890 event.

Mill Canyon

Mill Canyon is located 8 km south of Hazel Dell. Fumal (2012) finds evidence of the 1906 earthquake rupture and a penultimate earthquake that falls within the early to mid-nineteenth century. Fumal (2012) found that the ground surface of the 1906 rupture was initially unclear, with 12 separate exposures of the fault zone, and identified the 1906 ground surface using 3D excavations. Fumal’s unit 4 is the top of an organic rich layer that contains historic artifacts including weathered fence posts from a fence erected in 1854 by the property owner. The top of unit 4 was the ground surface throughout the second half of the nineteenth century. Little to no sediment was deposited at the Mill Canyon site in the intervening time between 1838 and 1906 (Fumal, 2012). Fine sands (his units 2 and 3) deposited soon after 1906 bury and preserve the fissures and scarps formed during the 1906 earthquake. Although Fumal (2012) did not identify evidence for the 1890 earthquake at Mill Canyon, because of the depositional hiatus during the nineteenth century, it is
possible the earthquake is not stratigraphically distinguishable from the 1906 earthquake. Lawson (1908) reports cracks that occurred along the fault in the same location in 1906 as the earthquake 16 years earlier (1890), south of the Pajaro River. If this was surface rupture related to the 1890 event that extended between Hazel Dell and past Mill Canyon, it is likely that the paleoseismic evidence for 1890 would be indistinguishable from the 1906 earthquake.

Fumal (2012) presents two OxCal age models for timing of the penultimate (MC-2) at Mill Canyon. In Fumal’s model 1 the lower age limit of key stratigraphic units were constrained by the lack of non-native pollen (Fumal, 2012). Based on our own experience at Hazel Dell, 8 km away, we have found that historic sediments lack the non-native pollen commonly associated with Spanish cattle migration, although invasion of these non-native plants is widely thought to precede Spanish settlement (Mensing and Byrne, 1998). The presence of non-native pollen is informative of the age of a deposit; however, the lack of pollen does not unambiguously represent the period prior to Spanish settlement. The lack of non-native pollen can represent poor pollen preservation in coarse-grained sediment, an ecological niche where invasive species such as Erodium cicutarium would not grow (i.e., a shady redwood grove is an unlikely environment for sun-loving Erodium), or a region in which the sediments predate introduction of the non-native species to the area. The buried pollen samples should be compared with modern environment analogs to the regional vegetation (Calcote, 1995). We prefer model 2 in Fumal (2012) because it does not use the lack of non-native pollen to constrain the timing of event MC-2 (Fumal, 2012).

Arano Flat

At the Arano Flat site 9.5 km south of Hazel Dell (Fig. 1) and 1.5 km south of Mill Canyon, Fumal, Heingartner, Dawson, et al. (2003) report a partially-buried channel that contains bottles from 1870 to 1890 and is offset 3.5 m across the fault; they interpret this to be offset by one event, 1906. They state that the 3.5 m displacement is unexpectedly high compared to the geodetic estimate of 2.3–3.1 m for the slip at depth (Thatcher et al., 1997) or the geologic estimate of 1.7–1.8 m of surface slip at Wright’s Tunnel (Prentice and Ponti, 1997), about 33 km northwest of Arano Flat. The bottles in the channel deposit were produced from 1870 to 1890, suggesting they could have been deposited prior to the 1890 earthquake (identified bottle of A. Boschee’s German Syrup, L. M. Green proprietor, circa the 1870s; Fumal, Heingartner, Dawson, et al., 2003). Given this, the anonymously high 3.5 m displacement of the channel containing the bottles, we propose that the 3.5 m offset is the cumulative displacement from both 1890 and 1906 earthquakes. We argue that within the dating constraints provided by the bottles, one cannot preclude that the channel was only offset in 1906, and 3.5 m displacement could be the sum of 1890 and 1906 offsets, which are not distinguishable due to the lack of stratigraphy at this time.

