FINAL TECHNICAL REPORT

ASSESSING THE TIMING OF THE PENULTIMATE AND PRE-PENULTIMATE EARTHQUAKES OF THE SAN ANDREAS FAULT PENINSULA SEGMENT USING DENDROCHRONOLOGY

COLLABORATIVE RESEARCH PROJECT WITH CAROL PRENTICE, THE U.S. GEOLOGICAL SURVEY

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ABSTRACT

This collaborative pilot project is a dendrochronological reconnaissance investigation on the Peninsula Segment of the San Andreas fault (SAF) to determine whether using tree ring analysis could refine the event chronology for pre-1906 large magnitude earthquakes, and specifically to address whether or not the historical 1838 earthquake was associated with rupture of the Peninsula San Andreas.

Existing paleoseismic data of the northern San Andreas fault, obtained primarily from trenching and offshore turbidite studies, provide support for multiple rupture segmentation models. The models are partly constrained by the uncertainty limitations on various earthquake ages derived from radiometric age-dating of stratigraphic deposits. Accurate data on the timing of past events from multiple sites and rupture segments are essential for evaluating rupture segmentation models of the northern San Andreas fault and for estimating the probability and size of future earthquakes in the San Francisco Bay region (Working Group on California Earthquake Probabilities [WGCEP], 2003). The timing and recurrence of earthquakes along the northern San Andreas fault, and its multiple hypothesized rupture segments, are among the most critical issues for reducing uncertainties in probabilistic analyses of seismic hazard in northern California. For instance, the San Andreas fault is thought to be one of the most hazardous faults in the San Francisco Bay Region (SFBR). The Uniform California Earthquake Rupture Forecast (UCERF, 2008) assigns a probability of 21% that the northern San Andreas fault will produce an earthquake M≥6.7 in the next 30 years. One scenario considers the rupture of the entire northern San Andreas fault in an earthquake of M8 with a 2% probability. Reducing the uncertainties associated with dating methods is essential in calculating more precise probabilistic rupture scenarios. Specifically, the source of the historical 1838 earthquake has been suggested to be the Peninsula Segment of the SAF; however, no paleoseismic study has provided unequivocal evidence that this event occurred on the Peninsula San Andreas. The proposed dendrochronologic study has the potential to significantly reduce the uncertainties of the earthquake chronology of the Peninsula Segment. In order to achieve this goal, we performed a reconnaissance study along the Peninsula Segment to identify and evaluate the feasibility of dendrochronologic investigations. We identified sections of the fault where 38 suitable trees for dendrochronologic analysis are present and collected and analyzed eight preliminary tree core samples. Seven out of eight samples yielded ages of 100 years or younger. One sample; however, yielded an age of approximately 129 years including a growth suppression period following early 1900. Results of this study suggest that further more extensive dendrochronologic studies with a calibrated sampling approach are likely to provide useful data.

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1. INTRODUCTION

We conducted a dendroseismological reconnaissance investigation of the northern San Andreas fault (SAF) to test whether tree-ring analysis can provide earthquake timing and recurrence data of late Holocene earthquakes along the Peninsula Segment (Figure 1). Existing paleoseismic data obtained primarily from trenching provide support for multiple rupture segmentation models that are only partly constrained due to large uncertainties (i.e., 68 to 200 years) on the timing of individual earthquake events (Figure 2). Accurate data on the timing of past events are therefore essential for evaluating and refining rupture segmentation models of the northern San Andreas fault, and for estimating the probability and size of future earthquakes on the fault and probabilities of future earthquakes in the San Francisco Bay region (Working Group on California Earthquake Probabilities [WGCEP], 2003). An outstanding paleoseismic problem is that the penultimate event on the Peninsula Segment has not been unequivocally constrained using more typical geochronological methods. Dendrochronology (the study of annual growth layers in woody plants) may be a means for reducing this uncertainty because annual tree growth layers are markers that provide absolute ages; if disruption of growth is related to a nearby earthquake, then the technique has the ability to resolve timing of the event not only to a particular year, but to the exact season of occurrence. This annual/seasonal precision could allow the identification of the penultimate and possibly pre-penultimate events on the SAF Peninsula Segment, thereby reducing the uncertainty. This technique has been used successfully in past studies (Sheppard and Jacoby, 1989). We therefore employed dendrochronology to develop an earthquake timing data for the penultimate and pre-penultimate large earthquakes on the northern SAF Peninsula Segment.

Northern California contains abundant remnant old growth forests with oaks, firs, and pines, and large well-preserved trunks of historically logged coastal redwoods (*Sequoia sempervirens*) that occur along the SAF zone between Watsonville and San Francisco. Numerous dendrochronological studies have demonstrated that fault movement accompanied by surface rupture can fracture, twist, tilt or vertically displace trees that grow on or directly adjacent to the surface rupture of the fault (Lawson, 1908; LaMarche and Wallace, 1972; Meisling and Sieh, 1980; Jacoby, 1994; Jacoby, 2000; and Carver et al., 2004). Internal tree deformations associated with fault rupture are manifested in the growth patterns of annual tree rings and the presence of reaction wood; whereas the external effects include topped tree crests, fractures, trunk asymmetries, tilting, root and limb damage and scars, and drowning. These zones of earthquake-related external damage are preserved as a temporary reduction in width of annual growth rings and, as mentioned above, can be used to provide the exact timing of events down to the season of a given year.

