NEHRP FINAL TECHNICAL REPORT, 2006

USGS External Grants 06HQGR0150 (Goldfinger) and 06HQGR0107 (Nelson)
Title: Holocene Seismicity of the Northern San Andreas Fault Based on Precise Dating of the Turbidite Event Record Collaborative Research with University of Granada and Oregon State University.

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ABSTRACT

Numerous turbidites along the northern California continental margin are influenced by the northern San Andreas Fault (SAF). Our research focus is to: 1) analyze recurrence times of Holocene turbidites as proxies for earthquakes on the northern California active margin; 2) compare the age, frequency, and recurrence time intervals of turbidites using two methods: a) radiometric dating, (^{14}C method) and b) relative dating, using hemipelagic sediment thickness and sedimentation rates (H method) and 3) compare the paleoseismic records of northern California and Cascadia active margins where the ^{14}C and H methods have been applied. We observe that on these tectonically active continental margins, during the sea-level high-stand of Holocene time, triggering of turbidity currents is dominantly controlled by earthquakes and paleoseismic turbidites have an average recurrence time of ~ 550 yr in northern Cascadia Basin and ~ 200 yr along northern California margin. This difference in

frequency of turbidites in a subduction zone compared to a transform fault margin suggests significant differences in earthquake activity that compare favorably with independent onshore paleoseismic indicators. We have extensively used statigraphic correlation of turbidites along strike to establish continuity of event deposition, and applied multiple tests of synchroneity to test each individual event for earthquake origin.

FY 2006 Investigations Undertaken

The objective of this project is to confirm the hypothesis that turbidites deposited in channel systems along the northern California continental margin resulted from turbidity currents triggered by earthquakes on the northern San Andreas Fault and to probe that the northern San Andreas might be a good locality to test the method sand hypotheses of turbidite paleoseismology previously applied to Cascadia. During our 1999 Cascadia cruise, we collected two piston cores and one box core from Noyo Channel, 150 km south of the southern end of the Cascadia subduction zone. During June and July, 2002, we collected 69 piston, gravity and jumbo Kasten cores from channel and canyon systems draining the northern California margin on the Scripps vessel R/V Roger Revelle. We operated with an international science party of 37 scientists and students from the US, Russia, England, France, Belgium, Germany and Spain. We mapped previously unmapped channel systems with the new Simrad EM-120 multibeam sonar recently installed on the Revelle.

During the cruise, we sampled all major and many minor channel systems extending from Cape Mendocino to just north of Monterey Bay. Sampling both down and across channels in some cases was done, and particular attention was paid to channel confluences, as these areas afford opportunities to test for synchronous triggering of turbid events. While at sea, all cores were scanned using the OSU GeoTek multisensor track core logger (MST), which collects p-wave velocity, gamma-ray density, and magnetic susceptibility data from the unsplit cores. Cores were then split, and run through the MST again to collect high-resolution line-scan imagery. After the MST runs, cores were sampled with a high-resolution magnetic susceptibility probe at 1cm intervals, then were hand logged by sedimentologists. The principal use of physical properties is as grain-size proxies. The internal depositional pattern, including sandy intervals, muddy turbidite tails, bioturbated intervals and hemipelagic clay can be

distinguished in the magnetic and density logs in conjunction with the supporting X-ray, image, and lithologic log data.

In 2006, Julia Gutierrez spent one month at Oregon State, in part, to verify that grain size in turbidites is represented by the physical properties of density and magnetic susceptibility. Examples of analyses are shown for turbidites T19 and T20 in gravity core 24GC from the northern California continental margin (**Fig 1**). At Oregon State University (OSU), we are using density, color reflectance, and magnetics data as a proxy for determination of the turbidite tail-hemipelagic boundary to enhance the hemipelagic sediment analysis.

Samples for micropaleontology were taken and analyzed in real-time, providing a rapid determination of how deep into the Holocene or Pleistocene each core had penetrated. At sea and OSU, samples were taken for mineralogy, and were analyzed for heavy minerals to attempt to distinguish tributary canyon systems by their mineralogic characteristics.

We are continuing our radiocarbon dating and analysis of physical property signatures as a stratigraphic framework for the Northern San Andreas System. At University of Granada, Nelson has established a semi-independent time series for SAF events based on the hemipelagic sediment thickness (H) deposited between turbidite events.

The turbidite record for the northern San Andreas Fault, in general, is more difficult to assess because: 1) there are no good regional datums like Mazama ash or consistent Holocene to Pleistocene faunal changes to correlate turbidites, 2) the turbidites are more difficult to distinguish visually in the upper part of cores because colors are less distinct between the hemipelagic and turbidite tail sediment and 3) the amount of compaction varies for different coring systems (i.e. in 2006 we calculated 27 % in 49TC, 30 % in 54KC and 17% in 50BC at Noyo Channel, based on differences in thickness for correlated layers in different cores) (**Fig. 2, Table 1**). For this reason, we have made alternative calculations for H analysis at Noyo Channel to test calibrated ^{14}C ages that were calculated using the OxCal software to calibrate and refine radiocarbon probability models (http://www.rlaha.ox.ac.uk/orau/oxcal.html). Goldfinger et al., 2007, used this method to incorporate external constraints such as sediment thickness, sedimentation rates, and historical data to refine the ^{14}C probability distributions for a given event.

