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FINAL TECHNICAL REPORT

RENEWAL: DETERMINATION OF A HIGH RESOLUTION PALEOEARTHQUAKE CHRONOLOGY FOR THE NORTHERN SAN ANDREAS FAULT AT THE VEDANTA MARSH SITE, MARIN COUNTY, CA

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National Earthquake Hazards Reduction Program Element II:
Research priorities to understand earthquake occurrence and effect

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Technical Abstract:

Trench exposures and three-dimensional excavations along the 1906 trace of the northern San Andreas fault (SAF) at the Vedanta Marsh near Olema, CA have yielded new data on the timing and amount of slip during the penultimate earthquake. Our chronological model indicates that the penultimate earthquake occurred during 1725 to 1805 A.D. and probably before the establishment of the Mission Dolores in 1776. Exposure of a 3-m-wide gravel-filled channel faulted in 1906 and the penultimate earthquakes indicates a cumulative right-lateral offset of 7.8-8.0m. Local measurements of 5m offsets in the 1906 earthquake suggest that the cumulative slip is likely distributed as 5m in 1906 and 3m of slip in the penultimate earthquake. These data indicate that the North Coast segment of the SAF north of San Francisco is capable of rupturing in an Mw ~7 earthquake. The short recurrence interval (155 ± 25 yrs) between the penultimate and 1906 earthquakes on a seismic source 45 km north of San Francisco is likely to increase the overall earthquake probability forecast for the Bay Area.

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Introduction:

The main objective of this NEHRP research is to obtain a high-resolution chronology of paleoearthquakes on the 1906 rupture trace of the San Andreas fault and to determine slip-per-event of pre-1906 earthquakes through detailed three-dimensional excavations. Determining the timing of past San Andreas fault earthquakes has great significance for the long-term seismic hazards of the densely populated San Francisco Bay region. The results of this research will be used to test earthquake rupture models of the San Andreas fault and to improve the earthquake probability estimates published by the U.S. Geological Survey. The anticipated outcome of this research will be a better definition of the earthquake cycle in the San Francisco Bay area.

This research was conducted on the Vedanta Retreat property in Olema, Marin County, CA (Fig. 1). The Vedanta site has proven to be an excellent paleoseismic site because 1) the fault zone is wide with multiple fractures and definable event stratigraphy, 2) the layers contain *in situ* organic material that will provide age control, and 3) the margins of channel deposits, downed Douglas fir trees, and landslide debris lobes detected in trench exposures can provide piercing points to match across the fault in order to determine paleo-slip.

To clearly define the timing and slip of past earthquakes, we need redundancy in the observable and collectible data. Previous trenching investigations conducted at Vedanta site in 2001 and 2002 have yielded abundant data including marsh stratigraphy classification, earthquake events observation and radiocarbon dating. Following is a summary of research conducted during the 2004 field season in which 3-D excavations recovered an offset paleochannel that documents a cumulative coseismic displacement during the last two earthquakes.

Investigation undertaken:

Previous trench investigations revealed a paleochannel cut by the northern San Andreas Fault in Trench 4. During the 2-month 2004 field season, 3-D excavations were conducted carefully on both side of the Trench 4 along the fault trace in order to accurately document the cumulative coseimic displacement of the offset paleochannel.

Two large pits were excavated to a depth of around 1.5 m and a width of 2 to 4 m (Fig. 1). The excavations were progressively hand dug to uncover the buried channel, while leaving

the channel intact. The pit floors were gridded, photographed, and logged on both graph paper and mosaic photos.

At the end of the 2004 field season, a trench party was held at the Vedanta trench sites. Around 20 people coming from the USGS, the Point Reyes National Park Service, and other agencies, organizations or corporations came to the site and provided comments.

Preliminary results of this researchwere presented at the 2004 AGU Fall Meeting in San Francisco and at the 2nd Annual Northern California Earthquake Hazards Workshop held at the U.S.G.S. in Menlo Park on January 18-19, 2005.

Preliminary Publications:

Niemi, T.M., Zhang, H., and Fumal, T.E., 2005, Determination of a high resolution paleoearthquake chronology for the northern San Andreas fault at the Vedanta marsh site, Marin County, CA (Renewal), in Annual northern California Earthquake Hazards Workshop, January 18-19, 2005, Zoback M.L. (ed.): U.S.G.S. Open-file Report, p. 70.

Zhang, H., Niemi, T.M., Allison, A.J., and Fumal, T.R., 2004, Noncharacteristic slip on the northern San Andreas fault in Olema, CA (abst.): *Eos Transactions AGU*, 85 (47) Fall Meet. Suppl., Abstract T13C-1395.

