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Refining age constraints for northern Hayward fault earthquakes to evaluate Hayward-Rogers Creek rupture scenarios

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Summary

A second paleoseismic trench was excavated on the south bank of San Pablo Creek, along the northern Hayward fault In July 2013. In prior trenching (Williams and Baldwin, 2010) identified four, possibly five late event horizons, with the second to earliest event (E4) being the most equivocal. In 2013 four of the 2010 event horizons were recognized, including modestly confirming evidence for Event 2, and substantial confirming evidence for E1 E4 and E5. However burrowing and a compromised sediment record prevented recovery of convincing evidence for a pre-penultimate event (Event 3). Event 4 was weakly recorded in the 2010 exposures by a small stratigraphically-bracketed fold. In 2013 additional and substantial evidence for this event was established. In addition the 2010 chronology was lengthened to include up to 8 events. Evidence for two (possibly three) earlier events was developed, with partial to substantial evidence for each (Figure 1). Suggestive but intriguing evidence of bimodal fault behavior is indicated by the style and extent (or preservation) of surface disruption which ranges from modest (E2, E3, E4, E6, E7), to substantial (E1, E5). More modest event evidence consists largely of upward terminations, bracketed local folding and small fissures. It is conceivable that some or all of these features were produced by aseismic fault offset of long-lived ground surfaces. It is not credible however that E1 and E5 features, (a large fissure and sand infill associated with E1 and extensive surface shattering associated with E5) could have been produced by creep.

Context

Hayward fault crosses San Pablo Creek (SPC) near the base of the East Bay Hills in San Pablo, California. At this location the prominent southern terrace of SPC is blanketed with placed fill over a layered sequence of overbank flood deposits. The creek is a large drainage of the East Bay Hills with a catchment area of ~ 110 km^2. Despite upstream control, the creek experienced over-bank flow in 1940, 1958, and 1998 (Anderson and Balazs, 2004), so is prone to regular flooding and accompanying overbank deposition required for accumulation of a substantial paleoseismic record. The excavation site is within the corporation yard of Saint Joseph's Cemetery.

The 5-m deep San Pablo Creek trenches expose a small (3m wide x 2m deep) fault-bounded basin located beneath substantial placed fill and concrete debris. The basin extends more than 4m parallel to faulting between the 2010 and 2013 trenches and preserves an ~1000-year sequence of San Pablo Creek flood deposits over mudstone bedrock.

The Northern Hayward fault (NHF) is argued to represent a modest or negligible earthquake source (Bürgmann et al., 2000, Simpson et al., 2001; Lienkaemper et al., 2010, 2011), new paleoseismic findings at the San Pablo Creek site (SPC), near the mid point of the NHF, indicate, however, that this section of the Hayward fault has slipped repeatedly in significant surface rupturing events which are expressed by fault scarps, distributed fracture horizons, episodic tilt, and large in-filled fissures. If strain across the NHF is relieved primarily by creep processes, the rupture history recorded at San Pablo Creek may record only the largest events rupturing dynamically through the ~30 km length of a decoupled NHF segment which extends from Berkeley to northern San Pablo Bay (Figure 1). The substantial separation of the adjoining locked faults suggests an alternative model in which some amount of secular strain accumulates as elastic slip potential across the NHF, enabling it to rupture in conjunction with the relatively frequent large earthquakes of the adjoining fault segments. It is plausible in either context (decoupled or slow strain accumulation) that some, and perhaps all of the events recorded at SPC express linked ruptures of the Rogers Creek fault (RCF) and southern Hayward fault (SHF). To test the possibility that the NHF ruptures only in conjunction with one or both of the adjoining locked segments, we propose to develop an earthquake chronology with sufficient resolution to compare and contrast to chronologies from the adjoining fault segments (e.g. Budding 1991, Hecker et al., 2005; Lienkaemper and Williams, 2007; Schwartz et al., 1992). If the surface rupturing events recorded at SPC are a subset of paleoseismic events rupturing the adjoining fault segments, it would indicate that the NHF segment typically ruptures in conjunction with adjoining segments. The proposed field investigation and integrative analysis is designed to support fault hazard modeling, particularly to provide earthquake timing data for the northern Hayward fault to be utilized in updates to the UCERF-3 evaluation of the northern portion of the eastern San Francisco Bay Area, from Oakland to Richmond.