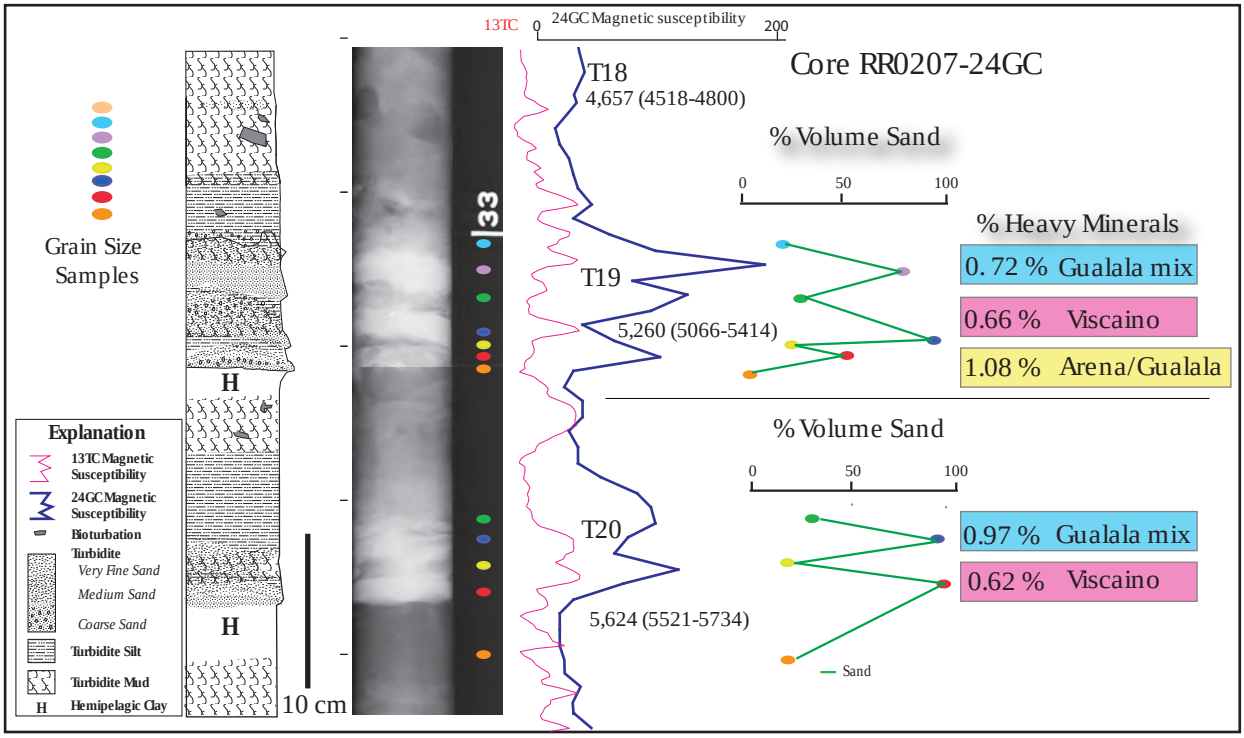

Figure 1. Grain Size analysis, magnetic susceptibility/density signatures and X- radiography in turbidites T19 and T20 in core 24GC below the Gualala-Noyo-Viscaino channel confluence (Base of T18 is also shown; see Figure 1 for location). Light tones in the x-radiograph represent dense sand/silt intervals, darker gray tones represent clay/mud. Colored dots are grain size samples. Blue trace is the magnetic susceptibility signature. Green plot is percent sand (obtained with Coulter laser counter method). The good correspondence between grain size, density, and magnetic susceptibility for the lithologies in NSAF cores is apparent, and permits use of density and magnetics as mass/grain size proxies due to the large number of analyses that would otherwise be required. These typical turbidites are composed of 1-3 fining upward sequences, each truncated by the overlying "pulse". No hemipelagic exists between pulses, indicating the three pulses were deposited in a short time interval. Only the last pulse has a fine tail, indicating final waning of the turbidity current. We interpret these signatures as resulting from a single multipulse turbidity current. Number of coarse pulses commonly remains constant in multiple channel systems for a given event. "H" denotes hemipelagic sediment between turbidites. Correlative magnetic susceptibility trace for Gualala core 13TC is also shown, as are correlative 14C ages projected from core 54KC in Noyo Channel. Source provenance affinity for each sand pulse is shown to the right, and keyed to source regions in Figure 1. This shows the arrival of discrete source pulses with a dominant lithology from multiple channel systems.

TABLE 1.- Turbidite Recurrence times at Noyo site

TURBIDITE	*H Rec (yr) 54KC	49PC	49TC	50BC	Average * H Rec	H Ages	OxCal ^{14}C Ages	OxCal ^{14}C ** Rec
1	203	207	203	207	205	97	97	142
2	174	176	174	178	176	302	239	170
3	180	179	180		180	478	409	
4								
5	151	187	188		188	658	559	270
6	151	311	282		296	846	829	348
7	172	206	199		203	1142	1177	202
8	155	231	207		219	1345	1379	260
9	206	148	164		185	1564	1639	240
10	206	215	216		212	1749	1879	270
11	155	207	207		207	1961	2149	210
12	155	215	216		215	2168	2359	260
13	206	169	216		211	2383	2619	180
14	206	169	181		194	2594	2799	

*** H Oxcal Recurrences obtained through sedimentation rates using OxCal ages and original H from each core (see Appendix 1).**
**** Correlative difference between OxCal ages (i.e, 239 yr - 97 yr is 142 yr, the Recurrence time between T1 and T2)**