Niemi, T.M., Kayen, R., Zhang, H., Dunn, C.R., and Doolin, DM., 2004, LiDAR Imagery of the San Andreas Fault zone at the Vedanta and Olema Ridge Paleoseismic Trench sites, Pt. Reyes, CA (abst.): *Eos Transactions AGU* 85 (47) Fall Meet. Suppl., Abstract G13B-0811.

Results:

The great San Francisco earthquake of April 18, 1906, was generated by a 470-km-long rupture of the northern San Andreas fault (SAF; Fig. 1). The earthquake produced maximum horizontal offsets of 5-6m north of San Francisco (SF) with generally smaller offsets measured south of the city (Lawson, 1908). This coseismic slip gradient (Fig. 1) was confirmed by modeling geodetic data (Thatcher *et al*., 1997). The decrease in slip on the southern section of the rupture may reflect the release of strain in 18th and 19th century earthquakes that are thought to have occurred on the SF Peninsula and in Santa Cruz Mountains segments of the SAF (Toppozada *et al.,* 2002; Fumal *et al*., 2003). Furthermore, the geologic and GPS-modeled SAF slip rate on the SF Peninsula is lower than on Point Reyes Peninsula presumably due to the partitioning of slip on to the San Gregorio fault (Niemi and Hall, 1992; Hall *et al*., 1999; D'Alessio, *et al*., 2005). Together these data suggest that the 1906 SAF rupture trace north and south of the Golden Gate behave as different fault segments.

Faults typically are subdivided into segments based on structural or historical ground rupture boundaries and are assumed to behave in a distinct or typical pattern over several earthquake cycles (*e.g*. McCalpin, 1996). In their study, the Working Group on California Earthquake Probabilities (WGCEP, 2003) defined four primary segments on the northern SAF: the Santa Cruz Mountains, the Peninsula, the North Coast, and the Offshore segments (Fig. 1). Earthquake probabilities for the SF Bay Area were determined by using various rupture scenarios that combined simultaneous faulting on 1, 2, 3 or all 4 SAF segments (WGCEP, 2003). Whereas a random (floating) and several non-1906 rupture segment models were considered, the WGCEP heavily weighed the characteristic earthquake model (Schwartz and Coppersmith,

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1984) where the slip distribution in 1906 is considered characteristic. However, since historical data do not extend over a complete earthquake cycle, little is known about the long-term fault behavior of the northern SAF. This paper describes paleoseismic research conducted on the North Coast segment of the SAF north of SF at Vedanta Marsh that constrains the timing and coseismic slip in the earthquake prior to 1906 and tests the characteristic earthquake model.

Site Description

The Vedanta trench site is located in a marsh near the town of Olema approximately 45-km north of SF. The 1906 trace of the SAF closely follows the northeastern margin of the marsh along the break-in-slope at the base of a ridge of upper Pleistocene fluvial deposits (Figs. 1B; Hall and Hughes, 1980). Gravity models indicate that Holocene and late Pleistocene sediment thickens from 40 m along the southwest margin of the marsh to about 80 m toward the SAF suggesting asymmetrical tectonic subsidence across the basin (Grove and Niemi, 2005).

Documentation of the effects of the earthquake at the Vedanta Marsh, which was the Shafter Ranch in 1906, was recorded by G.K. Gilbert (Lawson 1908) starting two weeks after the earthquake. Here, the1906 rupture followed a single strand within a secondary zone of cracking 3-4.5 m wide. Local subsidence caused water to pond to at least a depth of 70 cm along the fault trace.

In this study, nine trenches, 2 to 4 m deep, were excavated across the SAF (Fig. 1C). Stratigraphic relationships were recorded using 1.0 x 0.5m grid using photographic and graphic logging methods.

Stratigraphy and Earthquake Evidence

The late Holocene stratigraphy exposed in the trenches consists of well-sorted gravel up to 1 m thick overlying a sequence of fine-grained marsh sediment interbedded with thin fluvial gravel lenses (Fig. 2). This sequence interfingers eastward with poorly-sorted, colluvial gravel derived from the adjacent Pleistocene terrace. Faulting is expressed as a 2-m-wide zone of upward-branching splays (Fig. 3). Stratigraphic evidence for earthquakes includes upward fault terminations, in-filled fissures associated with surface rupture, soft-sediment deformation such as folding, unconformities or abrupt changes in deformation between stratigraphic units, and rotated and truncated blocks along the fault.

The upper gravel that caps the entire sequence is divided into layers 1-6. Layers (1-3) consist of a modern fill and colluvium produced by mechanized equipment. These layers are not faulted by the 1906 earthquake and contain artifacts such as barbed wire, horseshoes, square nails, fence posts, and slabs of road pavement.