The event AF-2, identified by Fumal, Heingartner, Samrad, et al. (2003) occurred while their unit 19, a very dark-gray silty clay was at the ground surface. This unit has some organic soil development, suggesting it was a stable ground surface at the time of the earthquake. This event generated a depression 1.5 m wide × 1.5 m deep at Hazel Dell, a fissure 1 m wide × 1.5 m deep at Mill Canyon, and a fissure 1 m wide × 1 m deep at Arano Flat. The color version of this figure is available only in the electronic edition.

Figure 9. Photomosaic logs showing evidence for 1838: (a) event E3 at Hazel Dell; (b) event MC-2 at Mill Canyon (log from Fumal, 2012; reprinted with permission from T. Dawson); and (c) event AF-2 at Arano Flat (log from Fumal, Heingartner, Samrad, et al., 2003). This earthquake forms large fissures of comparable size and depth at all three sites and occurs while organic soils are at the surface at all three sites. This earthquake generated a depression 1.5 m wide × 1.5 m deep at Hazel Dell, a fissure 1 m wide × 1.5 m deep at Mill Canyon, and a fissure 1 m wide × 1 m deep at Arano Flat. The color version of this figure is available only in the electronic edition.
determinations from detrital charcoal samples collected from their trenches and presented in a table in Fumal, Heingartner, Samrad, et al. (2003) (see Table S1 and Fig. S3 in the electronic supplement). No model was included in their Open-File Report (Fumal, Heingartner, Samrad, et al., 2003). Using their dates we find that AF-2 has a 2σ modeled age range of A.D. 1760–1861. Given the beginning of the historical period at 1769 this was almost certainly a historical event.

Grizzly Flat

Schwartz et al. (1998) present evidence for 1906 and one earlier event at Grizzly Flat. Fumal (2012) reviewed trench logs for Grizzly Flat, reinterprets logs for possibly two additional earthquakes that postdate the penultimate event identified by Schwartz et al. (1998). Fumal renumbers the events; GF-1 is the 1906 event, GF–2* and GF–3* are added, and GF–4* is the penultimate event identified by Schwartz et al. (1998). Trench log evidence for GF–2* is the weakest with only one line of evidence; upward decreasing vertical separation of units 4a and 6c on the north wall of the north trench (Fumal, 2012). GF–3* occurred while their unit 6c was at the ground surface. Evidence of GF–3* includes upward fault terminations within unit 6c and absence of the unit between two fault strands suggest lateral slip that is not reflected in overlying stratigraphy (Schwartz et al. 1998; Fumal, 2012).

Fumal also addresses two possible problems with age constraints for GF–4* used in the original model. Schwartz et al. (1998) use dendrochronologic constraints from redwood growth rings from a single nearby tree as a maximum age for the oldest earthquake at the site. Dendroseismology is the study of perturbations in annual growth rings as a result of seismic disturbance. At Grizzly Flat, the abrupt decrease in growth ring width from one redwood stump was interpreted as earthquake evidence. Because trees can be individualistic in response to disturbance, typically multiple trees should be sampled to ensure the disturbance in growth ring width is not unique to one tree (Jacoby, 2000). Other disturbances may force change in annual ring growth including; climate change (i.e., drought), disease or infestation, landslide, rockfall (Jacoby, 2000; Kozaci, 2012). To preclude these possibilities, the stump should be cross correlated with other local redwoods near and far from the fault to both confirm the observed stunted growth pattern near the fault and to exclude the possibility that the change in ring width was not a result of some other regional disturbance. The authors dated only the wider growth rings and used a preferred age that excluded low probability ranges with no explanation for the excluded data. Fumal provides an alternate age model for Grizzly flat that incorporates the reinterpreted event evidence and does not use the dendrochronologic age constraint used by Schwartz et al. (1998). In Fumal’s model (Fumal, 2012), GF-1 occurred in 1906, and GF–2* has a modeled age range of 1828–1906, and could be 1890, though the geologic evidence for this event is the weakest. GF–3* has a modeled age range of 1733–1872 and probably occurred in 1838. GF–4* has a modeled age range of A.D. 1105–1545.