Developing a well-constrained earthquake chronology of late Holocene surface rupture, especially the historical 1838 earthquake, along the Peninsula Segment of the northern San Andreas fault is critical

to understanding the earthquake cycle and possible rupture scenarios used for probabilistic earthquake models. Site-specific dendroseismologic studies can provide well constrained data on earthquake timing and recurrence information, and when compiled with existing event timing information derived from paleoseismic trenching, can be used to further refine segment boundaries and regional scale fault behavior models. While some information on the fault characteristics and chronology of both 1906-type multi-segment ruptures and smaller, single segment ruptures is available for the four hypothesized rupture segments of the northern San Andreas fault, there remains considerable uncertainty on the timing of the penultimate and pre-penultimate events.

2. PREVIOUS WORK

The application of dendrochronology for earthquake studies is a concept that has a proven record of success for characterizing large, damaging earthquakes within the last several earthquake cycles of a fault. For instance, LaMarche and Wallace (1972) evaluated several coast redwood forests growing along the northern San Andreas fault between Woodside and Gualala, California. This study visited sites that were documented originally by Lawson (1908) as suffering earthquake-related damage from the 1906 earthquake. The study interpreted that a surface-rupturing earthquake occurred between 1400 and 1650 A.D. on the basis of growth ring anomalies preserved in a living and tilted coast redwood near Fort Ross (LaMarche and Wallace, 1972). In addition, Meisling and Sieh (1980) used tree cores from conifers growing along the 1857 rupture at Wrightwood and Frazier Park on the southern San Andreas fault, and interpreted earthquake damage attributed to the 1857 earthquake.

More recently, Jacoby (1994; 1995a and 1995b; 1997) and Carver et al. (2004) demonstrated how careful examination of tree cores, stumps, and felled logs can provide well constrained earthquake timing information within the last thousand years or so. Jacoby (1994 and 1995a) developed a preliminary cross-dating catalog of coast redwoods and earthquake history for the northern San Andreas fault by visiting several localities described previously in Lawson (1908) and LaMarche and Wallace (1972). By collecting and analyzing the annual growth rings from cores and slabs of old growth trunks and felled logs, as well as living old growth redwood trees in the Gualala and Fort Ross area, Jacoby (1995) interpreted the presence of two and potentially three pre-historic events occurring around 1260 A.D., 1330 A.D. and 1710 A.D. The 1260 A.D. event is considered uncertain because there are fewer samples to corroborate this event. Jacoby (1997) also spent a considerable effort developing a regional chronology of undisturbed redwoods for control purposes, and this work has recently been refined by other researchers who have extended the length of the dating chronology past 1,000 years (N. Pederson, personal communication). This regional chronology allows dendrochronologists to correlate and cross-date with younger trees and old stumps in order to establish fault chronology information, and to tie in dead and buried logs with inner portions of the chronology through cross-dating (Stokes and Smiley, 1968).

3. SAN ANDREAS FAULT PENINSULA SEGMENT

The Great San Francisco earthquake of 1906 produced surface rupture from San Juan Bautista to Shelter Cove (Lawson, 1908; Thatcher et al., 1997; Prentice et al., 1999) along four major segments that from north to south include the: Offshore, North Coast, Peninsula, and Santa Cruz Mountains segments (WGCEP, 2003) (Figure 1). This study focused attention on the Peninsula segment to specifically address the presence or absence of the historical 1838 earthquake.

The Peninsula segment (SAP) of the northern San Andreas fault extends from the Golden Gate southward to near Los Gatos, where a large-scale restraining bend defines the boundary with the Santa Cruz Mountains segment (WGCEP, 2003). The segment boundaries of the SAP are based on geologic, historical, and seismic data from the 1838, 1906, and 1989 earthquakes, variability of geodetically determined and geologically measured slip in the 1906 earthquake, differences in long-term geologic slip rates, and changes in fault orientation relative to the bounding and adjacent fault segments (Figures 1 and 2).

Previous paleoseismic studies on the Peninsula segment provide evidence of poorly constrained large magnitude earthquakes occurring in the late Holocene (Wright et al., 1999; Hall et al., 2001), and possibly in 1838 (Toppozada and Borchardt, 1998); whereas paleoseismic investigations on the Santa Cruz Mountains and North Coast segments provide possibly a more complete event chronology over the last approximately 2,000 years (Fumal et al., 2004; Niemi et al., 2004; Zhang et al., 2004; Kelson et al., 2006; Goldfinger et al., 2008). WGCEP (2003) provides an estimated mean recurrence of 378 years for 1906-type events, and 230 years for ruptures occurring only on the Peninsula segment of the SAF.