Layers 4-5 consist of gravelly channel deposits that in places have distinct graded bedding, cross-stratification, and sand lenses. In other places, these deposits have a matrix of fine-grained sediment (layer 6) and are bioturbated and partially colluvial in nature. Figure 3A shows a well-developed fissure that is filled with gravel of layer 4 and blocks of underlying layers and indicate that layer 4 was at the ground surface at the time of the 1906 earthquake.

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The stratigraphic sequence below layer 6 reflects predominantly fine-grained deposition within the marsh. The erosion at the base of unit 6 has removed the underlying layer 9 and 10 in some locations. This change in sediment deposition from fine-grained to coarse-clastic sediment was possibly triggered by the regional deforestation and denudation caused by the arrival of European settlers and loggers in the late 19th Century. Historical erosion, channel incision, and increased sedimentation rates have been documented for this region (Niemi and Hall, 1996; Knudsen *et al.,* 2002). Efforts to drain the Vedanta marsh over the past 150 years (Lawson, 1908) have also lowered the water table about 1.5 m causing burrows and erosional contacts.

The fine-grained marsh deposits consist of interbedded clay, clayey silt, silt (layers 9, 12, 21) and organic-rich, or woody or peaty layers (layers 10 and 20). The organic layers are composed of both decayed vegetative mats formed *in situ* and detrital organic debris washed into the marsh from the adjacent upland ridges. The organic horizons are sometimes associated with charcoal, wood ash, *in situ* burns with oxidized sediment patches, and burnt logs. Trenches in the central part of the site exposed occasional narrow, well-defined channels filled with well-sorted fluvial sand and gravel.

Where the silty clay layer 9 and underlying peat layer 10 are fully preserved, we found evidence for the penultimate earthquake (Event II). Event II faulting terminates at the top of peat layer 10. Ground fissures (Fig. 3) formed during this earthquake are filled with blocks of layer 10 peat and deformed blocks of the underlying ash of burn layer 11. Silty clay Layer 9 caps the earthquake horizon. In some exposures, Event II terminates at the erosional contact between layer 10 and layer 6.

Age Constraints

Age control for the Vedanta marsh sedimentary layers is derived from radiocarbon dating of organic material including peat, wood, and charcoal extracted from each of the horizons. A range of radiocarbon ages for each layer reflects the varying source areas for the carbon materials that have been dated. Wood preserved in the marsh is derived from the adjacent upland ridge and can include the long-lived Douglas fir tree [*Pseudotsuga menziseii* (Mirb.) Franco]. Detrital carbon is often older than the layer that contains it. Sixty-eight radiocarbon dates were obtained for layers 4-12. Table 1 contains a list of the radiocarbon data and a scatter plot of radiocarbon sample age verses stratigraphic depth used in the layer dating analyses is shown in Figure 4.

We used the OxCal program to model the ages of each of the layers and earthquakes. OxCal is a Bayesian statistical computer program (Bronk Ramsey, 2006) that calibrates radiocarbon ages and incorporates available chronological constraints including stratigraphic ordering and historical data to trim the possible age range of a unit or event. The OxCal program also provides a quantitative means to identify and exclude ages that are inconsistent with the chronological model as a whole.

A summary of the chronological model that utilized thirty radiocarbon dates above layer 20 is shown both in Figure 2 and Figure 5. Layers 1-3 are constrained by artifacts to be 20th century. Layer 4 is the horizon for the 1906 earthquake. The horizon of the penultimate earthquake (Event II) is constrained stratigraphically to the top of Layer 10. Event II post-dates

layers 11 and 12 and pre-dates layer 9. Based on our radiocarbon dating and age model analyses, the penultimate earthquake occurred within a two-sigma calendar age range of 1725-1805 A.D. Since northern California earthquake catalogues are fairly complete for large earthquakes (M~7) after the establishment of the Mission Dolores in San Francisco in 1776 (Toppozada *et al.*, 2002), we can further constrain the timing of the penultimate earthquake to 1725-1776 A.D.

Channel Offset and Coseismic Slip

In order to constrain the amount of slip in the penultimate earthquake, we exposed a buried channel that is offset by Events I (1906) and II (Fig. 3). In Trench 4, Event II faulting clearly truncates a channel gravel deposit (layer 12 d) that lies near the base layer 12. The lens-shaped paleochannel is about 3 m in width and approximately 30 cm thick (Fig. 3B). The channel gravel stratigraphically overlies silty clay layer 21. The channel margins, exposed in Pit 1 and 2 located north and south of Trench 4 respectively, trend N80^{0}W and intersect the N40^{0}W-striking main fault trace at about a 40^0 angle (Fig. 3).