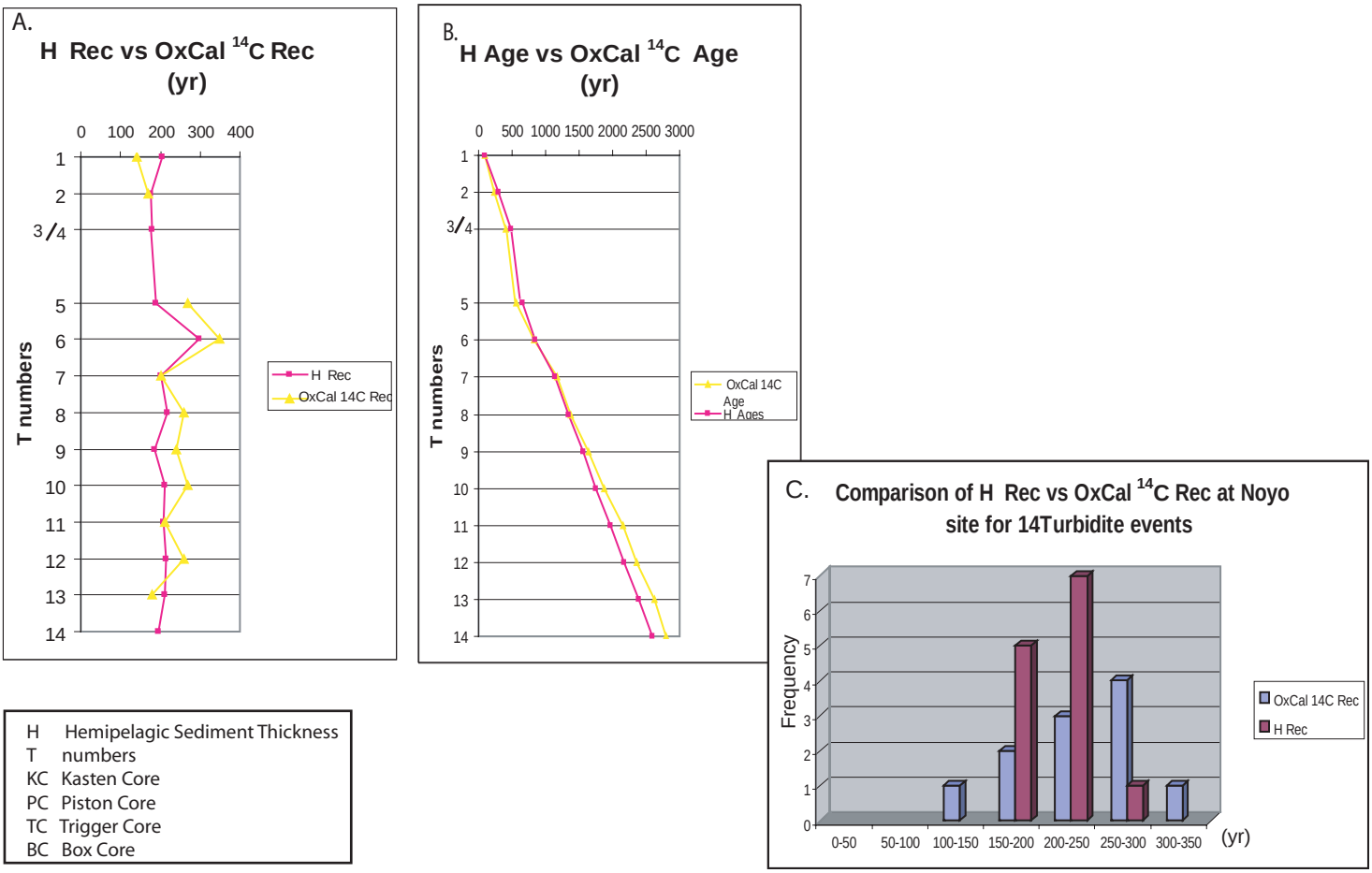

FIGURE 2. Noyo Channel Recurrence Analysis based on 14C ages obtained with the OxCal Software 49PC (piston) and 49TC (trigger), 54 KC (Kasten) and 50BC (box) cores. Plots display results of Table 4. Plot A shows the hemipelagic sediment recurrence times (H Rec) in dark pink and the OxCal recurrence times (OxCal 14C Rec) in yellow through 14 correlative turbidites. Note that the hemipelagic sediment recurrence time is an average curve between all the recurrence times obtained in the four cores at Noyo channel (see Table 1 above) . Both curves are in good agreement but in general, the hempelagic sediment recurrence times show less variation than 14C times. Plot B shows the OxCal 14C Age in yellow vs the hemipelagic sediment ages (H Ages) in dark pink through the same 14 turbidites. Note the H ages are equal or younger from T6 to T14 whereas they are a little bit older in T2, T3/4 and T 5 (Table 4). Histogram C exhibits the distribution of turbidite recurrence frequencies at Noyo Channel for the first 14 turbidite events. Note the H recurrence bars (H Rec) show a more normal distribution than the OxCal recurrence bars (OxCal 14C Rec), with maximum, recurrence times of ~250 yr and minimum times of ~150 yr.

At OSU, we are using OxCal, to constrain earthquake ages. Multiple ages for a given event are taken into consideration, and rather than averaging, iterative Bayesian models are used to narrow the probability distributions for events that are known to correlate, and/or have independent constraints such as the known1906 San Francisco earthquake, the first San Francisco mission, and also the time between earthquakes established using hemipelagic constraints (Goldfinger et al., 2007, Nelson et al., 2000, Ramsey, 2001). Where age data are missing, sedimentation rates and hemipelagic intervals alone can be used. Ages calculated in this way can substitute for undatable events, and serve as a check on the ^{14}C ages. Using ^{14}C ages modified by the OxCal methodology, we have done a parallel H analysis for Noyo Channel obtaining recurrence times and ages based on hemipelagic sediment thickness (Fig. 2, Table 1, and Appendix 1). The basic methodology to obtain these recurrences follows the same techniques used in Cascadia Basin, except that for the Noyo Channel data we do not use Cal. yr B.P. ages. Instead, we use ^{14}C ages modified by OxCal with all the constraints included (sampling depth, erosion, and hemipelagic sediment thickness). The same analysis has been done for each core independently because each one has a different compaction rate.