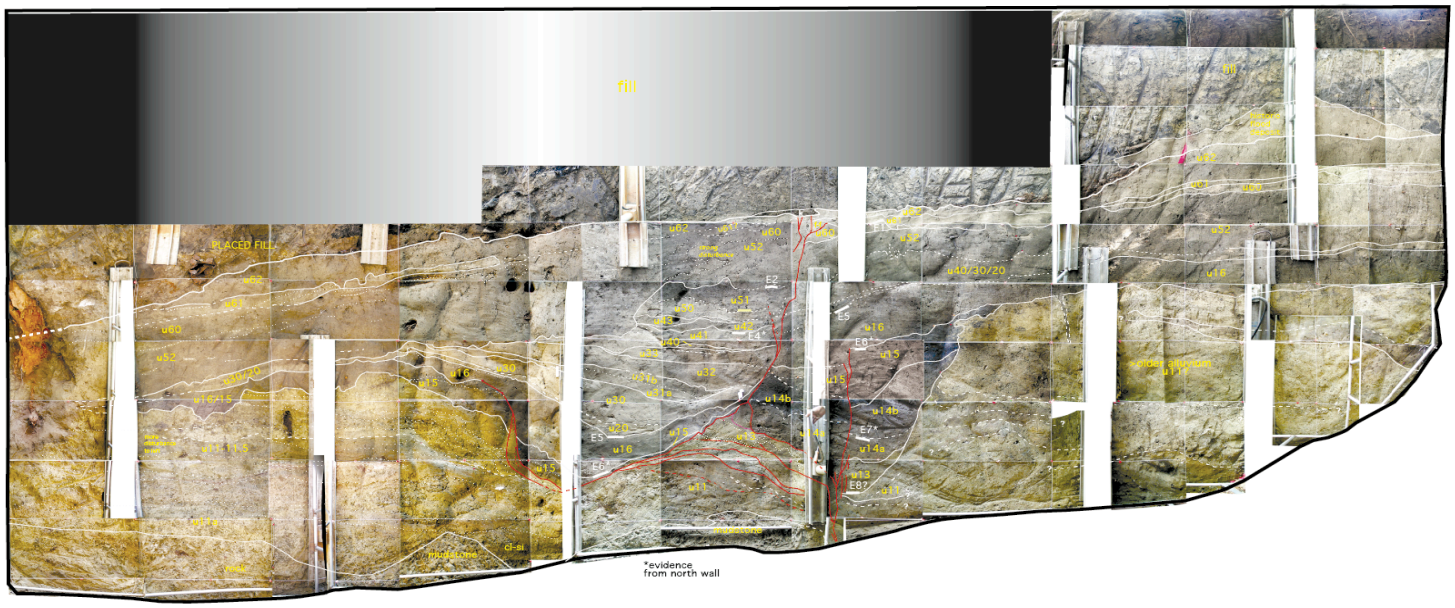

Figure 1. Trench log, south wall of San Pablo Creek site Trench 3, 2013. Unit numbers are in yellow, event horizons noted in white. Primary evidence for events 2, 4, 6 and 7 is located on the north wall log, in progress. Portions of the north wall log containing primary event evidence are included in this report.

Table 1

2013	2010
young fill (e.g. tires, asphalt, fabric etc.)	*young fill* (e.g. tires, asphalt, fabric etc.)
older fill (e.g. nails, glass, ceramics)	*older fill* (e.g. nails, glass, ceramics)
historic flood deposit (e.g. blue potion bottle in flood deposit)	*Not recognized in 2010*
u62 modern soil dev on u62 (no artifacts found)	u62 modern soil dev on u62 (no artifacts found)
u61 silty sand (fills fissures)	u61 silty sand (fills fissures, liquifacton deposit(?))
E1 fissure; u-t	**E1** prominent fissure; u-t
u60 weak paleosol on flood deposit	u60 weak paleosol on flood deposit