Cumulative offset for the past two earthquakes was measured by matching both the northern and southern channel margins across the fault that splays into subparallel strands separated by about a meter (Fig. 3). The north margin of the channel is offset 8 m from point A to B, and the south margin is offset 7.8 m from point C to D. An additional constraint on the offset of the channel is based on matching a gravel bar deposit across the fault (points E – F) that yields 8 m of separation. The channel bar can also be trace farther north to point G in Pit 1. The straightness of the channel margins, the fact that the fault is only one or two strands and that the northeastern margin of the channel lies adjacent to the dense Pleistocene deposits in the ridge all suggest that there is little if any distortion of the channel away from the fault.

The stratigraphic relationships in the vicinity of the offset channel do not allow us to unequivocally determine how the 8m of slip is distributed between the past two earthquakes. Layers 4 through layer 10 were removed in the 1940s when a drainage ditch was excavated along this part of the fault. However, field observations recorded in the notebook of David Star Jordan after the 1906 earthquake (Niemi *et al.,* 2006) indicate two 5 m offsets: a tree offset from its roots located ~150 m southeast of the trench site (location 1, Fig. 1B) and an offset path to the Shafter barn located ~300 m northwest of the site (location 2, Fig. 1B). About 1,300 m northwest at what was known as the Skinner Ranch in 1906, four surface offset ranging from 4.4-4.9 m were measured along a 150-m-long single fault strand (Lawson, 1908, p. 71).

Along the 1906 earthquake rupture, faulting appears to have been concentrated along a single, narrow zone in places and distributed over several faults and shear zones in other places. This may account for some of the coseismic slip variability documented along the 1906 rupture trace (Thatcher *et al.,* 1997). The 1906 surface rupture at the Vedanta site is documented to have been on a single fault trace (Lawson, 1908). These data help support the inference that the buried offset channel had a similar 5 m coseismic slip in the 1906 earthquake as those measured ~150 m and 350 m from our excavation site. If we assume that 5 m of slip occurred during the 1906 earthquake across the buried channel, then about 3 m of slip occurred in the penultimate earthquake.

Discussion and Conclusions

Our data indicate that the North Coast segment of the SAF north of San Francisco is potentially capable of rupturing in an earthquake smaller than the 1906 earthquake with a shorter recurrence interval. We date the penultimate earthquake to 1725-1776 A.D. An interval of 130 to 181 years (155 ± 25 yrs) lies between the 1906 earthquake and the penultimate earthquake defining a shorter recurrence than previous estimates. Niemi and Hall (1992) using the 24 ± 3 mm/yr determined at the Vedanta wind gap site and a slip of 4.9-5.5-m calculated a 221 ± 40 yr repeat time for a 1906-type earthquake. Bufe and Varnes (1993) modeled the Bay Area seismicity, computed a recurrence of 1906-type earthquakes of 269 ± 50 yrs, and estimated that the previous great earthquake occurred in 1637. Schwartz *et al.* (1998) surveyed available paleoseismic data from the northern San Andreas fault and suggested that an earthquake about A.D. 1650 ruptured the entire northern SAF. The concept of repeating in a single rupture with similar coseismic slip along the entire 1906 trace was one scenario adopted in probabilistic earthquake forecasts (*e.g.*, WGCEP, 2003).

Comparisons with earthquake chronologies from other paleoseismic sites along the northern San Andrea fault suggest that the penultimate earthquake at Vedanta Marsh may have ruptured the entire North Coast segment. Our data closely match the date for the penultimate earthquake of 1660-1812 A.D. at Fort Ross (Kelson *et al.*, 2006). Knudsen *et al.* (2002) report data on cores collected from Bodega Harbor and Bolinas Lagoon. At Bodega Harbor, these authors report coseismic subsidence from the penultimate event that is constrained to have occurred between 1470-1850 A.D. These data strengthen the hypothesis that the North Coast segment of SAF that includes our site on Point Reyes Peninsula and north at Fort Ross may behave as a coherent rupture segment. Turbidite data from cores recovered in the Noyo Canyon along the Offshore SAF segment suggest that the penultimate earthquake near Point Delgada occurred during the interval 1505-1820 A.D. (Goldfinger *et al.*, 2003) leaving open the possibility that the North Coast and Offshore segments either ruptured simultaneously or in closely timed earthquakes.