As in Cascadia Basin at the Noyo location, the hemipelagic sediment thicknesses were measured between the turbidite events in cores 49 PC/TC, 54KC and 50BC and an independent analysis of recurrence interval times for each core was done considering its individual compaction rate. The total H is added to obtain the cumulative H and the sedimentation rates are calculated using OxCal ^{14}C ages. The sedimentation rates are calculated using a moving window. The recurrence times were then averaged for each correlative turbidite. In some cases we average the recurrence times from three cores and in cases where one core has an extreme value, the average is based on two cores (except for events one and two where 4 recurrences are averaged) (Table 1). To obtain H ages we follow the same procedure used for Cascadia Basin. For OxCal ^{14}C recurrence times, we determine the time between each set of correlative turbidites.

We collected new data from the cores to assist in stratigraphic correlation, and completed the stratigraphic correlation for the uppermost ~ 3000 years along the NSAF. To compensate for a very low sedimentation rate during this time in some cores, we collected 3mm spatial density magnetic data. These new data allowed correlation between cores that the coarser original data did not, resulting is successful along strike

correlation. We also collected XRF analyses from several cores on a test basis to investigate the possibilities tehse data offer for fine scale detection of hemipelagic-turbidite tail boundaries, and for stratigraphic correlation with these high resolution data. These data were collected and the XRF facility at Woods Hole Oceanographic Institution courtesy of Livieu Ghosan.

FY 2006 Results

Hemipelagic Thickness (H) Analysis

In FY 2005 at University of Granada we continued refining the new techniques based on the thickness of hemipelagic sediment between turbidites (H). These techniques can be used to independently evaluate and correct the AMS radiocarbon (^{14}C) ages because of the following reasons:

- The deep sea provides an independent time yardstick derived from a constant rate of hemipelagic sediment deposited between turbidites.
- Hemipelagic thickness/sedimentation rate = years which provides a set of turbidite recurrence times and ages to compare with similar ^{14}C data sets
- H can be used to evaluate data reliability (e.g. correct ^{14}C ages for sampling depth and erosion of sampled interval).
- H data is available for every turbidite event from multiple cores at each location compared to a single incomplete set of radiocarbon ages at each location.

Hemipelagic and radiocarbon Oxcal Methods Results

The tectonic setting of the northern California margin has been widely studied onshore, and turbidites offshore of this region have also been demonstrated to correlate well with the onshore earthquake record even though no good datum such as the Mazama Ash or colour change of Pleistocene to Holocene hemipelagic sediment have been found (Goldfinger et al., 2003a; 2003b; 2007).

To aid in the analysis of seismo-turibidtes, the objective of the project has been a

comparison of turbidite ages, frequencies, and recurrence intervals using two methods applied previously in Cascadia: 1) radiometric dating, based on radiocarbon ages of Foraminifera in the hemipelagic sediment just below each turbidite modified by Oxcal (see FY2006 undertaken) (^{14}C method), and 2) relative dating, based on the measure of the time interval between two turbidites, using hemipelagic sediment thickness and sedimentation rate (H method). These two approaches provide complimentary semi-independent methods to determine turbidite recurrence times. We focus on the H method to refine turbidite ages, determine the most accurate recurrence time history and frequency of turbidites and show the dominant control by earthquake triggering in the active tectonic margins as the northern California.

The hemipelagic thickness analysis has been applied to the cores 49PC, 49TC, 54 Kasten core (KC) and 50 box core (BC) of the Noyo Channel key site on the northern California Margin (Table 1).

In the northern California margin we find that the maximum and minimum of H recurrence times are 296 yr and 176 yr, respectively and the maximum and minimum of OxCal ^{14}C recurrence times are 348 yr and 142 yr. The average H recurrence time is 207 yr and the average OxCal ^{14}C recurrence time is 232 yr (Table 1). The pattern of recurrence and age variations down the core for the first 14 events at Noyo Channel is plotted in Figure 1A and B. Note that events 3 and 4 are considered as one turbidite event because there is an absence of hemipelagic sediment between pulses in a single continuous turbidite.

The recurrence curves show parallel results suggesting that both data sets are compatible but that H recurrence times have less variation compared to ^{14}C recurrence times. Comparing both data set, turbidites T2, T7 and T11 exhibit almost equal recurrence times, but the rest of the events have lower values of H recurrence times (about 40-50 yrs of difference). The highest frequency of H recurrence times is between 200-250 yr (Fig. 2C). The OxCal ^{14}C recurrence times show maximums between 300-350 yr and the distribution of frequencies is lower and broader than H recurrence times. The OxCal ^{14}C Age compared to H age plot has younger ages from T1 to T5, similar ages from T6 to T8 and older ages from T9 to T14, with an increasing difference down the core, that, similar to Cacadia dates also appears to be related to the cumulative error down core in H ages.

Confluences and Mineralogy

Figure 1 shows the stratigraphy of two typical NSAF turbidites in core 24GC below several confluences of Viscaino, Noyo, and Gualala Channels. At this site, we find that the multiple coarse pulses which also reveal the heavy mineral assemblage from individual canyon sources, stacked vertically in order of arrival at the core site. The turbidites at this site also have no hemipelagic sediment between the sand pulses, indicating little time passage between deposition of each pulse (the alternative, removal by erosion, is possible, but would have to occur in each turbidite at every correlative site). Further downstream, we observe bimodal heavy mineral coarse fractions, with mineralogic peaks representing the separate provenance components (**Figure 1**). **Figure** 1 also shows the magnetic susceptibility trace for the same two correlative turbidites, upstream of the confluences, in core 13TC. We observe no significant change in the stratigraphy between these two sites, despite input from multiple sources at the confluences. Further downstream at the site of core 31PC, we find that individual turbidites have the same stacking of coarse pulses, but the provenance input is less distinct, suggesting further mixing downstream. Goldfinger et al. (2007) show our stratigraphic correlation detail for a series of cores upstream, near, and downstream of the confluences of Viscaino, Noyo, Gualala, Albion, and Cordell Channels from ~3500 ybp to ~10,000 ybp because the upper section is poorly preserved in some of the downstream cores. The downstream cores have, as yet, only a few dated turbidites, in part due to the low foram abundance at water depths in excess of 3500 m at these sites. The section ages are bounded by several late Pleistocene ages and the age of 4676 (4525-4810) ybp for T18 in core 26PC which we use to constrain the upper part of the correlation.