Summary of Earthquakes

Here, we summarize and correlate event evidence for all paleoseismic sites on the Santa Cruz mountains section of the San Andreas fault. At Hazel Dell, our E3 formed an approximately 7 m long × 1.5 m wide × 1.5 m deep fault-bounded depression (Fig. 9). The E3 earthquake horizon and overlying units incorporate historical artifacts (axe-cut wood chips) that place this event in the post-European time period. At the Mill Canyon site event MC-2 forms a large fissure 1 m wide × 1.5 m deep. This event occurred while unit 5, a sand and gravel with some soil development, was at the ground surface and falls within the range A.D. 1789–1904 (using Fumal’s OxCal model 2; Fumal, 2012). Fumal identifies 1838 as a candidate historical earthquake for this event (Fumal, 2012). The MC-2 earthquake produced a much larger fissure (Fig. 9), than those associated with the 1906 event horizon at the site. At Arano Flat, event AF-2 forms a fissure 1 m wide × 1 m deep, similar size and depth as the fissures associated with this event at both Mill Canyon and Hazel Dell (Fig. 9). Event 3 at all three sites occurred in a window of time while the landscape was stable and soils were developing at all three sites (Fig. 9). The largest event reported in historic time for the Santa Cruz and Watsonville areas occurred in 1838. The June 1838 earthquake is the largest event reported in early historic time for the Santa Cruz and Watsonville areas, and best explains the amount of deformation associated with the fissures observed at Hazel Dell, Mill Canyon, and Arano Flat and falls within the timing constraints from all three sites. Grizzly Flat also has event evidence that falls within this time period, GF–3* (Fumal, 2012), so the 1838 event may have ruptured the full 14 km between these sites (Fig. 10).

The penultimate earthquake at Hazel Dell is also historic, examining the historic record reveals that the 24 April 1890 earthquake generated surface rupture along the same trace that ruptured 16 years later, in 1906, south of the Pajaro River (Lawson, 1908). An offset channel deposit at Arano Flat contained bottles dating between 1870 and 1890 and has 3.5 m cumulative displacement from 1906 to 1890. If the observed Arano Flat displacement of 3.5 m is a combined displacement for the 1890 and 1906 earthquakes, and at least 0.5 m of the 3.5 m occurred in 1890 (and the remaining 3 m occurred in 1906), then there is a greater than 95% chance that a rupture would extend the 1.5 km between Arano Flat and Mill Canyon, using the methodology of Biasi and Weldon (2006, 2009). There is a depositional hiatus in this time period at the Mill Canyon site, because of this it is probable that the 1890 and 1906 earthquakes ruptured the same stratigraphic horizon and are not paleoseismically distinguishable as separate events. We infer that the 1890 event...
occurred at Mill Canyon, based on reinterpreted surface rupture evidence from Arano Flat and given the high probability that the surface rupture extended the short distance between these two sites (Biasi and Weldon, 2006, 2009). Similarly, given an observed displacement of at least 0.5 m at Arano Flat and using Biasi and Weldon (2006, 2009), there is ~90% probability the rupture would extend the 9.5 km distance between Arano Flat and Hazel Dell. There is weak evidence of an earthquake at Grizzly Flat during this time (Fumal, 2012); however, it is possible that the 1890 earthquake did not extend this far north (Fig. 10).