Even though 1906 slip is well known to have varied along the strike of the rupture (Lawson, 1908), in areas of a single, straight fault trace such as at the Skinner Ranch, offsets are notably similar (ca. 5m). A ~ 3m-slip measurement for the penultimate event slip coupled with the short recurrence (155 ± 25 yrs) at the Vedanta site would indicate that the earthquake was a smaller magnitude compared to a 5m slip in the Mw 7.8 San Francisco 1906. Using an empirical equation relating moment magnitude to either average or maximum displacements (Wells and Coppersmith, 1994), 3 m of strike slip indicates an Mw~ 7 earthquake. Our data further indicate that 2.1 to 2.7 m of slip have accumulated since the 1906 earthquake based on a 24 ± 3 mm/yr strain accumulation rate. Given our interpretation that this segment of the northern SAF is capable of rupturing in an earthquake of a magnitude smaller than 1906, the fault appears presently capable of generating a damaging (M>6) earthquake.

The 1906 earthquake had a profound effect on Bay Area seismicity (WGCEP, 2003). While a large number of earthquakes occurred on numerous Bay Area faults prior to the 1906 earthquake, a period of seismic quiescence followed the 1906 earthquake (Harris and Simpson, 1998). These data suggest a regional earthquake cycle may be controlled by 1906-type earthquakes. Our data for a penultimate SAF earthquake dating to 1725-1776 A.D clearly show

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that historical records are not long enough to capture the full variability in the seismic history. Furthermore, heavy reliance on the 1906 SF earthquake cycle may result in underestimation of other rupture scenarios. Shorter earthquake recurrence on a seismic source north of SF will likely increase the overall earthquake probability for the densely populated Bay Area.

Acknowledgements

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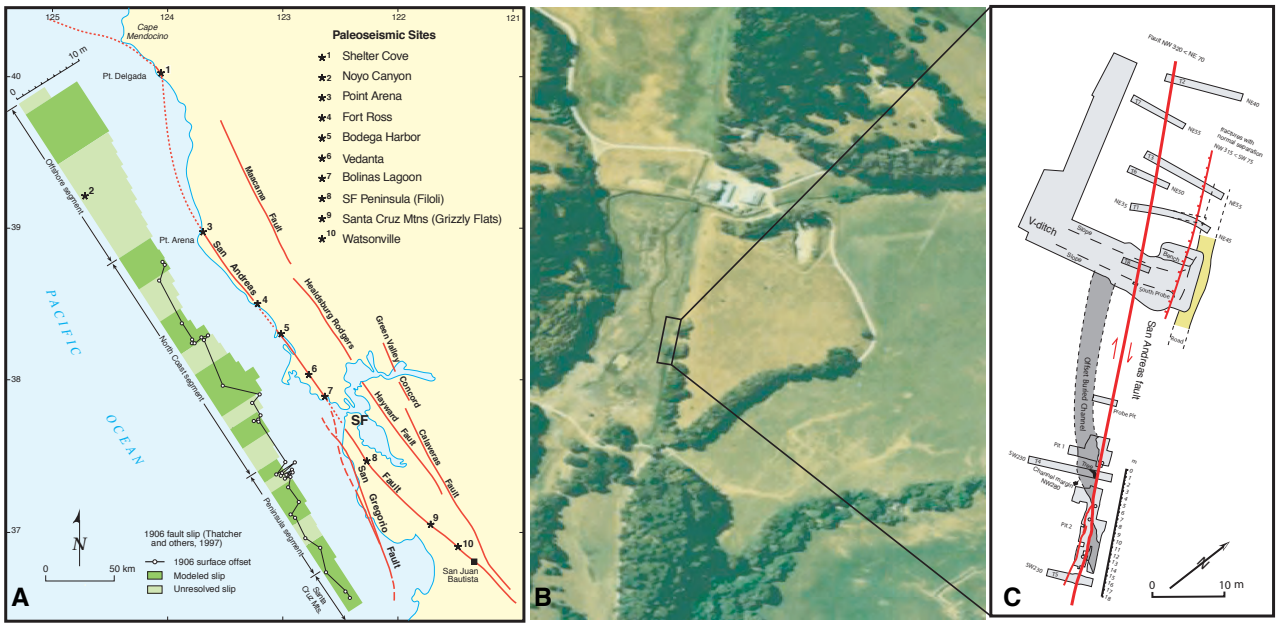

Figure 1: A) Map of the major faults in the San Francisco Bay Area showing the San Andreas fault (SAF) segments as defined by WGCEP (2003) and the distribution of surface and geodetic slip produced by the 1906 earthquake rupture (Thatcher *et al*., 1997). Stars denote paleoseismic sites. SF= San Francisco. (Modified from Kelson *et al*., 2006). B) Air photo showing the location of trenches excavated across the 1906 SAF trace at the Vedanta marsh site. C) Map of trenches (pale blue), offset channel (dark gray), and faults (red).