At the Town of Portola Valley, located on the Peninsula segment of the San Andreas fault, Baldwin et al. (2008) interpret three, and possibly four, earthquake events within approximately the past 1,000 years. From warped marsh and fluvial deposits, and scarp-derived colluvium, Baldwin et al. (2008) interpret three earthquakes that from oldest to youngest include: Event 1 (1030 to 1490 A.D.); Event 2 (1260 to 1490 A.D.); and Event 3 (1906 A.D.). An alternative interpretation of Event 2 is that a fourth event (Event 2B) may have occurred between 1410 and 1640 A.D. The timing of Event 1, 1030 to 1490 A.D., overlaps with the event chronology for two prehistoric earthquakes interpreted from other paleoseismic sites on the northern San Andreas fault. The youngest stratigraphic units do not provide the resolution necessary to assess whether or not the historical 1838 rupture, which has been assigned by other workers to the Peninsula segment of the San Andreas fault, ruptured the fault at this site. The age ranges for events interpreted at the Portola Valley site are consistent with results from several other sites along the Peninsula segment and northern San Andreas fault; however, the age constraints allow broad ranges in event timing that may influence these apparent consistencies.

This pilot study consists of dendrochronological reconnaissance investigation on the Peninsula Segment of the San Andreas fault (SAF) to refine the event chronology for the penultimate and pre-penultimate large magnitude earthquakes, and specifically to address the absence or presence of evidence for the historical 1838 earthquake (Figure 3).

Numerous possible dendrochronological sites have been identified during this investigation both from field reconnaissance, review of geologic literature, and discussion with paleoseismologists working on the northern SAF. We have tentatively identified at least three potential dendrochronology sites (Filoli, Los Trancos, and Portola Valley) on the SAP (Figures 3, 4, 5, and 6).

For the Peninsula segment, the Filoli site is located in close proximity to Hall et al., (1999) and Clahan (1996) trench site. This site consists of a large grove of coast redwoods that encircle a well-known Native American midden directly along the fault. LaMarche and Wallace, (1972) demonstrated that fault-zone trees along the SAP date back to ~1400 A.D., again allowing for the recognition of the penultimate and pre-penultimate events. The Portola Valley site contains a large redwood that has a missing top section that may have been snapped off during 1906. We visited these sites, identified during our desktop studies, and identified target trees to be sampled. Descriptions including photographs, GPS coordinates, and tree locations with respect to fault trace were recorded during this investigation period.

4. METHODOLOGY AND RESULTS

Thirty-eight trees were recorded and seven trees were sampled as part of the pilot study in order to look for trauma symptoms in annual ring growth trends, and then use these to refine apparent age estimates of an associated earthquake event. Trees were selected according to their proximity to the SAF trace, apparent age (based on their size), and potential seismogenic trauma, as reflected in their macro-morphology (outer appearance) (Figures 7 and 8). Tree growth anomalies are described as macro and micro. In general, macro anomalies are uncharacteristic morphological features on a tree. Micro anomalies, on the other hand, are abrupt changes in growth rates and trends of tree rings (Kozaci, 2012).

During this pilot study, we identified 38 trees on or within close proximity of the SAF trace (Figure 3). These trees appear to be old enough to record damage from the penultimate and pre-penultimate events, and exhibit possible fault rupture and/or strong ground motion-related macro-morphologic trauma symptoms. Macro-morphologic trauma symptoms include abnormal growth patterns such as candelabra growth, fallen or tilted trees. We used a Swedish increment borer to extract core samples for tree ring growth analyses.

Seven trees were cored at chest height (approximately 1.5 meters above ground surface) and analyzed as part of this study. SAF-DND-15 was cored in both fault parallel and fault perpendicular orientations. Sample cores were mounted on stands and sanded prior to analyses (Figure 9). Mounted cores were scanned at high resolution for initial age estimation. Due to the nature of this pilot study and initial findings, cross-dating was not performed. Seven samples out of eight were approximately 100 years old or younger, not extending back to the 1838 earthquake.

Sample SAF-DND-28, extracted from an oak tree living on the SAF scarp within 5 meters of the main trace, yielded an age of approximately 129 years, extending back to at least 1886. The annual ring growth of this sample is generally continuous except for approximately 10-15 years following early 1900s. During this period, SAF-DND-28 produced narrow rings compared to its general growth trend (Figure 10).

5. DISCUSSION

Ring boundaries on oaks may at times be relatively diffuse compared to coastal redwoods. However, they can be used successfully for documenting seismic effects on trees, especially when multiple trees can be identified and dated. Even a decade-long uncertainty associated with growth suppression and/or potentially missing rings within this growth suppression interval would provide an age dating opportunity with smaller uncertainty margins compared to the uncertainties associated with radiocarbon dating that targets a post-1800 A.D. event.

Annual ring growth trends observed on SAF-DND-28 during the decade following 1900 indicate a period of growth suppression, suggesting that this tree may have been affected by the 1906 earthquake surface rupture. The growth trend prior to 1900 and since 1930 has been relatively consistent. In contrast, the growth interval between 1900 and 1930 indicates significant growth suppression. Within this period, it is also possible that some rings may be completely missing, suggesting tree growth stopped for a year because the tree redirected all its resources to survival. While it is not possible to definitively correlate this growth suppression exclusively with the 1906 surface rupture, it is, nevertheless, a plausible explanation. This suppression of growth related to earthquake damage would be strengthened with further studies including more samples yielding a similar signal in combination with correlation to regional dendrochronologic standards developed for establishing climate records.