Earthquake Length and Magnitude Estimates

A 14 km long surface rupture could be generated by an $M_w 6.4$ earthquake based on scaling relationships such as Hanks and Bakun (2002). This would be a minimum estimate for the 1838 earthquake, if the rupture spanned all four sites, as we argue. The geologic evidence combined with the historic record suggests that the 1838 earthquake was a much larger magnitude than this, so had a longer rupture and likely spanned much of both the Peninsula and Santa Cruz mountains sections, if not the full 140 km length (Tuttle and Sykes, 1992; Toppozada et al., 2002). This earthquake generated fissures 1.5–1 m wide and deep at Hazel Dell, Mill Canyon, and Arano Flat. We propose that at least 1.5–1 m of slip occurred in this event to open fissures of equivalent width and depth. Using the empirical relationship between maximum displacement and magnitude (Wells and Coppersmith, 1994) we estimate that the 1838 earthquake was at least moment magnitude $M_w 7.0$, for a minimum displacement of 1.5 m at Hazel Dell. For this magnitude, we estimate a minimum rupture length of 62 km, assuming a seismogenic depth of 13–15 km and using the small earthquake (up to $M_w 7$) scaling relationship of Hanks and Bakun (2002). This rupture length estimate, based on our geologic estimate of slip in this event, agrees well with rupture length estimates by earlier researchers (Tuttle and Sykes 1992; Toppozada and Borchardt, 1998; Toppozada et al., 2002) and suggests the 1838 event ruptured most of the Santa Cruz mountains section, and some portion of the Peninsula section, but not necessarily the full 140 km length of both sections. Additionally, using a technique that correlates point measurements of displacement along a fault with the empirical relationship between surface rupture length and moment magnitude (Hemphill-Haley and Weldon, 1999) we estimate these displacements were generated by an ~$M_w 7.0$, with a range of $M_w 6.8–7.2$ within the 95% confidence interval. For this estimate we use four displacement measurements from Hazel Dell, Mill Canyon, Arano Flat, and Filoli (1.5 m, 1 m, 1 m, 1.6 m ± 0.7, respectively) and assume 83% of the fault is sampled (for the 83 km distance between sites) for a 100 km rupture length (Tuttle and Sykes, 1992). We prefer this method and range of estimated magnitudes for the 1838 earthquake.

The 1890 earthquake and its aftershocks were widely felt from Santa Cruz to San Juan Bautista (Holden, 1892). Based on geologic evidence this rupture extended at least the 10 km from Hazel Dell to Arano Flat and probably extended south of the Pajaro River (Lawson, 1908), totaling at least ~14 km. Using the scaling relationships of Hanks and Bakun (2002), we estimate a moment magnitude range of $M_w 6.2–6.4$ for these rupture lengths. In light of new paleoseismic data and earthquake and aftershock descriptions from Holden (1892), the 1890 earthquake was greater than earlier magnitude estimates based on the historic record alone (Toppozada et al., 1981; Tuttle and Sykes, 1992; Bakun, 1999). We propose a range of displacements of 0.5–1.7 m in the 1890 event, based on the combined 1906 + 1890 displacement of 3.5 m at Arano Flat. If the 1906 earthquake generated 1.8 m displacement (the upper limit from Wright’s tunnel; Prentice and Ponti, 1997), then we assign the remaining difference of the cumulative displacement to the 1890 event, an upper value

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**Figure 10.** Time–space diagram for the SAS showing the distribution of paleoseismic investigation sites. Distance north of SJB is shown at the top of the figure. Sites from north to south are Grizzly Flat (Schwartz et al., 1998; Fumal 2012), Hazel Dell (this study), Arano Flat (Fumal, Heingartner, Dawson, et al., 2003; Fumal, Heingartner, Samrad, et al., 2003), and Mill Canyon (Fumal, 2012). Distance from Hazel Dell to neighboring sites are shown at the bottom of the figure. Modeled event age ranges are shown as rectangles for all four sites; horizontal lines are event correlations between sites. The color version of this figure is available only in the electronic edition.
Paleoseismic Evidence of the 1890 and 1838 Earthquakes on the SAS of the San Andreas Fault, near Corralitos

of 1.7 m of slip. The lower slip estimate, 0.5 m, is based on the high probability the rupture extended between Arano Flat and Hazel Dell (see the Summary of Earthquakes section). Scaling relationships between maximum displacement and magnitude for strike-slip earthquakes by Wells and Coppersmith (1994) yield a moment magnitude range of $M_w$ 6.6–7.0 for this range of displacements. Additionally, the empirical relationship between average displacement and magnitude for strike-slip earthquakes (Wells and Coppersmith, 1994) yields a moment magnitude range of $M_w$ 6.8–7.2 for this range of displacements. Regardless of the method used to estimate moment magnitude we find that the 1890 earthquake was $> M_w$ 6.2.

We note that the moment magnitude estimates using empirical regressions for strike-slip earthquakes (Wells and Coppersmith, 1994) and the upper range displacement value of 1.7 m are high relative to magnitude estimates from historical intensity observations (e.g., Bakun, 1999). This suggests that perhaps our upper range estimate of displacement for this event, 1.7 m, is high. For this reason we favor the lower magnitude range for these empirical estimates (Wells and Coppersmith, 1994) for a 0.5 m displacement.