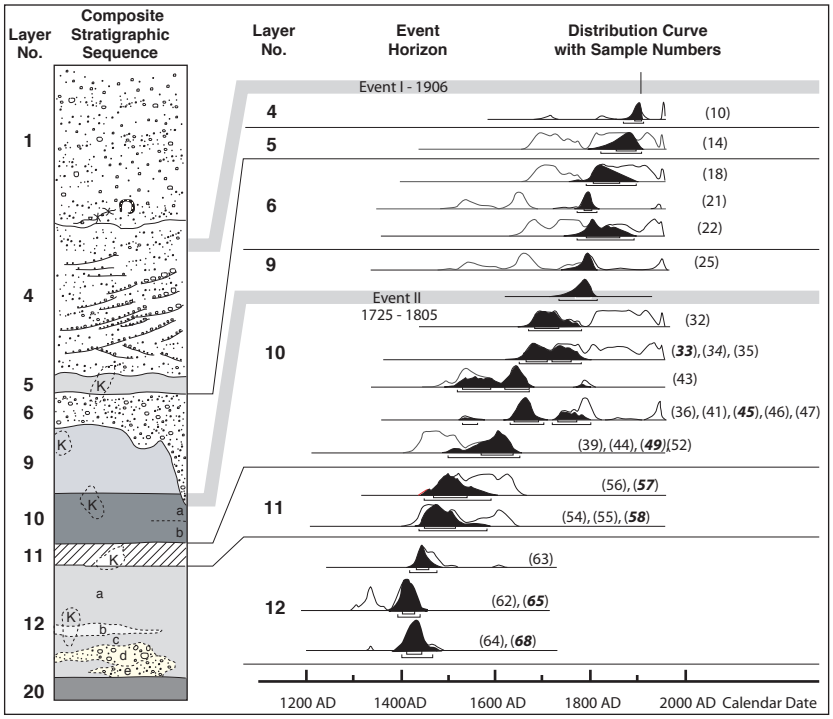

Figure 2: Composite stratigraphic section with the probability distribution function of radiocarbon data analyzed for each layer and for the 1906 and penultimate earthquakes (Events I and II, respectively). Layers 10 and 20 are organic-rich peat horizons. Layers shown in light gray are fine-grained clastic sediments and gravel layers are shown with pebbles. The probability distribution functions were determined using the OxCal program (Bronk Ramsey *et al.*, 2006). See Figures 3 and 4and Table 1 for more details on age modeling.