6. CONCLUSIONS

The initial results of our pilot study present a good potential for the application of dendroseismology on the SAF Peninsula Segment. One test sample retrieved from an oak tree yielded a potential signal for the 1906 earthquake on the annual ring growth trend. A detailed and comprehensive sampling within the areas identified in this report has the potential for demonstrating the absence or presence of the historical 1838 earthquake on the SAF Peninsula Segment. The comprehensive sampling approach will need to be calibrated based on the results of this pilot study. The results from a future comprehensive study will immediately be applicable to correlation for the paleoseismic trench investigation by Carol Prentice, Judy Zachariasen, and Ozgur Kozaci at Crystal Springs South Site. We plan to extend our field reconnaissance southward from Los Trancos Open Space, where trees along the fault trace are preserved within parks such as Montebello Open Space Reserve and Stevens Creek County Park.

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Table 1. Summary table for core samples

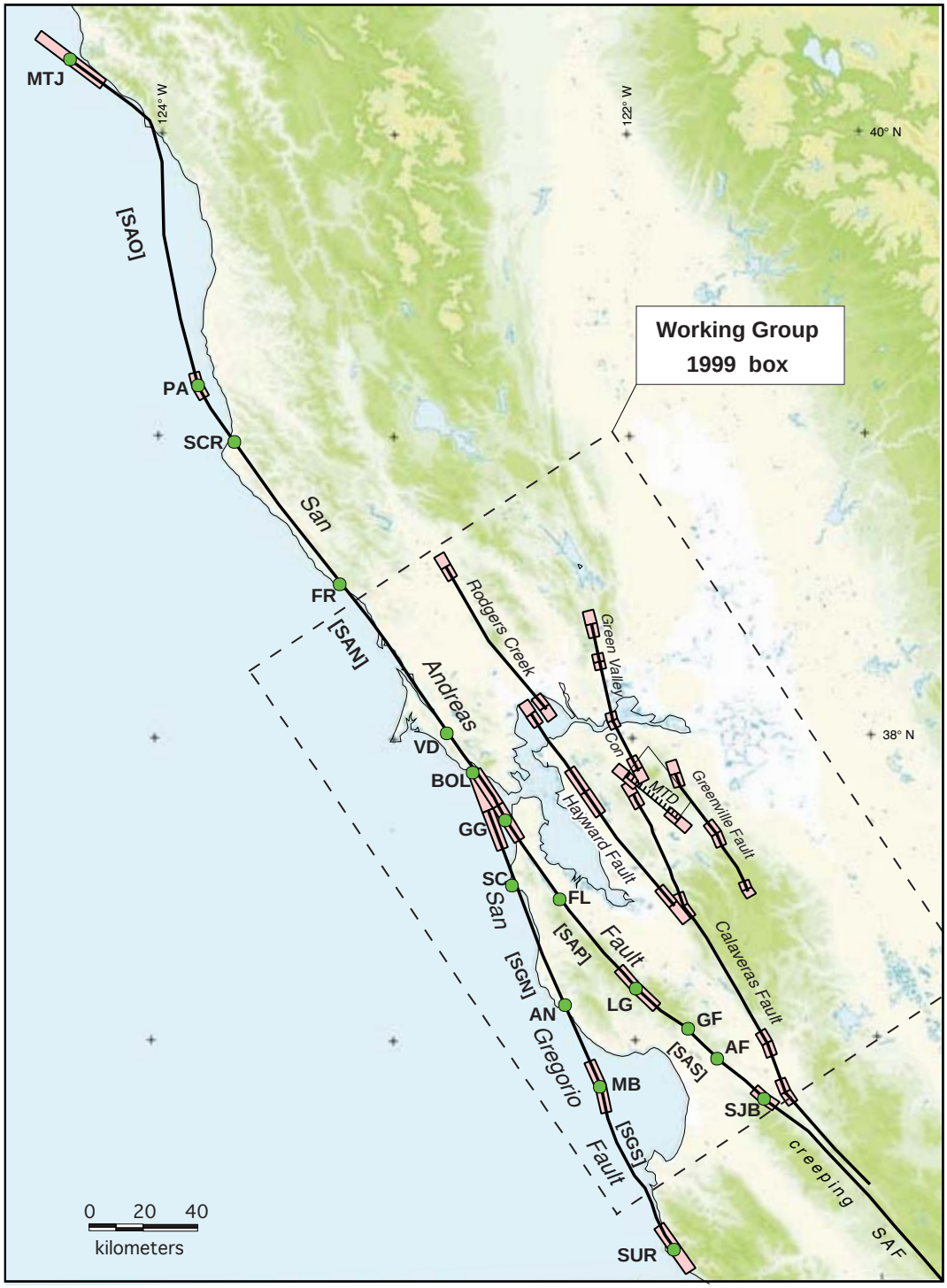
Sample ID	species	Sampling Year	Latitude (N)	Longitude (W)	last year on core	first year on core	years on core	Remarks
SAF_D15A	*Sequoia sempervirens*	2014	37°19'8.53"	122°10'6.23"	2014	1950	64	fault parallel sample (35°)
SAF_D15B					2014	1952	62	center rings crumbly, fault perpendicular sample (280°)
SAF_DND23	*Querqus agrifolia*	2015	37°28'29.70"	122°19'4.24"			< 50	difficult to decipher ring boundaries
SAF_DND25	*Querqus agrifolia*	2015	37°28'32.73"	122°19'7.19"			< 50	difficult to decipher ring boundaries
SAF_DND28	*Querqus agrifolia*	2015	37°28'59.29"	122°19'36.42"	2015	1886	129	good oak sample, possible 1906 earthquake signal
SAF_DND29	*Querqus agrifolia*	2015	37°29'1.50"	122°19'38.36"			< 100	difficult to decipher ring boundaries
SAF_DND30	*Querqus agrifolia*	2015	37°29'0.95"	122°19'37.60"				difficult to decipher ring boundaries
SAF_DND32	*Querqus agrifolia*	2015	37°28'57.56"	122°19'35.08"			< 100	difficult to decipher ring boundaries
SAF_DND36	*Querqus agrifolia*	2015	37°27'25.40"	122°18'4.44"	2015	1913	102	good oak sample