u52 strong paleosol, ±massive	u52 strong paleosol, ±massive
E2 ±fissure; u-t;	**E2** ±fissure; u-t; 70cm sag + u52 infill
u51	u51
E3 **not observed in 2013**	**E3** small graben; u-t
u50	u50
u43,	u43,
u42	u42
E4 small fissure, bracketed fold – North Wall	**E4** equivocal bracketed fold
u41	u41
u40 **marker** coarse well-sorted sand	u40 **marker** coarse well-sorted sand
u33	u33
u32 (fills acc-space)	u32 (fills acc-space)
u31 (folded+fills acc-space)	u31 (folded+fills acc-space)
u30 (folded+fills acc-space??)	u30 (folded+fills acc-space??)
u20	u20
E5 u-t in u16 below u20	**E5** prominent u-t in u16 below u20
u16 folded+fills acc-space (soil dev on u16)	u16 folded+fills acc-space (soil dev on u16)
E6 after or mid u15 time, definitely pre u16 North Wall	**E6** **not observed in 2013**
u15 (soil dev on u15)	u15 (soil dev on u15)
u14a	u14a
E7 after or mid u14 time, pre u15	**E7** **not observed in 2013**

u14	u14
u13	u13
E8? post u11.5, pre u13	**E8?** **not observed in 2013**
u11.5	u11.5
u11	u11
u5	u5