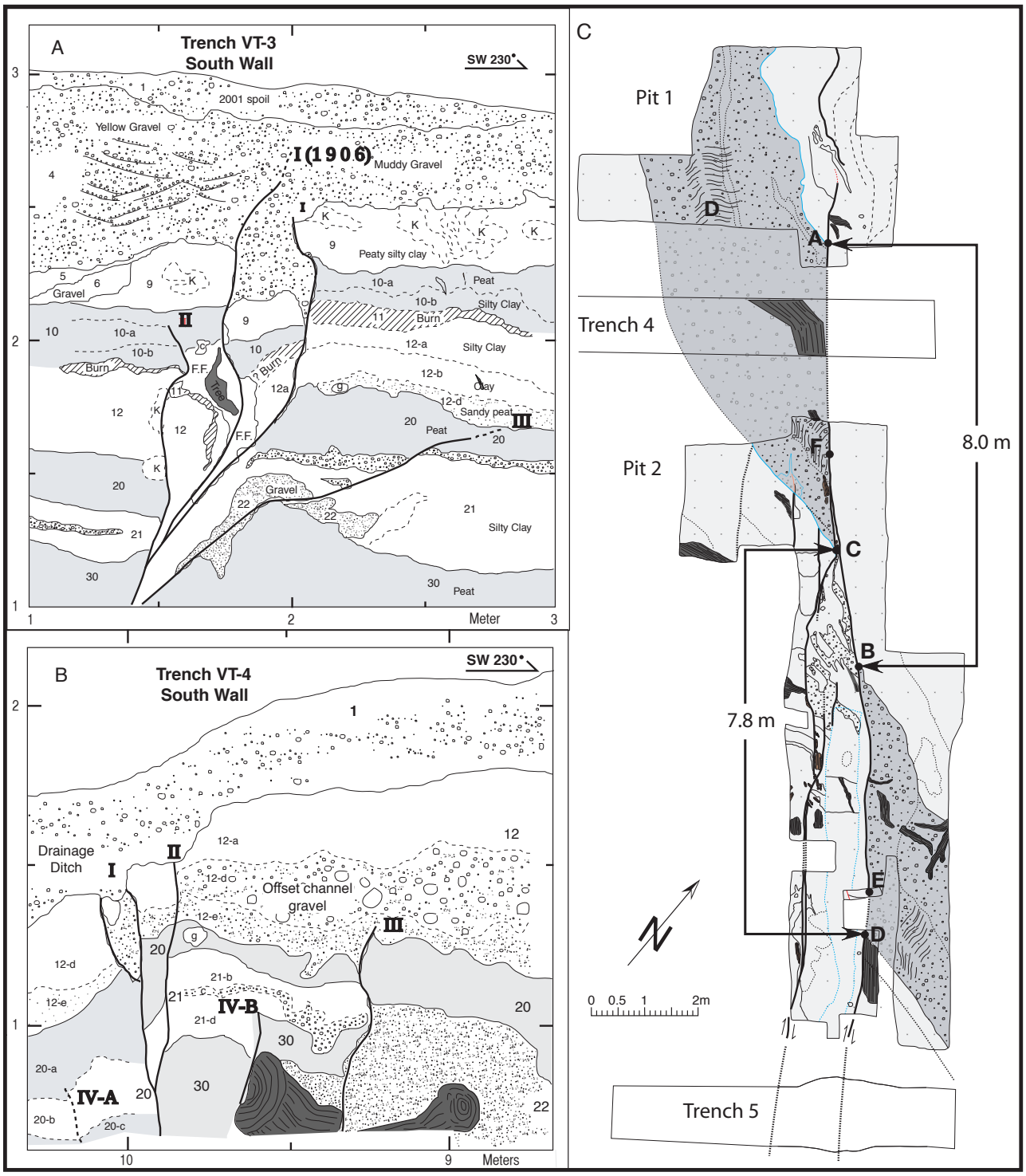

Figure 3: A) Graphic log of a portion of the south wall of Trench VT-3 showing stratigraphic the event horizon for the 1906 earthquake (Event I) in layer 4 and the event horizon of the penultimate earthquake (Event II) in layer 10. B) Graphic log of a portion of the south wall of Trench VT-4 showin the eastern faulted margin of the offset channel (layer 12d). In both figure A and B, the layers are numbered and earthquake horizons have roman numerals. K=krotovina (animal burrow). C) Geologic map of the buried channel exposed in 3-D excavations north and south of Trench VT-4. See figure 1 for location of the trenches.

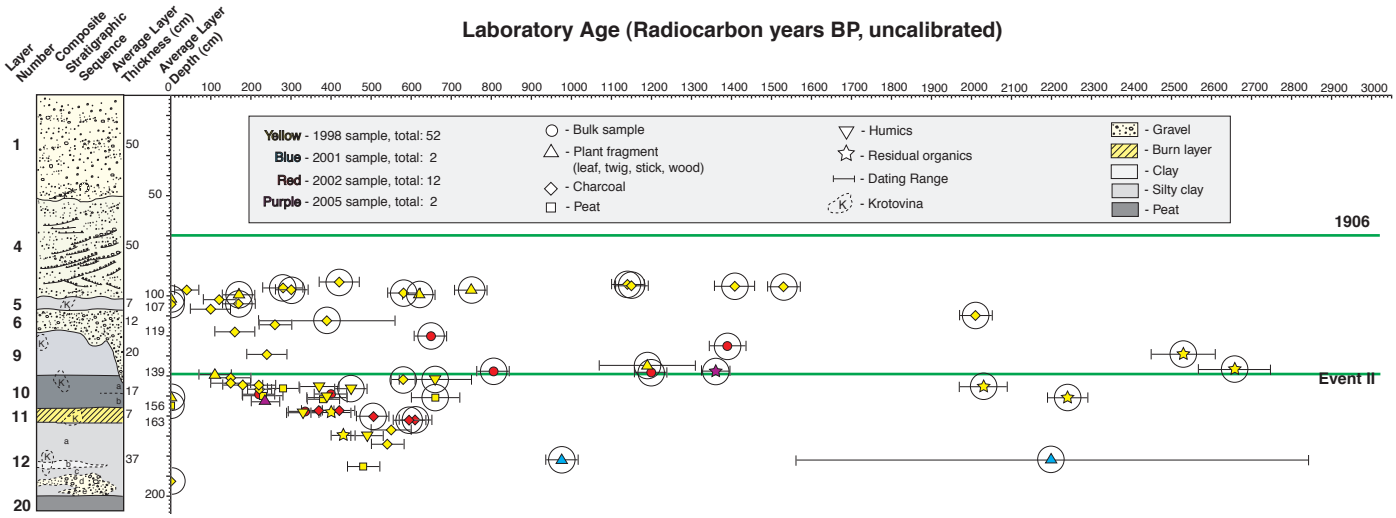

Figure 4: Scatter plot showing all uncalibrated radiocarbon age ranges with depth for stratigraphic horizons 1-12 mapped in the Vedanta trenches. Samples have been color coded for year of collection and symbols show the time of organic material analyzed. The diagram also shows the location of the event horizon for the 1906 earthquake and the penultimate earthquake (Event II). Samples with large circles were statistically removed from the age analyses using the OxCal program (Bronk Ramsey, 2006).