Footnotes

No core reaches year of interest, 1838

Cores are not crossdated

Last year on core is not shown if bark could not be retrieved



Map of the northern San Andreas fault system, with segmentation (segment boundaries shown with pink boxes). From WGCEP (2003). Segments of San Andreas fault (SAF): SAO - Offshore; SAN - North Coast; SAP - Peninsula; SAS - Santa Cruz Mountains. Selected sites along SAF (dots): FL - Filoli; LG - Los Gatos bend in SAF; GF - Grizzly Flat; AR - Arano Flat; SJB - San Juan Bautista. Inset: WGCEP (2003) map of the Peninsula (SAP) and adjacent segments. CSS is Crystal Springs South site.

Figure 1. Map of the Northern San Andreas Fault System, including the Peninsula Segment (SAP).

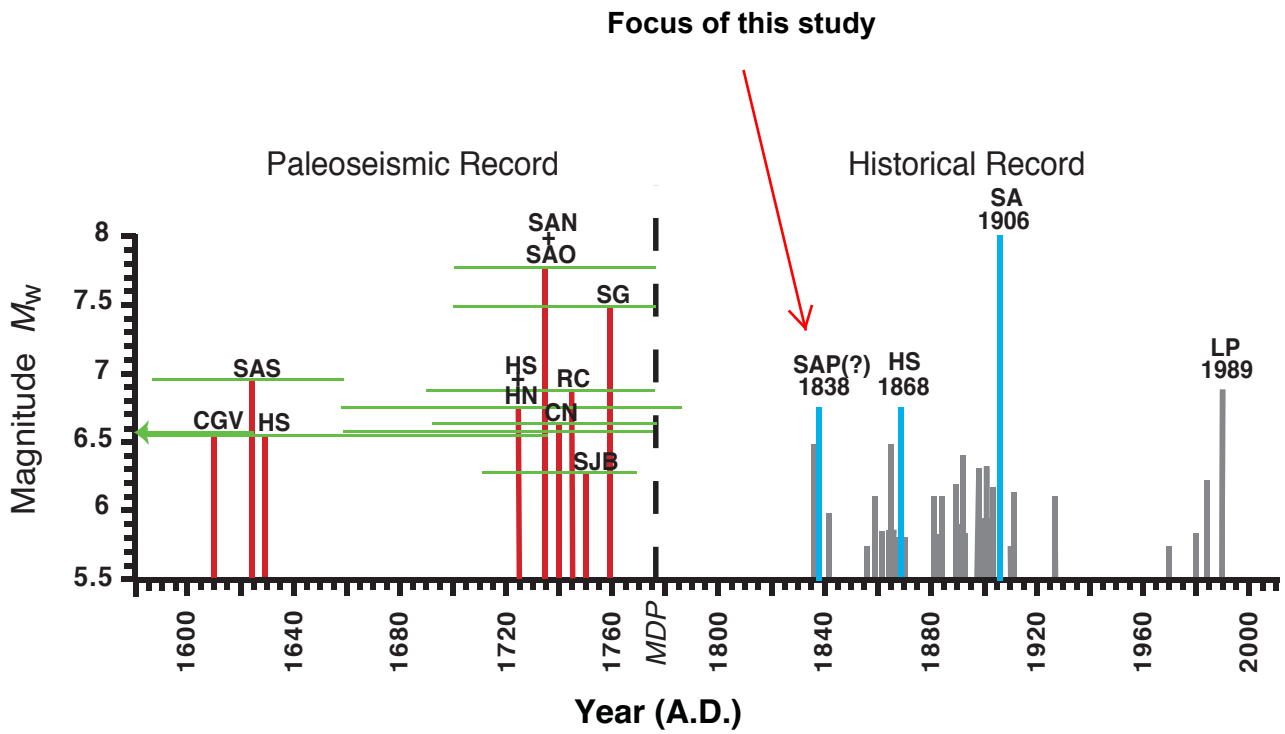


Figure 2. San Francisco Bay Region earthquake history, 1600-2010, showing rupture source sequences (after Schwartz et al., 2014). MDP, initial construction of Mission Dolores and the Presidio (1776). The vertical blue lines are dates and magnitudes of historical surface ruptures. The vertical gray lines are moderate magnitude historical earthquakes (Bakun, 1999). Historical 1838 earthquake is one of four M6.5+ earthquakes known to have occurred in the region; however, the fault and segment it ruptured yet to be proven with field evidence.