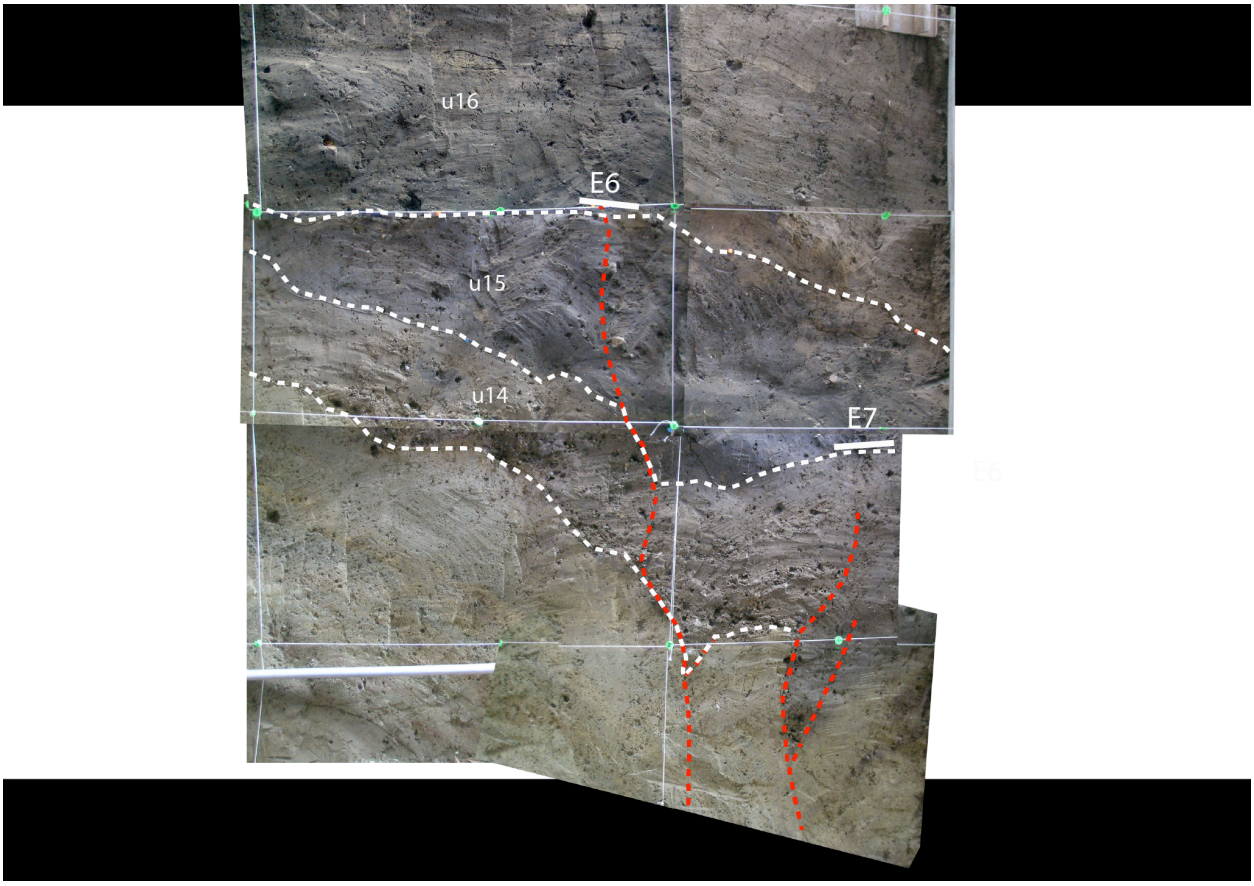

Figure 2. Primary evidence for Events 6 and 7 are simple upward fault terminations against erosional horizons on units 15 and 14, respectively. Exposure located in Trench SJC-3, north wall, 2013.

Findings

The principal activity of the reported work is development of a substantial multi-event prehistoric earthquake record for the northern Hayward fault at the San Pablo Creek site (Figure 2). A general chronological context has been developed for the site (Table 1), and complex faulting, extensional fissures and tilted fluvial beds have been described in a stratigraphic context. Evidence developed from the 2010 excavations indicate that at least four, and possibly five surface rupturing events occurred during the past ~1000 year period. The primary trench exposure disclosed well-bedded fluvial stratigraphy, and detrital and in-situe charcoal were collected from several stratigraphic intervals. Complex faulting, extensional fissures and tilted fluvial beds were described and indicate that continued paleoseismic exploration would clarify and amplify evidence of individual events and improve the possibility of developing a sufficient dataset to compare with the Mira Vista site on the NHF as well as the adjoining southern Hayward fault and Rogers Creek fault segments.

During 2013 a the most equivocal of the 2010 events (E4) was substantiated, and evidence for two and possibly three earlier events was developed.