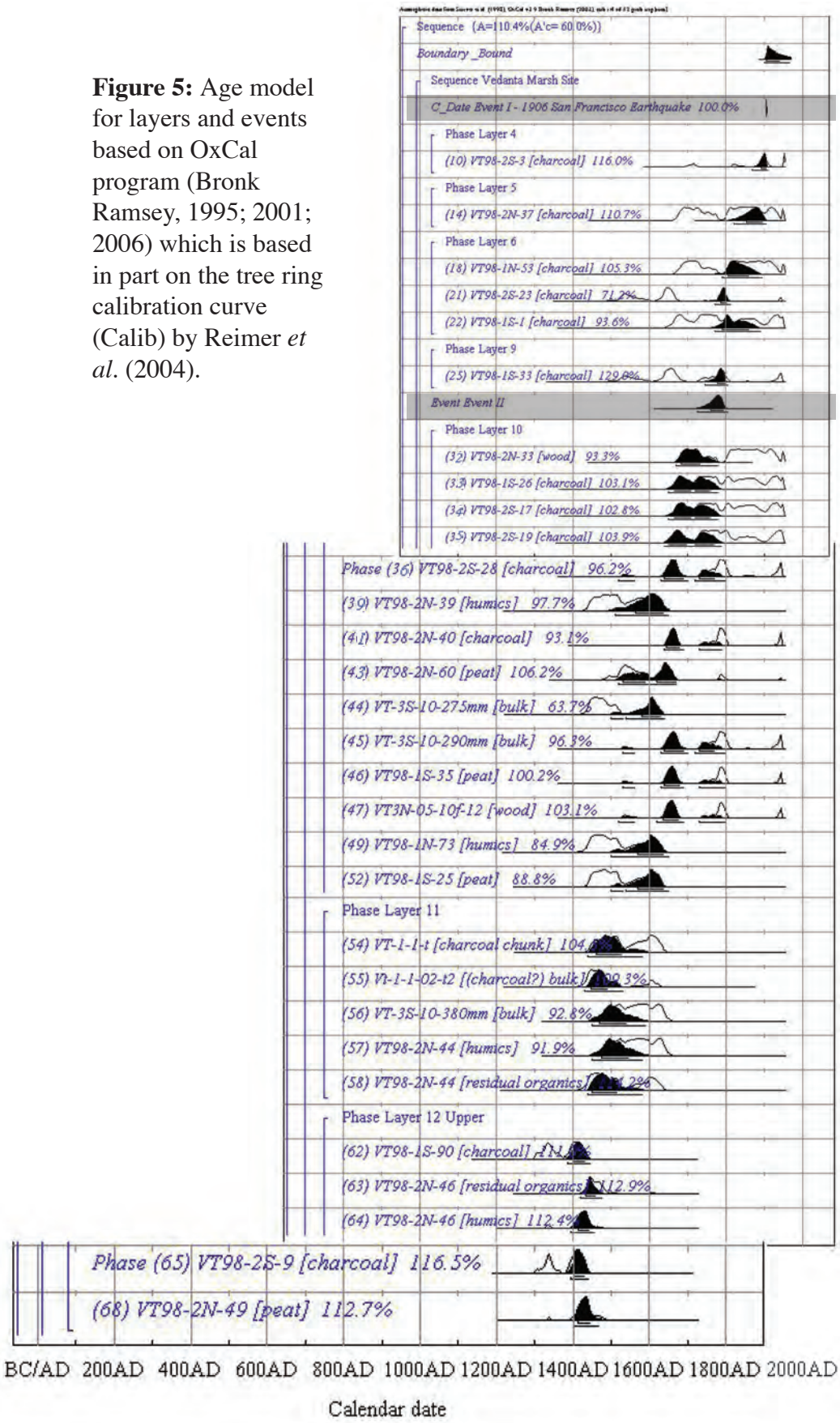

Figure 5: Age model for layers and events based on OxCal program (Bronk Ramsey, 1995; 2001; 2006) which is based in part on the tree ring calibration curve (Calib) by Reimer *et al*. (2004).