While additional ^{14}C ages are still needed, we test for synchroneity by carefully matching events between upstream cores at Noyo and Gualala Channels and correlative events in the downstream cores in this time range. We matched the stratigraphy and checked for presence/absence of hemipelagic sediment between events (or an erosive event that removed it) as well as the multiple cues used in physical property correlation. We observe that upstream (49PC) and downstream cores (e.g. 25GC) both contain 22 events in this time range. Differences between the two are minor, and appear mostly attributable to local basal erosion. These tests include correlation with core 31PC, which is actually below a total of four confluences, with input from a total of six channels, while cores 24GC, 25GC, and 26PC each sample three channels. The good

correlation between these cores suggests that input mixing at each confluence has little effect on the stratigraphy of the turbidites, even though the number of sources increases at each confluence. We infer that synchronous triggering is the only viable explanation for this, and are unable to suggest an alternative. Non-synchronous triggering should produce an amalgamated record that increases in complexity below each confluence, with only partial correlations if any, for the synchronous events. The mixing and stacking of the provenance components further suggests synchronous arrival at the confluence. From these results we infer that the sites included in this analysis pass a strict test of synchroneity, and are most likely of earthquake origin. Further analysis of the remaining confluence sites is in progress. A similar use of mineralogic provenance to fingerprint source channels and test for earthquake origin has been used in the Sea of Japan by Shiki et al. (2000).

Stratigraphic Correlation

We have made a preliminary correlation of events along the length of the NSAF margin using subsurface correlation of the physical property logs as described above. This has been hampered somewhat by the fact that the turbidite signal for most of the NSAF channels is subdued by comparison to Cascadia. This is not surprising, given smaller earthquakes and greater epicentral distance to the canyons. The correlation is made within a ^{14}C age framework, with some vertical stretching of cores required due to varying sedimentation rates.

Figure 3 shows the regional correlation or turbidite stratigraphy spanning the Holocene, and **Figure 4** shows the upper ~2100 years of record, making use of high-resolution magnetic susceptibility data (3 mm spacing, point sensor). We focus here on the upper 2100 years of the record; the analysis of earlier periods in the Holocene is the subject of ongoing investigation. Our Noyo Canyon cores, 49PC and companion Kasten core 54KC, are particularly important because unlike all the other channel systems, Noyo Canyon is actually cut by the NSAF, and has an epicentral distance of zero. Most likely for this reason, the turbidite record there is expanded in thickness, making investigation of the details of each event much clearer in those cores. Cores to the south have much reduced sedimentation rates, even though they are closer to the Russian River source, the largest river along the North Coast section of the NSAF. We speculate that the low hemipelagic sedimentation rates might be related to capture of much of the Russian River drainage and diversion into the San Joaquin Valley, which