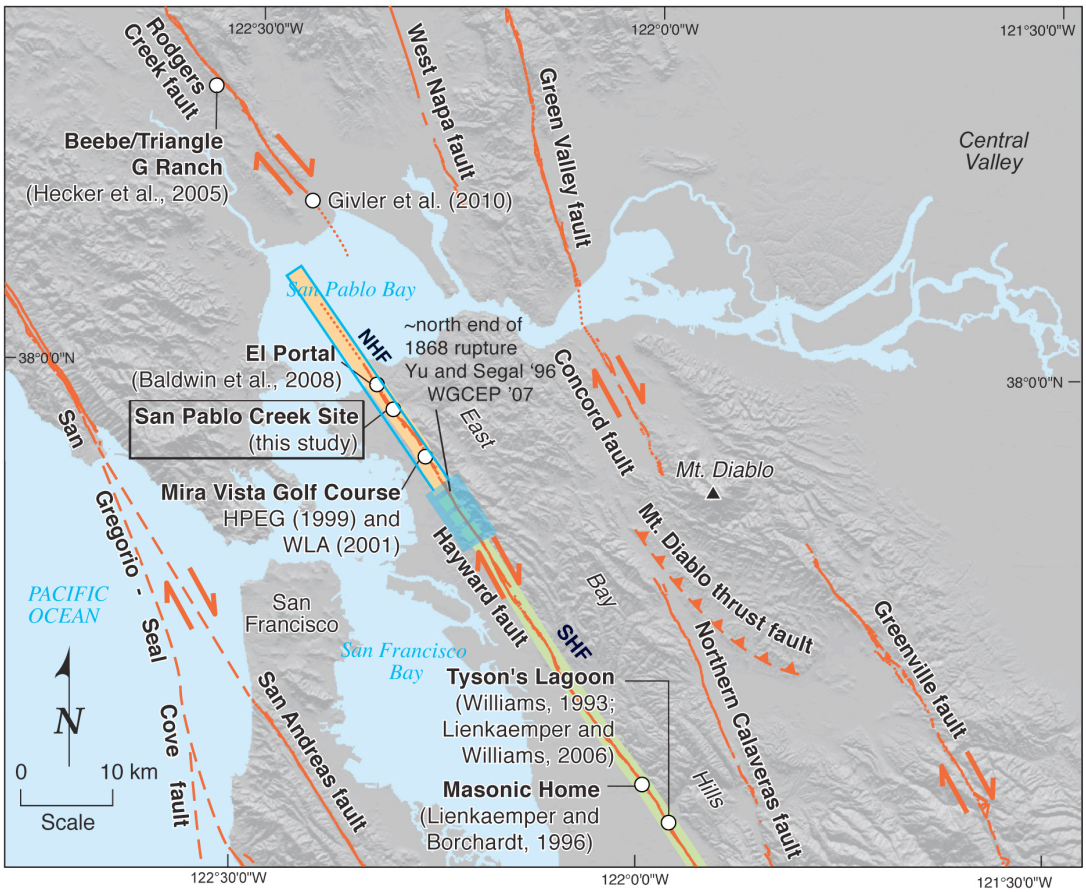

Figure 2. Regional fault map illustrating the location of the Northern and Southern Hayward fault (NHF and SHF, respectively) and locations of the San Pablo Creek site and fother field sites discussed in the text. Segment boundary approximated by area of blue box from WGCEP (2003, 2007) is the northern extent of 1868 rupture as derived from triangulation data (Yu and Segal, 1996), and is associated with evidence of reduced fault coupling (Bürgmann et al., 2000, Simpson et al., 2001; Lienkaemper et al., 2010)

Site stratigraphy consists of older channel deposits, Tertiary bedrock, and moderately to well-bedded, generally fining-up overbank deposits containing fine sands, abundant silt and traces of clay. The overbank stratigraphy contains common detrital and apparent in-situe carbon residues in several of the mapped intervals. Preliminary interpretation of stratigraphic and structural relations, coupled with limited radiocarbon results, indicates that the most recent surface rupture (MRE) occurred just prior to the late 18th or mid 17th century. While several sites have been explored previously along the entirety of the Hayward fault, the San Pablo Creek site is just the third showing clear promise to disclose a substantial earthquake record.