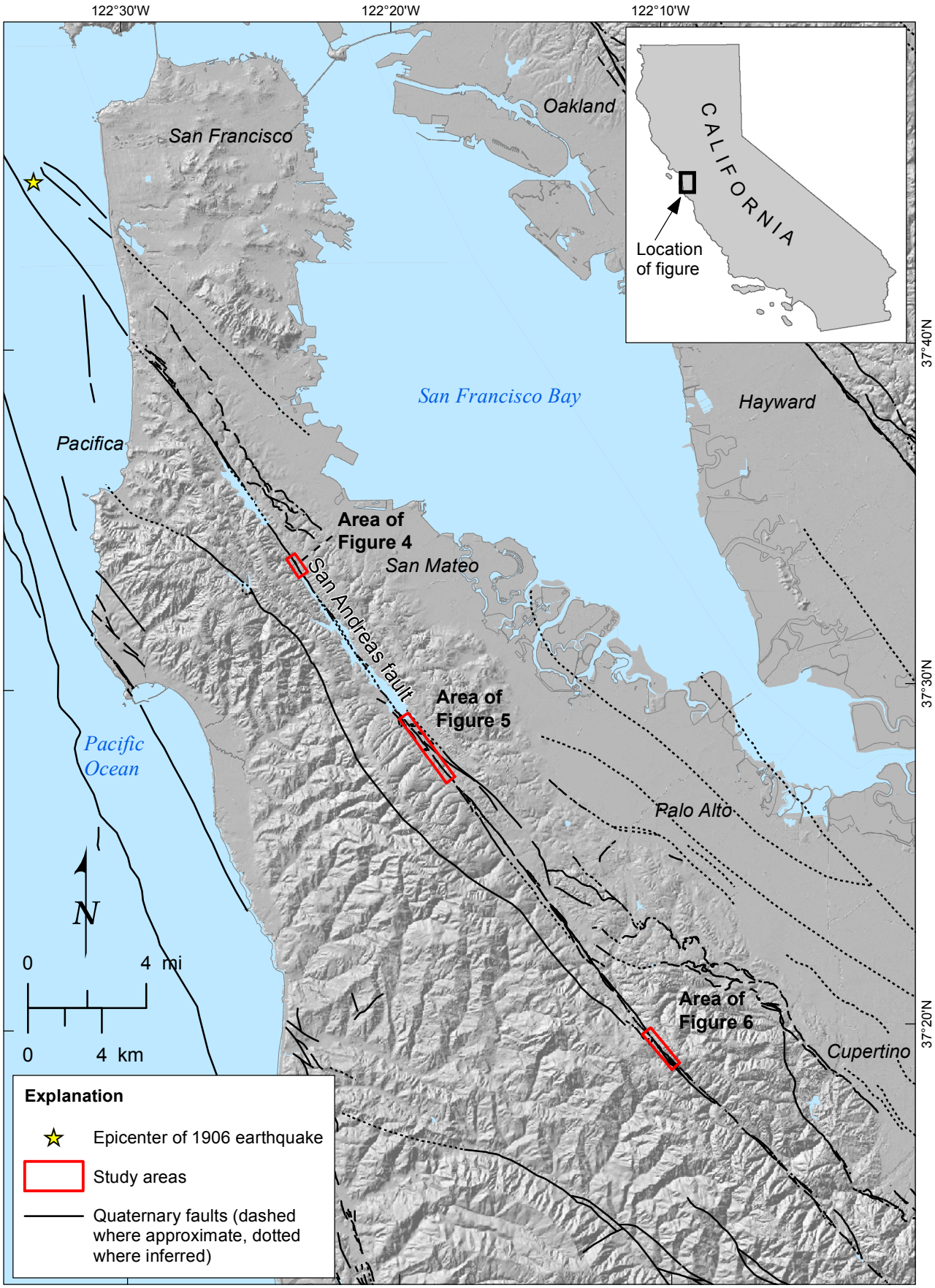


Figure 3. Location map showing visited sites.