We observe that ground rupturing historic earthquakes on the San Andreas fault are clustered in the nineteenth to early twentieth centuries and are followed by eight decades of seismic quiescence for earthquakes greater than $M_w$ 6 (prior to the $M_w$ 6.9 1989 Loma Prieta earthquake). Our composite paleoseismic record shows that in the 68 years before the 1906 earthquake the San Andreas fault ruptured at least a 14 km length of the Santa Cruz mountains section twice, with recurrence intervals of 52 and 16 years (1838–1890 and 1890–1906, respectively), and strain released in those events is two to three times greater than the strain that would have accumulated in that length of time (assuming a long term 17 mm/yr slip rate; WGCEP, 2002, 2007). A 3000 year earthquake record on the southern San Andreas fault reveals that there is no relationship between recurrence interval and offset (Scharer et al., 2010), and that earthquake recurrence fits neither time nor slip predictable fault behavior models (Weldon et al., 2004). Other plate boundaries with long geologic records also reveal clustered earthquake sequences that terminate with a great earthquake or outsized event, (e.g., Goldfinger et al., 2013). These broad periods of strain accumulation and relief are called supercycles, a cumulative cluster of multiple earthquakes that relieve the accumulated strain over a longer supercycle interval (Sieh et al., 2008). Relative seismic quiescence along the northern San Andreas fault in the last century has also been explained by a stress shadow cast by the 1906 earthquake (negative Coulomb failure stress change, e.g., Stein, 1999; Freed, 2005), with the prediction that seismic activity in a region picks up again as a region steps out of stress shadow from a previous great earthquake. Another model is that the SAS is a transition zone between creeping and fully locked sections of the SAF and may rupture more frequently in moderate-size earthquakes, like Parkfield, but less regularly. The 1906 earthquake propagated from the locked SAF in the north to the south and rupture ended near San Juan Bautista (Lawson, 1908). We suggest the 1906 displacements on the SAS were large enough that the earthquake essentially shut off the fault and affected how the fault usually behaves in the absence of great 1906-type events, such as the relatively smaller earthquakes observed during the nineteenth century. We prefer this last model, but until we refine the long recurrence behavior on this section of the fault we can only speculate.

The Arano Flat site has a long earthquake record (Fumal, Heingartner, Samrad, et al., 2003) and identifies multiple events in the 500 year period prior to 1838 (Fig. 10). Either the record at Hazel Dell is incomplete, as suggested by the lack of stratigraphy in the older section, or Arano Flat experiences more surface-rupturing earthquakes than Hazel Dell located a mere 9.5 km to the north. If there were more frequent events at Arano Flat than neighboring sites, it would suggest there is a transition zone within the southernmost Santa Cruz section and the creeping San Juan Bautista section to the south. In this scenario, some ruptures do not fit the whole SAS section. This scenario only fits the earthquake chronology at one site and does not fit scaling relationships we have discussed in this article (i.e., Biasi and Weldon, 2006, 2009). We find it more likely that the longer earthquake records at all other sites on the Santa Cruz section are incomplete.

Conclusions

We present a new paleoseismic record from Hazel Dell and combine it with three nearby paleoseismic records along the Santa Cruz mountains section of the San Andreas fault. The Hazel Dell site provides the first definitive paleoseismic evidence of two nineteenth century ground rupturing events on the Santa Cruz mountains section. We find that sediment accumulation and the preservation of earthquake evidence varied at all four sites, making it difficult to determine a complete record of earthquakes from just one site. Hazel Dell and Grizzly Flat each have a long multicycle sedimentation hiatus in the older stratigraphic record, whereas Arano Flat, Mill Canyon, and Grizzly Flat all have a sedimentation hiatus spanning multiple decades in the nineteenth century (Fig. 10). An incomplete stratigraphic section leaves some time as unaccounted—time in which earthquakes could occur and generate a paleoseismic earthquake record indistinguishable from subsequent earthquakes. By combining earthquake evidence from all four sites, we are able to compare similarities in event deformation, identify depositional hiatus at individual sites, and more confidently assess age distributions for the events.