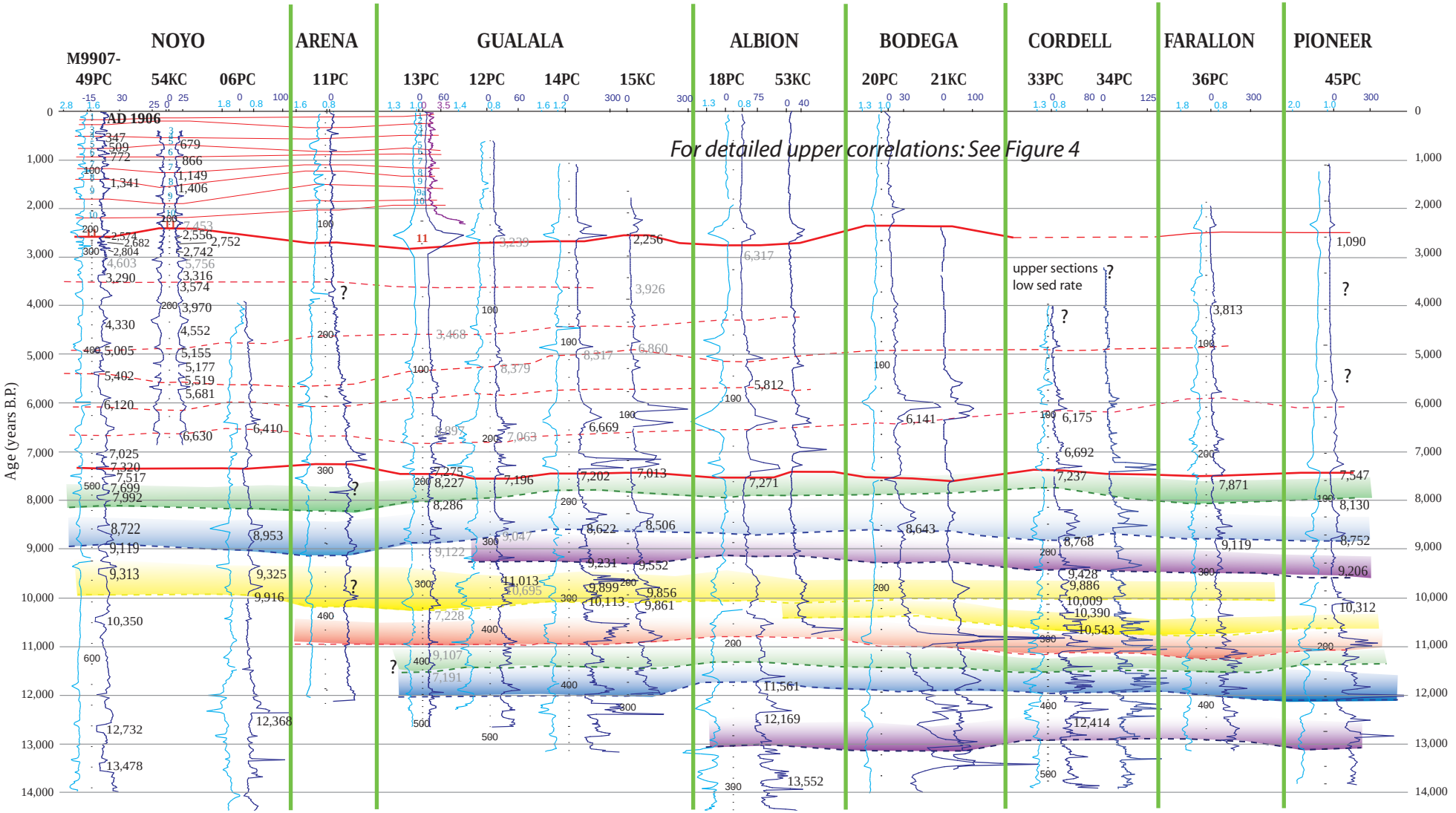

Figure 3. In progress Holocene correlation diagram for NSAF system cores. Light blue traces are gamma density, dark blue traces are magnetic susceptibility. (Kasten cores "KC" do not have associated density data as they are too large for the scanner). This correlation is approximately oriented in a 14C age framework, with some vertical stretching of cores based on differing sedimentation rates. Peak probability calendar ages corrected for sample thickness are shown in black (gray if questionable) below the dated turbidite, 2s range omitted for clarity. Upper ~2500 years of data shown in Figure 7 using 3 mm high-resolution magnetic susceptibility data. Significant correlation horizons, are shown, but not all individual events are depicted to reduce clutter. Color scheme matches events in Figure 4 for events common to both figures.

may have occurred during the Holocene (Hopkirk, 1974). By comparison to the robust Noyo record, most of the events along the NSAF in other channels are subdued, and indeed the upper 10 events shown in these figures are very fine silt turbidites not visible to the naked eye. Their unique signatures in the physical property data, however, allow good correlation between sites. We have collapsed a much larger set of core records onto the representative correlation diagrams shown in **Figures 3 and 4**. A key stratigraphic datum in this correlation is T11, which is a robust event correlated and visible as a sandy turbidite in all cores, dated at 2574 (2397-2681) ybp in Noyo Channel, and 2256 (2080-2401) ybp in Gualala Channel. We suspected that the original ^{14}C age for this event (~2600 ybp) was too old (possible basal erosion) and have used constraints from hemipelagic sedimentation rates surrounding this interval to estimate the ~2100 ybp age in **Figure 4**.

As in Cascadia, correlation of individual events based on the grain size distribution represented by the magnetic and density data are possible both along strike and down channel. Robust event "signatures" that can be recognized both within single channels, between multiple channel systems, and above and below confluences support the inference that they in fact represent the same source events, independent of other methods. We observe that the correlated events retain their essential character, typically made up of a stack of coarse pulses, for considerable distances along the margin. The "signatures" are observed to evolve downstream where coarse pulses merge with distance from the margin. The event "signatures" also evolve to some extent along strike in some cases, although in other cases stratigraphic sections at opposite ends of the fault system match as well as close neighbors. These properties can be observed through close inspection of **Figures 1-4**.

Radiocarbon Time Series and Comparison to Onshore Paleoseismic Sites

In terms of event ages and their distribution in time, the youngest 15 events have a mean repeat time of ~200 years, with a standard deviation of 60 years. Using peak PDF values for event ages, the minimum interval value is ~95 years between T7a and T7 and T12a and T12, and the maximum value is ~270 years between T5 and T6 and T10-T11 (we refer to the third event as "T3-4" because it is a doublet that may yet prove to be two events). We find these values reasonably consistent with previous paleoseismic data onshore. The ages shown in **Figure 6** include 11 ages reported by Zhang et al. 2006 from the Vedanta Marsh site, and 5 ages reported by Kelson et al. 2006 from sites