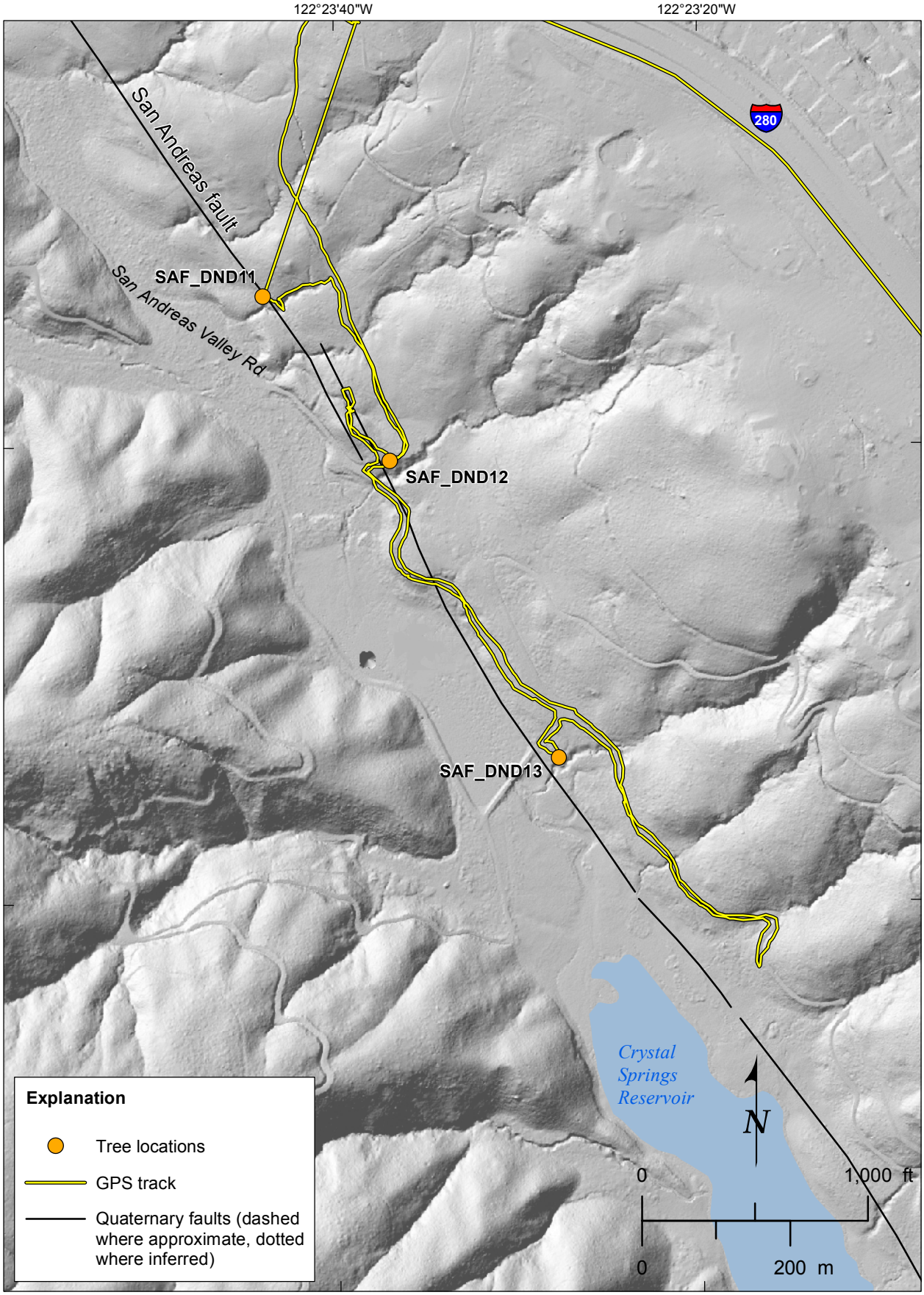


Figure 4. Identified sites north of Crystal Springs reservoir.

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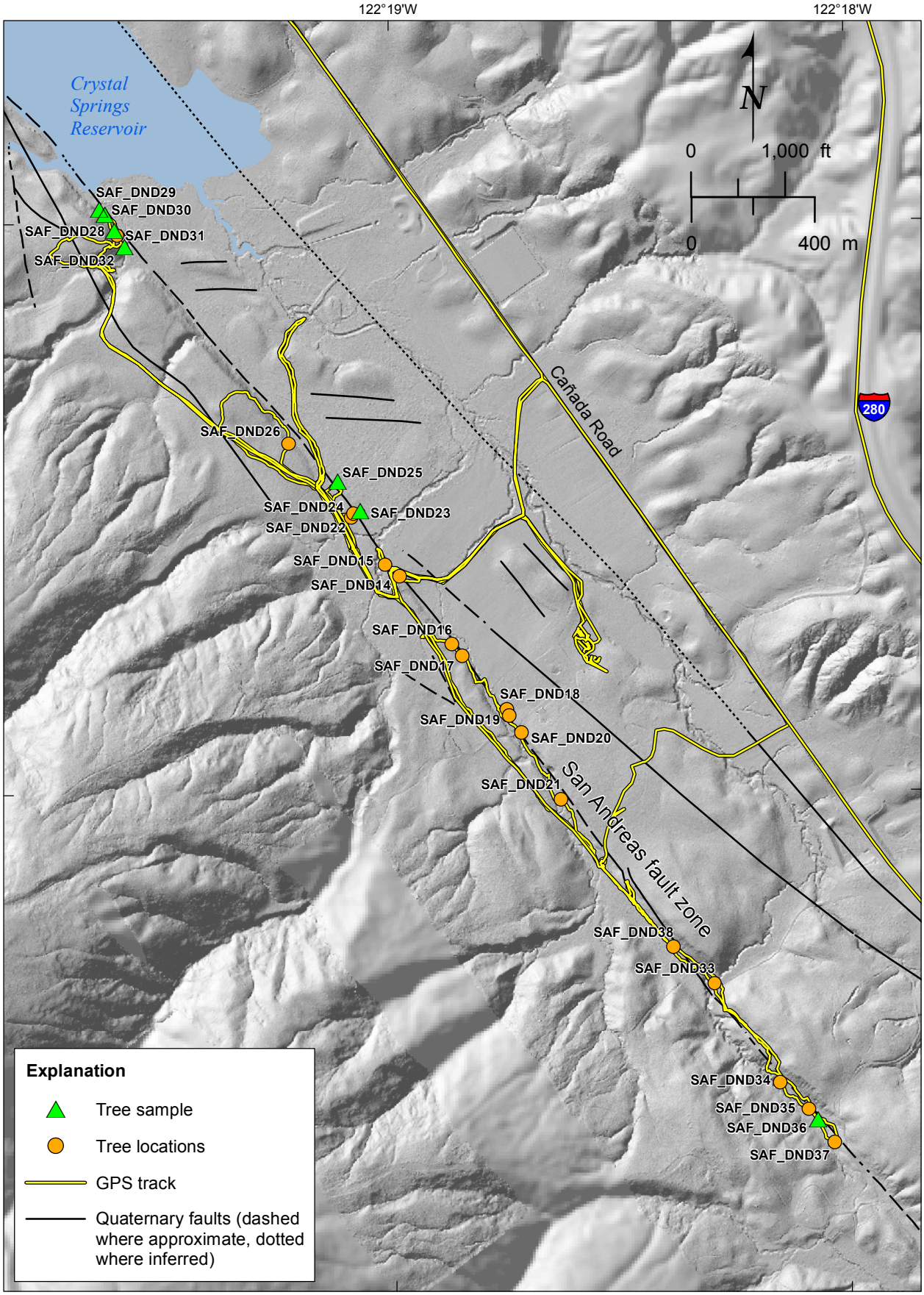