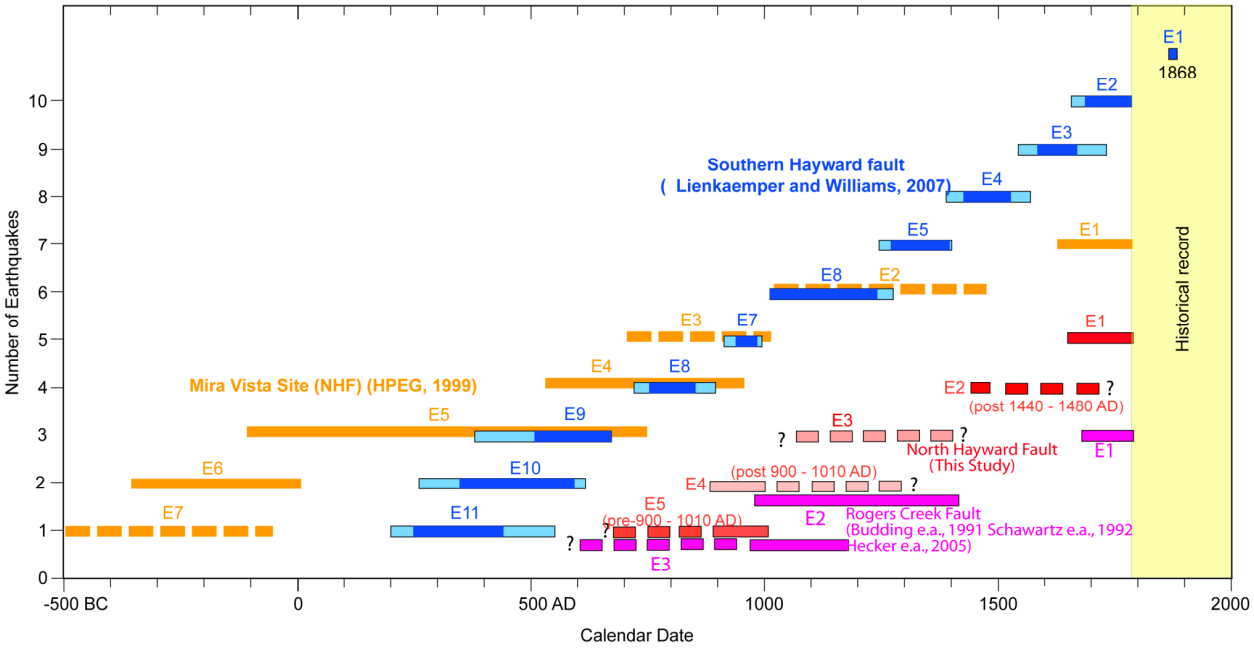

Figure 3. Event chronology data for the northern Hayward fault (orange- HPEG, 1999; red- this study); southern Hayward fault (blue- Lienkaemper and Williams, 2007); and Rogers Creek fault (magenta- Budding et al., 1991; Schwartz et al., 1992; Hecker et al., 2005). Event numbers are shown above each event bar symbol. Note that the orange-colored events shown as dashed were reported with less certainty than those that are solid (HPEG 1999). Red colored NHF events E3 and E4 have weaker physical evidence so are shown in lighter shading, Queries represent lack of constraining age data.