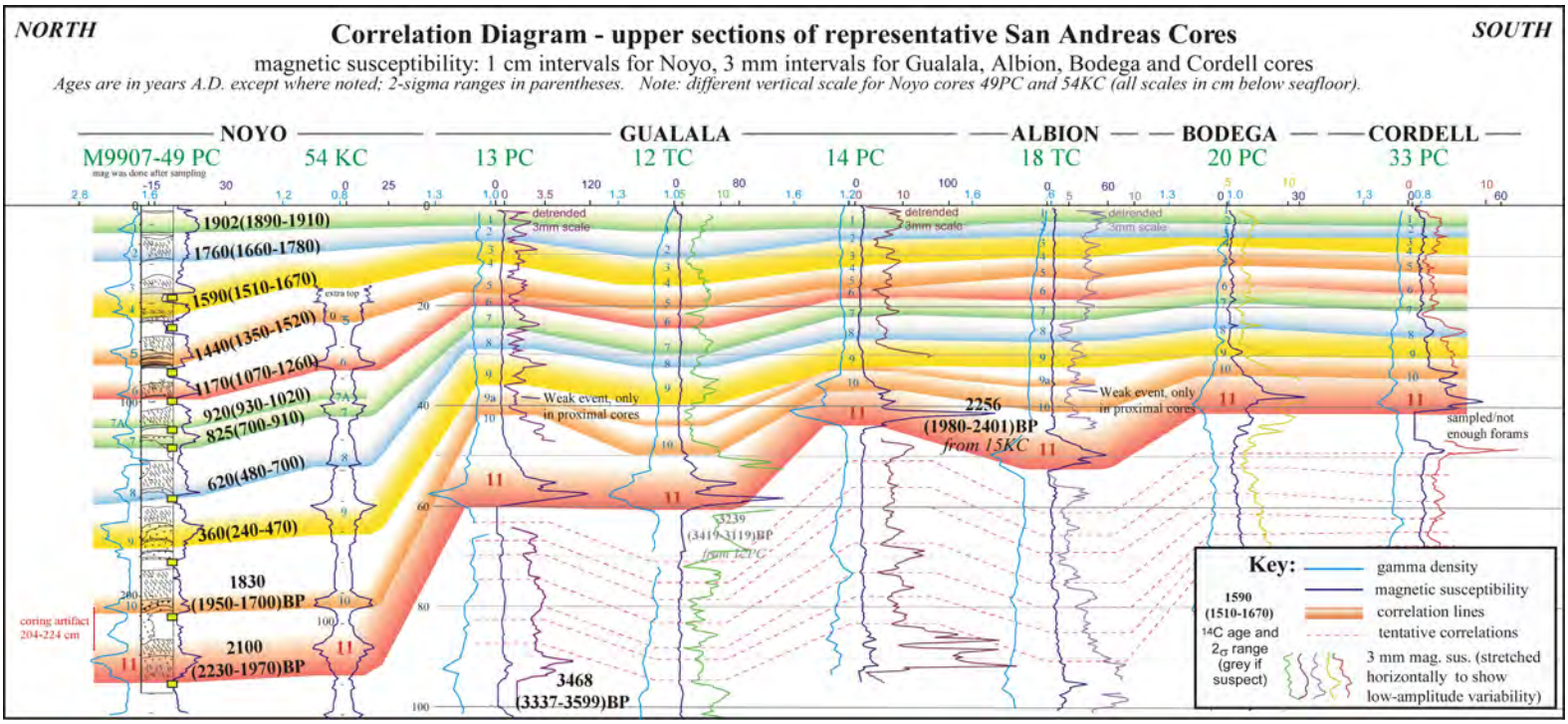

Figure 4. Correlation diagram for the uppermost ~ 3000 years in NSAF system cores. Channel locations shown in Figure 1. Light blue traces are Gamma density, dark blue are magnetic susceptibility. 1 cm resolution magnetic susceptibility data are shown for Noyo cores, and 3 mm high-resolution data are shown for all other cores. The 3mm magnetic susceptibility data is stretched horizontally (variable colored traces) to show the low amplitude signal resolved with this resolution. Event numbers in blue at core centers. NSAF cores all have a number of relatively thick events that serve as excellent datums, and are the basis for our regional correlations in Figure 4. The uppermost of these marker events, a very distinctive multipulse event dated at ~ 2100 ybp, is shown labeled "11" in red. Gualala, Albion, Bodega and Cordell and 54KC core tops have been vertically expanded for viewing to offset low sedimentation rates in the upper 2100 years for all cores. OxCal age peaks and ranges shown on cores 49PC and 54KC at left; these ages do not match figure 6 ages, for which data are insufficient for OxCal analysis. Gualala ages have been corrected for sample thickness only. Correlation for weak events T7a and T9a uncertain and not shown beyond Noyo Channel. T7a is datable, and included in our time series; T9a appears to be limited to two adjacent proximal core sites, and is not included in the recurrence statistics. 49PC high-resolution magnetic trace is punctuated by sample voids, indicated by yellow squares. Color scheme matches events in Figure 3 for events common to both figures.

at Fort Ross. These results indicate that the penultimate event occurred ~AD 1700-1750 north of San Francisco, and that the age correspondence is good for the last ~2300 years when comparing Noyo Canyon marine ages to Vedanta and Fort Ross land ages. For a given time interval, we see approximately the same total number of events (+ 1) onshore and offshore, suggesting either a coincidence, or that land and marine sites are recording the same events. Further support for a linkage between the turbidite series presented here and onshore earthquakes, is the good correspondence between land and turbidite recurrence intervals, which are 200 years and 230 years for marine and land ages respectively. Individually, most ages except Noyo T3-4 (a doublet) and T7a have significant overlap of age ranges (**Figure 6**). In addition, our event T3-4 was not reported at Fort Ross, and our event T9 was apparently not observed at Vedanta. Nevertheless, our preliminary stratigraphic correlation and age series, taken together, suggests that the previous 11 events may be correlated from Noyo Canyon to at least to the latitude of Vedanta, just north of San Francisco. If correct, our initial along-strike correlations imply rupture lengths for many (or most) events of > 250 km.

Contributions to paleoseismic and human hazards studies on the northern San Andreas Fault (SAF)

Our study of hemipelagic sediment thickness analysis has developed the first extensive data set to infer average recurrence times for paleoseismic turbidites on the northern California margin and compare them with the paleoseismic turbidites of the Cascadia margin. Great earthquakes on the northern California margin are greater than twice as frequent on average (200 yr) as those on the northern Cascadia Subduction Zone margin (~ 550 yr) and this is corroborated by the onland record .

At Olema, 45 km north of San Francisco, Niemi and Hall (1992) estimate that if the 4-5 m slip event recorded in 1906 was characteristic, the recurrence time for such events would be 221±40 yr. Both our data and 10 new ages from the Vendata site and sites near Fort Ross suggest an average recurrence interval of ~200-230 yr (Goldfinger et al., 2007).