Figure 5. Identified sites south of Crystal Springs reservoir.

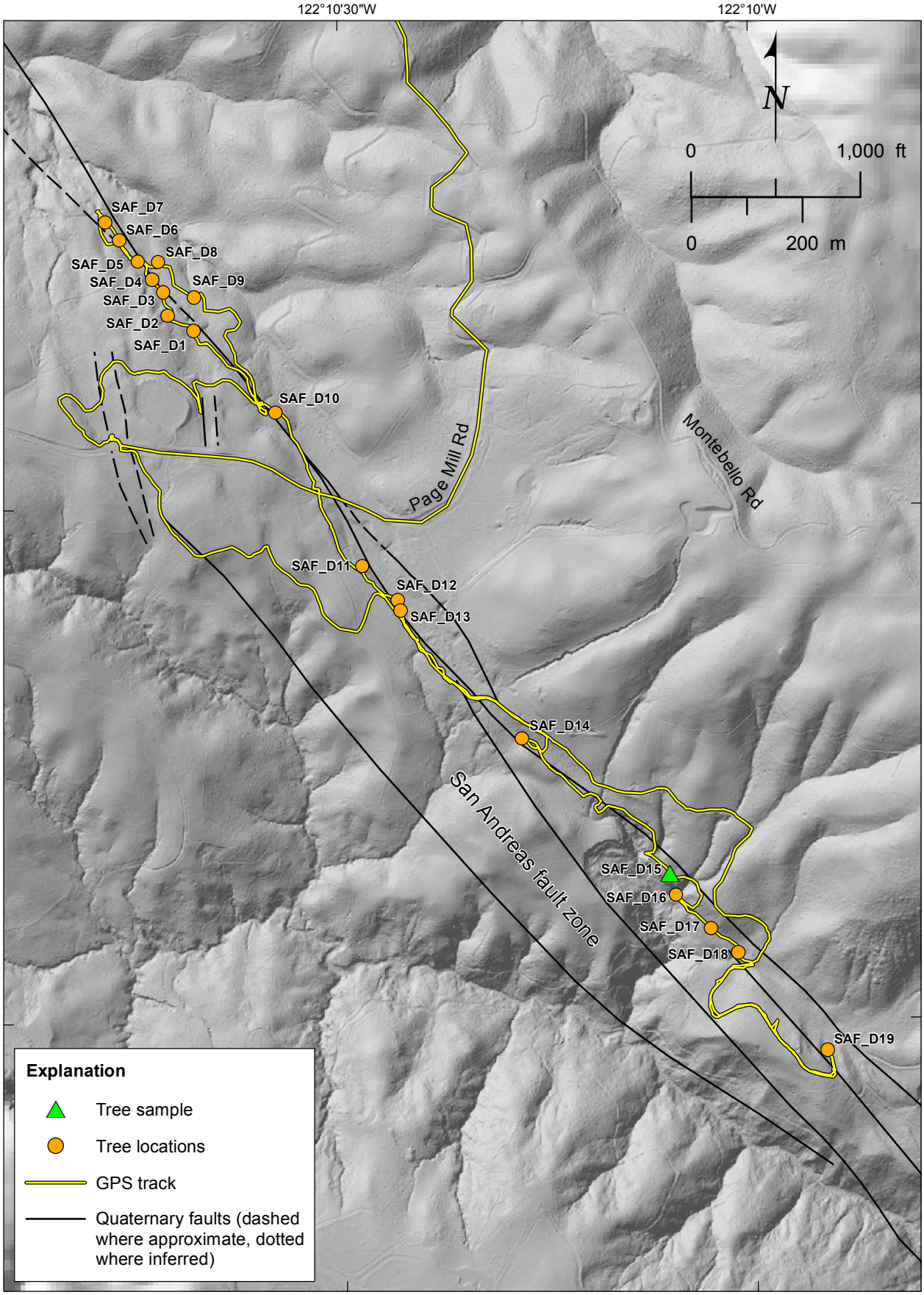

Figure 6. Identified sites in Los Trancos Open Space.

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Figure 7. Tree Sample Site SAF-DND-30.

Figure 8. Tree Sample Site SAF-DND-34.

Figure 9. Cores.

Figure 10. SAF-DND-28 core and close-up of core section 1900-1950.