Based on our interpretation of paleoseismic and historical accounts, the SAS of the San Andreas fault ruptured in 1838, 1890, and 1906. This section ruptured in three earthquakes closely spaced in time, culminating in the largest, the 1906 earthquake. If present results from Grizzly Flat and Hazel Dell are complete, they suggest there was an ~500 year
period of seismic quiescence prior to the flurry of surface-rupturing earthquakes in the nineteenth and early twentieth centuries. However, Arano Flat and Mill Canyon have longer earthquake records and greater stratigraphic resolution, and these identify likely earthquakes in the 500-year period prior to 1838. More paleoseismic work needs to be done on the SAS to resolve the surface-rupturing earthquake chronology in the period prior to the nineteenth century.

Data and Resources

Fault traces for a regional fault map (Fig. 1) are from the U.S. Geological Survey and California Geological Survey (USGS), 2006. Quaternary Fault and Fold Database for the United States, available on the USGS website http://earthquakes.usgs.gov/regional/qfaults/ (last accessed August 2013).


The OxCal program by Bronk Ramsey (2013) is available online at https://c14.arch.ox.ac.uk/oxcal.html (last accessed October 2013). OxCal Program, v.4.2, is from the Radiocarbon Accelerator Unit, University of Oxford, Oxford, United Kingdom.

EarthScope Northern California LiDAR project 0.5 m resolution data was obtained from http://opentopodis.ucsd.edu/gridsphere/gridsphere?gs_action=raster&cid=geonlidarframeportlet&opentopoID=OTSDEM.052008.32610.1 (last accessed December 2012). LiDAR data and material used in this study is based on services provided to the Plate Boundary Observatory (PBO) by NCALM. PBO is operated by UNAVCO for EarthScope and supported by the National Science Foundation (Numbers EAR-0350028 and EAR-0732947). This data and material is also based on (data, processing) services provided by the OpenTopography Facility, with support from the National Science Foundation (Award Numbers 0930731 and 0930643).

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Table A1
Radiocarbon Ages for the Hazel Dell Site

<table>
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<tr>
<th>Sample Name</th>
<th>Laboratory Number</th>
<th>Unit</th>
<th>(^{14}\text{C Age}) ± (1σ Lab Error)</th>
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<td>HD T7-4</td>
<td>Beta-254275</td>
<td>400a</td>
<td>650 ± 40</td>
<td>Charcoal</td>
</tr>
<tr>
<td>HD T7-6</td>
<td>Beta-254276</td>
<td>400a</td>
<td>640 ± 40</td>
<td>Charcoal</td>
</tr>
<tr>
<td>HD T8-31</td>
<td>Beta-254278</td>
<td>600b</td>
<td>1250 ± 40</td>
<td>Charcoal</td>
</tr>
<tr>
<td>HDT8-32-2008</td>
<td>CAMS-158279</td>
<td>600b</td>
<td>1270 ± 30</td>
<td>Charcoal</td>
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<tr>
<td>HD 4-1</td>
<td>Beta-264157</td>
<td>700a top</td>
<td>2260 ± 40</td>
<td>Charcoal</td>
</tr>
<tr>
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<td>Beta-264158</td>
<td>700b base</td>
<td>2120 ± 40</td>
<td>Charcoal</td>
</tr>
<tr>
<td>HD 4-9</td>
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<td>700c base</td>
<td>2300 ± 40</td>
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</tr>
<tr>
<td>HD 4-12</td>
<td>Beta-264160</td>
<td>900</td>
<td>2710 ± 40</td>
<td>Charcoal</td>
</tr>
</tbody>
</table>

*Samples processed at Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory and Beta Analytic Inc., Florida.
†The quoted age is in radiocarbon years using the Libby half-life of 5568 years and following the conventions of Stuiver and Polach (1977). Radiocarbon concentration is given as conventional radiocarbon age. Sample preparation backgrounds have been subtracted, based on measurements of samples of \(^{14}\text{C}-\text{free wood. Backgrounds were scaled relative to sample size.}*

Appendix

Listed in Table A1 are samples from key stratigraphic units used for AMS \(^{14}\text{C} \text{age determination.}

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