Along the Cascadia margin, the tsunami record at Willapa Bay, Washington, and the onshore record of Sixes Rivers, Oregon, show average recurrence times of great earthquakes for the past 4000 years (533 and 529 yr respectively) that agree quite closely with those of the turbidite paleoseismic record of the past 4000 yr (~520 yr)

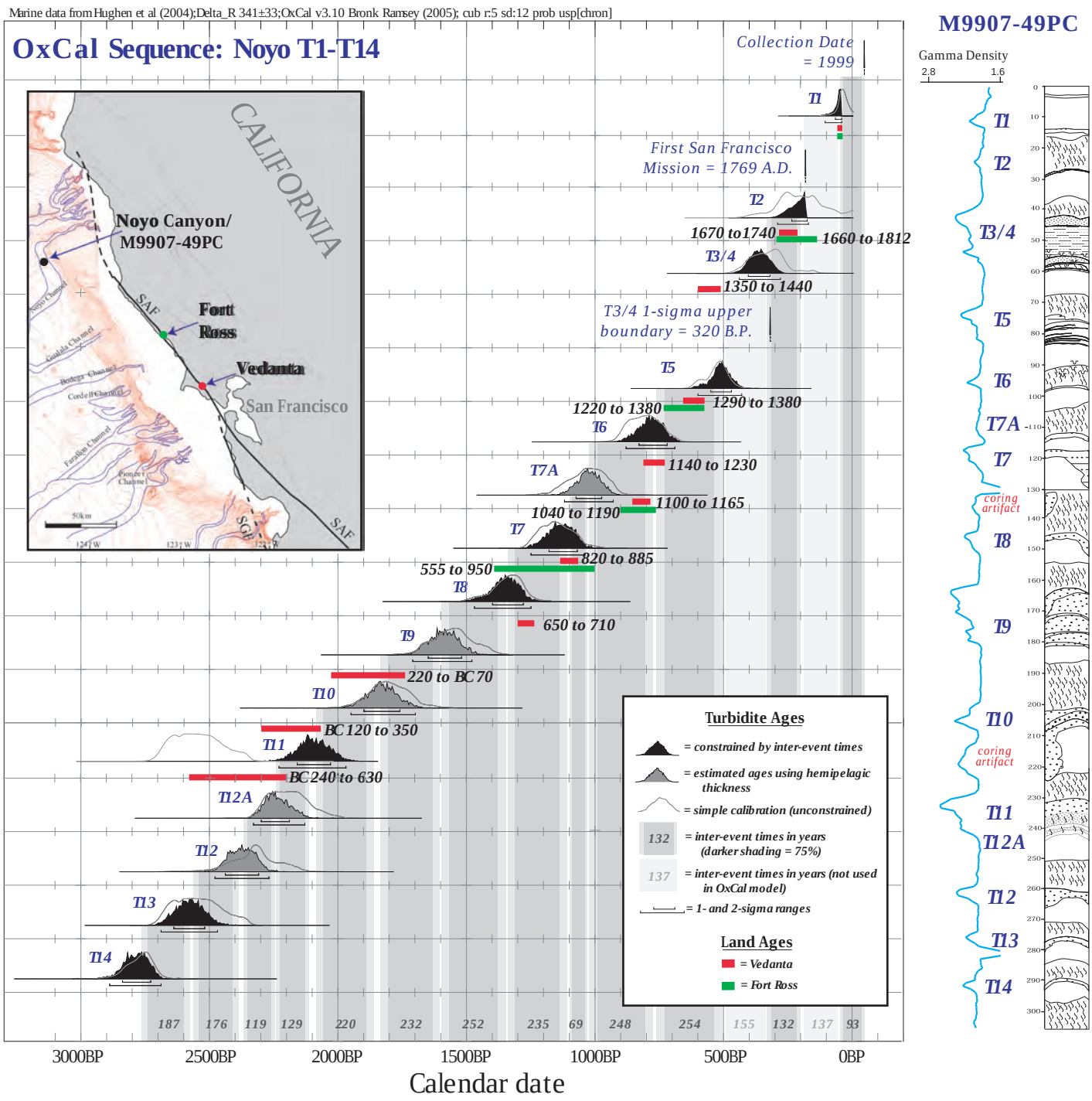

Figure 5. OxCal age model for the youngest 15 events in the NSAF offshore system, and comparison to onshore ages. Inter-event times based on hemipelagic sediment thickness (represented by gray bars) were used to constrain original 14C calendar age distributions (gray traces) using the SEQUENCE option in OxCal. Inter-event times were estimated by converting hemipelagic sediment thickness between each pair of events to time using the sedimentation rate. Events dated more than once were combined in OxCal prior to calibration if results were in agreement; if not in agreement, the younger radiocarbon age was used in the final model. Five ages are calculated from sedimentation rates where not enough forams were present for 14C dating. The resulting probability distributions (filled black, grey for undated events) are mostly in good agreement with land ages from Fort Ross except for T3-4 and T7a (green lines; [32]) and Vedanta (red lines; [31]). See inset for geographic locations. See Electronic Supplement for OxCal input data and sedimentation rate curves.

(Nelson et al., 2003). Consequently, we have the potential to go back in time using both the turbidite and onshore paleoseismic records to establish a more complete model of earthquake recurrence times to be applied in different active continental margin settings.

Our data showing two different recurrence frequencies is an important verification of the hemipelagic thickness and turbidite paleoseismic methods.

Non-Technical Summary

Cores from Noyo Channel on the ocean floor off northern California have been studied for sand layers. These sand layers are thought to represent times when great earthquakes on the northern San Andreas Fault have shaken the continental margin, resulting in landslides that transport the sand down the channels. We have determined the ages of these layers, and these ages suggest that major earthquakes have occurred on average every ~ 200 yr for the past ~ 2600 years with a minimum time of ~ 150-175 years between earthquakes. However, more cores and land records must be examined to verify this preliminary record of earthquakes.

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Availability of Data

All processed AMS radiocarbon age data is available in excel tables. Analogue records of core lithologic data are archived at the OSU core repository where the cores are stored.

Additional interpretative data of core logs are available in Adobe Illustrator files that reside at both OSU and UGR. The general GIS data base of swath bathymetry, seismic profiles, core locations etc. resides at OSU. The contacts for all the aforementioned data sets are Hans Nelson (odp@ugr.es), Julia Gutiérrez Pastor (juliagp@ugr.es) and Chris Goldfinger (gold@coas.oregonstate.edu) at the UGR and OSU addresses listed on the first page.