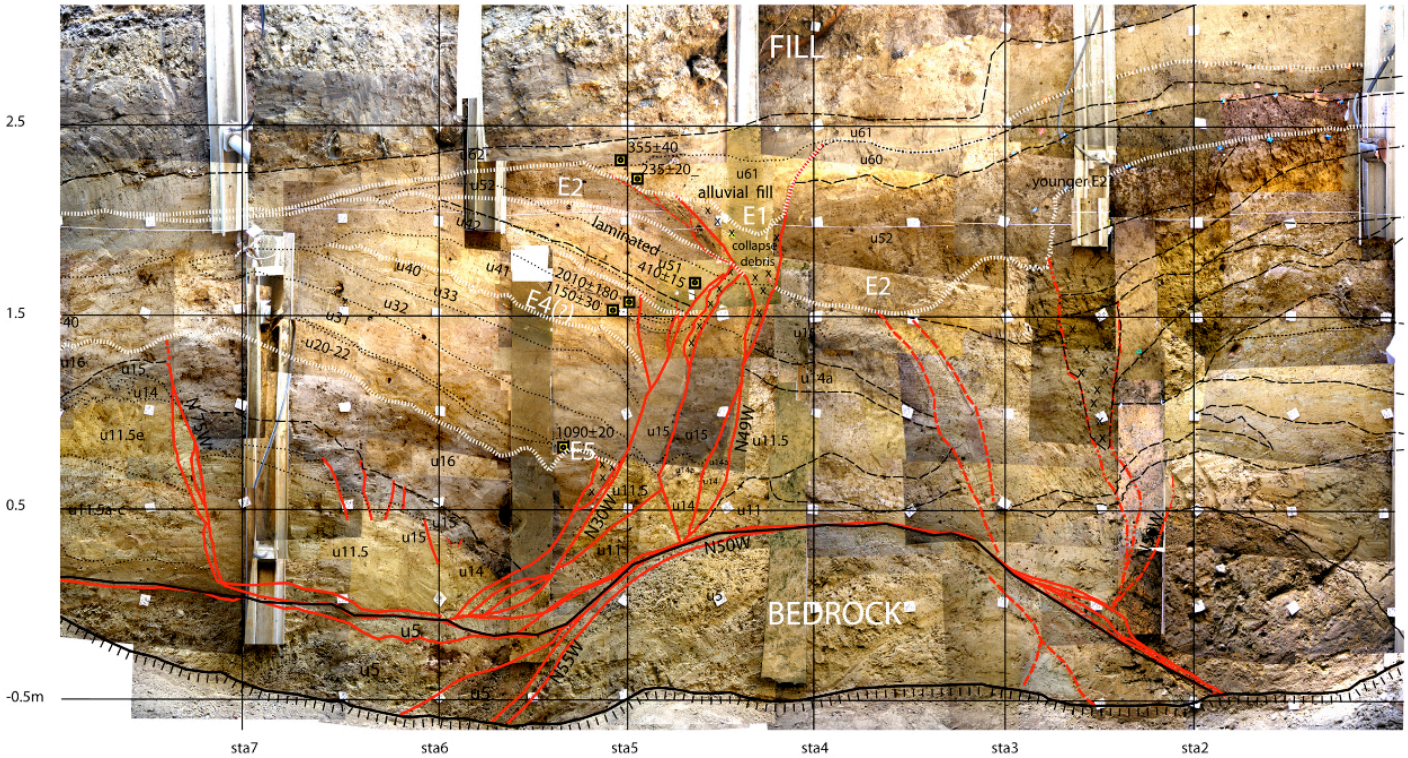

Figure 4. A portion of the south wall T2 trench log from an area of concentrated primary event evidence. Faults are located in red, dashed where unclear or inferred. Event horizons are illustrated by prominent dashed white lines. Event evidence consists of in-filled fissures (E1, E2, E5), upward terminations (E1, 3, E5), tilt and infill (E2), distributed un-rooted fractures (E5), and folding and infill (E3, E4). Event stratigraphy is presented in tabular form in Table 1.

Events

MRE (E1). The MRE is recorded by a large filled-fissure associated with a primary fault branch. Timing of this event is consistent with that at Mira Vista in that it is clearly older than the historical 1868 SHF rupture (Figure 2), but its age falls with a period that is difficult for radiocarbon calibration. A sample recovered immediately above the stratigraphic event horizon is dated 235±20 radiocarbon years. With remarkably small uncertainties (±10-15 years) the calibrated age of the sample is circa either AD~1655 or AD~1780. This result closely approximates the bracketed MRE results at Mira Vista. In the AD 1780 case, the event occurred within the same decade as arrival of the permanent Spanish Mission at San Francisco. Evidence for the MRE is considered substantial; Dating of the MRE remains preliminary.

E2. The penultimate event is expressed by multiple evidence of tilt and infill, upward terminations and fissure fill. One date has been obtained below the E2 event horizon and gives a calibrated maximum age for E2 as 550 calibrated years before present (CYBP), the minimum age so-far determined is pre E1 (AD 1640-1776). Current information for the ultimate and penultimate events show that E1 happened no more than ~360 CYBP, and E2 occurred no more than ~550 CYBP, thus E2 is bracketed between 360 and 550 years CYBP. While evidence for this event is considered substantial, age information is limited.

E3. The pre-penultimate event is recorded by a small area of upward terminations and extensional sag bounded by faulting. Evidence for E3 is credible, but is much less substantial

than that for E1, E2 and E5. Age constraint for E3 is "more than ~550 CYBP. E3 does not have a useful pre-event age constraint.

E4. E4 is weakly expressed and was considered to be the least likely of the asserted events to represent substantial NHF fault rupture. Evidence developed during the 2013 excavations indicates E4 is included in the set of modest event horizons with clear stratigraphic evidence." The T2 exposure (Figure 4) contains a small area of unrooted (downward terminating) detachment folding with apparent infill beneath that associated with E3. Additional evidence is required to substantiate evidence for this event. The north wall of trench T2 contains apparent sag and infill at the event horizon, providing additional support for the possibility that 4 may indeed be a credible event. On both walls the folding is located beside the most-strongly expressed zone of faulting. Age information is limited to a pre-event age of about 1050 CYBP

E5. E5 is a well-expressed event in the lower part of the section exposed in 2010., with an event horizon located immediately below a carbon sample dated at 1050 CYBP. The event is expressed by localized offset,apparent scarp formation, detached fractures, folding, and minor fissure fill. No lower age constraint has been developed for E5, but upper age-constraint for the event appears to be excellent.

In summary, physical evidence for three well-recorded events has been developed at the SPC site. Physical evidence for two additional events is preliminary and additional work is required to substantiate or remove these events in the record. All the substantiated and conditional event horizons are contained in a stratigraphic section containing 30 major subunits and extending to more than 1100 years in age.

E6 and E7 are indicated by upward fault terminations against erosional horizons developed on units 14 and 15, respectively, see extract from north wall trench log, Figure 2.

Acknowledgements

We are grateful to the managing staff of St Joseph's for permitting access for these studies. The project is designed to provide data for sufficient formal fault hazard modeling, specifically for the evaluation of the northern portion of the Hayward fault in the eastern San Francisco Bay Area.